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Safety indicators for the safety assessment of radioactive waste disposal

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Working Group on Principles and Criteria
for Radioactive Waste Disposal

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FOREWORD

Plans for disposing of radioactive waste 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 the approach to establishing that disposal facilities are safe, 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 Working Group under the International Radioactive Waste Management Advisory Committee (INWAC). The Working Group started its work in 1991 as the "Working Group on Principles and Criteria for Radioactive Waste Disposal". With the reorganization in 1995 of IAEA safety standards committees a closer linkage has been established between the Working Group and its parent committee, now titled the Waste Safety Standards Committee (WASSC).

The subject of this report, safety indicators complementary to dose and risk, was discussed in the first report of this Working Group "Safety Indicators in Different Time Frames for the Safety Assessment of Underground Radioactive Waste Repositories" (IAEA-TECDOC-767 (1994)). Subsequently an IAEA co-ordinated research project on the subject was started in 1999. At an early stage of that project, and, in part, as a starting point for the project, the subject of safety indicators in the context of the geological disposal of radioactive waste was reviewed. This report is the product of that review. The report was produced by consultants and critically reviewed by the Working Group on Principles and Criteria for Radioactive Waste Disposal. A number of ideas have been included in the report where there is no consensus on the validity or usefulness in the context of safety indicators. Their inclusion is deliberate to promote further debate with a view to eventual development of consensus.

Other reports of the Working Group are "Issues in Radioactive Waste Disposal" (IAEA-TECDOC-909 (1996)), "Regulatory Decision Making in the Presence of Uncertainty in the Context of the Disposal of Long Lived Radioactive Wastes" (IAEA-TECDOC-975 (1997)) and "Critical Groups and Biospheres in the Context of Radioactive Waste Disposal" (IAEA-TECDOC-1077 (1999)), respectively.

The reports of the Working Group on Principles and Criteria for Radioactive Waste Disposal contain the developing views of experts within the international community and should be of use to those engaged in producing national and international standards and guidance in this area. However, they should not be seen as representing a 'Member State consensus' on the subjects being discussed.

The IAEA wishes to acknowledge the contribution of Mr. B. Miller of the United Kingdom to the drafting of the report. The IAEA officer responsible for this publication was K. Hioki of the Division of Radiation and Waste Safety.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

In siting and designing disposal systems for radioactive wastes, a key requirement is that they should pose no significant long term hazard to human health, and should cause no unacceptable harm to the environment. Safety indicators are the characteristics or consequences of a disposal system by which potential hazards or harm can be measured, and may be evaluated in the course of making a safety case for a disposal system. The role and utility of different types of safety indicators over different time-scales have been discussed in a previous IAEA publication [1]. The most widely used indicators in the context of the long term safety of disposal systems are those of radiological dose and risk. The dose to human beings that are assumed to inhabit a specific location and to be exposed, in some way, to radionuclides migrating from the disposal system is typically evaluated in the course of making a safety case. The dose can be transformed to a corresponding risk level using a suitable dose/risk conversion factor [2], and taking account of the likelihood of the scenario envisaged for exposure. In general, a safety case needs to provide reasonable assurance that the eventual consequences of any migration of radionuclides to the accessible environment are in compliance with the dose and risk standards that are acceptable today [2, 3]. It would address both the adequacy of the design in respect of containment, isolation and multiple barriers together with the adequacy of the safety assessment.

The multiple barrier concept is of particular importance in respect of assuring an appropriate level of containment, both in terms of the timeframe over which containment can be assured and the rate of migration from the waste form as the containment features degrade over time. Another important element of containment is the retardation of materials migrating from the waste form and engineered barriers of the disposal facility and through the surrounding geosphere. In respect of isolating the waste from the accessible environment depth and disposal facility integrity play important roles, together with the siting of the facility in a area that is unlikely to be disturbed by human or natural events over the timeframes of concern. In evaluating the safety of disposal facilities both the adequacy and diversity of the containment and isolation functions need to be assured and a range of indicators can play a role in providing this assurance.

In view of possible radionuclide migration only taking place after long time scales, the use of safety indicators, other than dose and risk, to assess and confirm the safety of disposal systems for radioactive waste has been suggested repeatedly through the years. The IAEA publication [1] pointed to problems associated with the use of dose and risk as measures of safety, particularly in the far future. The difficulties are mainly related to the uncertainty surrounding their evaluation, to providing direct evidence of assurance and to public communication. It was concluded that a safety case can most effectively be made by the combined use of several safety indicators, including not only dose and risk, but also environmental fluxes and concentrations and the time-scales of relevant processes, while recognising that dose and risk remain the most fundamental indicators of safety.

In a report produced for the Swedish National Institute of Radiation Protection (SSI), geochemical fluxes of radionuclides and stable pollutants are discussed in general terms as references for the assessment of the safety of repositories [4]. In a more recent report produced for the Swedish Nuclear Power Inspectorate (SKI), geochemical data from the Äspö site in Sweden were reviewed to derive fluxes of naturally occurring radionuclides being released from the geosphere and concentrations of the same nuclides in natural waters [5]. Both reports follow a series of previous documents produced by licensing authorities in the Nordic countries showing that at least some regulatory authorities are considering the possibility of giving credit to safety indicators based on geochemical considerations [6, 7].

In Finland this idea has been put into practice and the Radiation and Nuclear Safety Authority (STUK) has recently issued a guide for the long-term safety of spent fuel disposal which includes constraints based on effective dose for the first few thousands of years and constraints based on activity releases to the environment for time periods further in the future, when probable climate changes introduce uncertainties into the assessment of human exposures [8]. These activity release constraints are expressed as nuclide specific activity fluxes across the geosphere-biosphere interface and are defined such that (i) at their maximum, the radiation impacts arising from disposal can be comparable to those arising from natural radioactive substances and (ii) on a large scale, the radiation impacts will remain insignificantly low. The disposal facility flux from the geosphere to the biosphere is suggested in the Finnish guide as a suitable long-term safety indicator to avoid large uncertainties related to the evolution of the biosphere.

In the 1980s, the US Nuclear Regulatory Commission (NRC) issued performance criteria for geological repositories, stated in terms of a number of safety indicators other than dose and risk (for example groundwater travel time, effective life of waste packages and release rates from failed waste packages). These have given rise to some difficulties for a number of reasons, however, and the Environmental Protection Agency (EPA) and the NRC have recently completed the development of new standards that are based on dose and risk criteria [9–11].

Thus, although the possibility of using safety indicators other than dose and risk is far from new, it has never been the subject of a comprehensive international evaluation and has never generated any broad consensus. The present document builds on earlier IAEA publications (especially [1]), and explores further the use of safety indicators, different to dose and risk, for the assessment of radioactive waste disposal facilities.

1.2. OBJECTIVES

There is currently no international consensus on how or whether new safety indicators, different from dose and risk, should be used. The objectives of the present document are to:

- place the use of performance indicators in general, and safety indicators in particular, in the context of the making of the safety case (the distinction between performance indicators and safety indicators is clarified in the following section),
- discuss and evaluate a variety of potential performance and safety indicators,
- discuss the potential benefits of using safety indicators in addition to dose and risk, and
- show how such indicators might be integrated, in practice, within a safety case.

It should be made clear at the outset that the additional indicators discussed in the report should be seen as supporting indicators of safety to **complement** dose and risk. There is no intention to suggest the replacement of dose and risk by alternative safety indicators. As pointed out in previous IAEA documents [1, 12], a safety case based on multiple lines of reasoning is likely to be particularly convincing, because of the broadness of its arguments.

The use of complementary safety indicators could be seen as adding breadth to the arguments within a safety case.

1.3. SCOPE

For the purposes of the present report, an *indicator* is taken to be any characteristic or consequence of a disposal system that has a bearing on the ability of the system to perform its safety functions. Indicators may be:

- directly measurable characteristics of the disposal system (e.g. radionuclide concentrations in groundwater at different locations and depths),
- characteristics derived from system understanding (e.g. container lifetimes and radionuclide fluxes across different boundaries in the disposal facility system), or
- characteristics derived from calculations of the long term evolution of the disposal system (e.g. dose).

A distinction is also drawn between a *performance indicator* and a *safety indicator*. A performance indicator provides measures of performance to support the development of system understanding and to assess the quality, reliability or effectiveness of a disposal system as a whole or of particular aspects or components of a disposal system. A safety indicator, which may be regarded as a special type of performance indicator, is used to assess calculated performance in terms of overall safety.

The most widely used safety indicators for assessing the safety of radioactive waste disposal are dose and risk. Other safety indicators that may be used in addition to dose and risk are referred to in the present report as *complementary safety indicators*.

This report does not attempt to develop and describe a comprehensive system of complementary safety indicators; instead, the focus is on a few indicators that are considered to be the most promising for assessing the long term safety of disposal systems. The safety indicators that are discussed in this report may be applicable to a range of disposal systems for different waste types, including near surface disposal facilities for low level waste. The appropriateness of the different indicators may, however, vary depending on the characteristics of the waste, the facility and the assessment context. It is assumed that the safety of any disposal system relies on a system of multiple passive barriers, with safety functions that may include a period of complete containment and very long migration times to the accessible environment (allowing decay of radionuclides to take place), as well as processes that ensure low concentrations and fluxes within system compartments and across system boundaries. The focus of the report is thus on the use of time-scales of containment and transport, and radionuclide concentrations and fluxes, as indicators of disposal system safety, that may complement the more usual safety indicators of dose and risk.

The exact manner in which complementary safety indicators would be used in safety cases is likely to vary among countries, depending, for example, on the particular requirements of individual licensing authorities. It is also possible that in some cases their use might become mandatory, through inclusion in regulatory requirements. In other cases, it might be up to the disposal system developer to choose from among the full set of potential indicators. In addition, it is conceivable that complementary safety indicators could be applied to all assessment time frames, alongside calculations of dose and risk, or they may be applied only to assessment times in the far future when quantitative dose and risk estimates are most uncertain. Nonetheless, whenever complementary safety indicators are used, the competent licensing authority has the tasks of reviewing their rationale and of evaluating the possibility of setting quantitative target criteria for them.

The application of complementary safety indicators is expected to be of most value when evaluating the consequences of repository evolution scenarios in which radionuclides released from the near-field are transported to the accessible environment by natural processes (e.g. groundwater movement). The approach is likely to be less useful when evaluating the consequences of scenarios in which the geological barrier is bypassed or degraded, such as those involving human intrusion or incomplete closure and sealing of the facility.

Although not discussed within the present document, the approach of constructing arguments for safety through the comparison of estimates of parameter values derived from assessment of evolution of the disposal system, such as radionuclide fluxes and concentrations, with natural ones is also feasible for evaluating the risk presented by the release of chemotoxic substances contained in radioactive wastes. This issue is being given more consideration as the potential environmental and health impacts of certain non-radioactive pollutants present in radioactive wastes are being appreciated. In addition, the ingestion of some radioactive elements, for example uranium, could present hazards associated with its chemotoxic proportion of equal significance to its radiotoxity.

Finally, it is not a purpose of the proposed safety indicators to provide an additional basis for disposal system site selection. It might be envisaged that comparisons between natural fluxes or concentrations and waste derived ones would suggest that sites with high levels of natural radioactivity would be most suitable for siting disposal facilities with correspondingly high migration rates of radionuclides. Conversely, a site characterised by unusually low environmental concentrations would seem less acceptable for siting a disposal system. The rationale for such conclusions is doubtful and controversial and the present report should not be seen to support that line of reasoning.

1.4. STRUCTURE

Section 2 summarises the broad elements that a safety case for an underground radioactive-waste disposal facility should possess and the role and use of performance and safety indicators within these elements. An overview of performance and safety indicators is given. Section 3 discuses the use of dose and risk as safety indicators and, in particular, problems that can arise in their use. It then goes on to describe how complementary safety indicators, used in conjunction with dose or risk, can assist in addressing some of these problems. Sections 4 to 6 describe, in more detail, some specific indicators that have the potential to be used as complementary safety indicators. Section 7 describes how, in practical terms, specific complementary indicators can be used within a safety case. Conclusions are given in Section 8. The Appendix discusses how fluxes of naturally occurring elements and radionuclides due to the operation of natural processes such as erosion and groundwater discharge may be quantified for comparison with fluxes of waste derived contaminants.

2. ROLE OF INDICATORS IN THE SAFETY CASE

2.1. BROAD ELEMENTS OF THE SAFETY CASE

The safety case for a disposal system for radioactive waste may be described as follows:

> "*A safety case is a collection of arguments, at a given stage of* (disposal system) *development, in support of the* long term *safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages*" [13].

As discussed in the OECD/NEA document [13], the safety case provides input to the step-wise decision making process of disposal system planning and development. The form of the safety case (types and weighting of arguments) will be guided by the needs of decision-makers for the decision at hand. Furthermore, for many (but not necessarily all) decisions, the content of a safety case is one of several considerations on which the decision is based.

The collection of arguments that make up the safety case includes those that support:

(i) the acceptability, in terms of safety, of the evaluated performance;

(ii) the quality and reliability of the various components of the disposal system, including the suitability of a chosen site and design to provide long term isolation;

(iii) the quality and reliability of the analysis used to evaluate the performance of the disposal system, including the quality and adequacy of information about the system and the applicability of methods and models used to analyse this information; and

(iv) the application of sound technical and managerial principles and capabilities necessary to conduct all activities within the disposal facility development programme.

Indicators, as defined in Section 1, are characteristics or consequences that can be measured or calculated and compared to rigid or more loosely defined measures or 'yardsticks' in order to formulate such arguments.

2.2. ROLE OF INDICATORS

A wide range of information is acquired in the course of developing a safety case. Some, but not all of this information is directly used in the formulation of models and data-sets for the evaluation of system performance and potential radiological impact. The results of such quantitative evaluations provide *safety indicators* that are used to construct arguments of type (i), above. Such indicators allow a judgement to be made as to whether the disposal system is acceptably safe in terms of risk to human health and harm to the environment[1].

Model input parameters (derived from measurements observations, experiments and/or process model calculations, or given as technical specifications), and the results of quantitative evaluations of parts of the total system, can, in some cases, provide *performance indicators*, that can be used to construct arguments of type (ii), above. For example, calculations may provide a measure of the time taken for a particular radionuclide to be transported across a particular barrier (clay backfill, host rock, etc.). If this time is

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[1] This reflects the increasing attention being paid to the protection of the environment, partly as a result of the 1992 UNCED Earth Summit in Rio de Janeiro [14, 15].

significantly longer than the radionuclide half-life, then this provides a supporting argument for the effectiveness of the barrier for the particular radionuclide. Performance indicators of this type can be useful tools in the description and explanation of disposal system safety functions and the analysis of the sensitivity of performance to uncertainty and variations in the disposal concept. They are thus useful not only in the building of a safety case at a particular stage of a disposal system programme, but also in the iterative processes of siting, design and licensing.

The indicators mentioned above are generally expressed as well-defined numerical values or ranges (e.g. model input and output) that can be used to develop rigorous technical arguments. More qualitative information, which is often not used in the formulation of models and data-sets for the evaluation of system performance, can also provide performance indicators. An example might be evidence for the presence of very old groundwater, which supports, at least qualitatively, the immobility, or very slow movement, of the water, and thus the long term reliability of the geosphere as a transport barrier. Similarly, the lack of exploitable mineral resources in the surroundings of a disposal system might provide an indicator to support the argument that future inadvertent human intrusion is unlikely. The retention of radionuclides by natural components of the disposal system can sometimes be supported by observations of natural analogues.

Additional information can be used to test general system understanding and specific models and databases (i.e. to construct arguments of type (iii), above). This use of indicators is discussed, in the context of the geosphere, in the synthesis of the fourth OECD/NEA GEOTRAP workshop [16] but is not considered to be within the scope of the present report.

Finally, although not discussed further in the present document, indicators may also be used in the wider context of an environmental impact assessment, to define environmental effects of the system that may be of concern to some interested parties, but do not necessarily have a direct relationship to safety.

2.3. YARDSTICKS FOR COMPARISON

Values determined for performance and safety indicators are not generally useful to the safety case if taken in isolation. A canister lifetime of 1000 years does not, for example, provide a safety case argument, unless used in conjunction with information as to how the inventories of individual nuclides, or the radiation hazard of the disposal system as a whole, reduces as a function of time. Thus, performance and safety indicators are compared to guidelines, criteria, reference values or other ‘yardsticks’ that are used to judge the effectiveness of barrier performance or the acceptability of calculated safety levels. A yardstick may provide a direct test of the ability of the overall system, or a system component, to contribute to safety by limiting the radiological impact or attenuating radionuclide releases. Alternatively, it may relate to a property that a system component should fulfil in order either to be effective itself as a barrier, or to provide a suitable environment for the operation of other parts of the system.

Yardsticks may be derived from a number of sources, including legislation or regulation, which typically provide guidelines or limits on dose or risk. Other sources may provide less rigidly defined guidelines, including:

- the guideline that the disposal system should not significantly perturb radiological conditions naturally present in the environment (observations from nature of radionuclide concentrations and fluxes, as discussed in later sections of this report);

- the results of sensitivity analyses conducted in performance assessment (which may indicate that, for example, a particular minimum container lifetime is critical to overall system safety);
- other, supplementary calculations (e.g. 'crossover time[2]' based on hazard indices, as discussed in Section 6);
- consideration of the physical processes by which the safety functions of the disposal system are provided (e.g. radionuclide half-lives - if transfer time is the performance indicator and decay during transport is the physical process under consideration); and
- societal values or expectations.

For performance indicators not required by legal or regulatory requirements (including complementary safety indicators), with the present stage of knowledge, the degree of detail with which yardsticks are defined should normally increase in a step-wise manner as disposal system planning and development progresses, and the disposal system becomes better defined and system understanding matures.

If a complementary safety indicator is to constitute a meaningful measure of safety, then it must be compared to a yardstick that conveys information regarding radiological (and other) impacts on humans and the environment. Waste derived radionuclide concentrations in or near the accessible environment and radionuclide fluxes across the geosphere-biosphere interface may provide useful complementary safety indicators, since they can be compared with reference values derived from existing natural conditions, as discussed in Sections 4 and 5.

In disposal systems that include very long lived containers (e.g. copper or copper-steel canisters), such that the expected containment time approaches or exceeds the 'crossover time', the containment time may be viewed as a complementary safety indicator, and is defined as such in the present report. The crossover time provides the yardstick for comparison, as illustrated in Figure 1. In other disposal systems where, for example, containment in canisters is expected to ensure only the decay of shorter lived nuclides, containment time should be viewed as an indicator of subsystem (canister) performance for specific radionuclides.

Safety and performance indicators generally would be compared to yardsticks expressed as fixed values or ranges, such as those mentioned above. In addition, however, 'relative' comparisons may be of value, particularly for performance indicators where no yardstick has yet been defined. For example, performance indicators may be evaluated and compared for different model assumptions or system design variations. Such comparisons can lead to enhanced system understanding with respect, for example, to sensitivity to uncertainty.

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[2] Crossover times are derived from calculations of the decay of radionuclide inventory with time, and information on natural concentrations; they denote the time needed for the 'radiotoxicity' of the waste to decay to a "natural" level - e.g. that of a specified volume of uranium ore (see Section 6). Natural levels of radioactivity do not, necessarily, always represent 'safe' levels and this indicator may need to be supported by additional analyses.

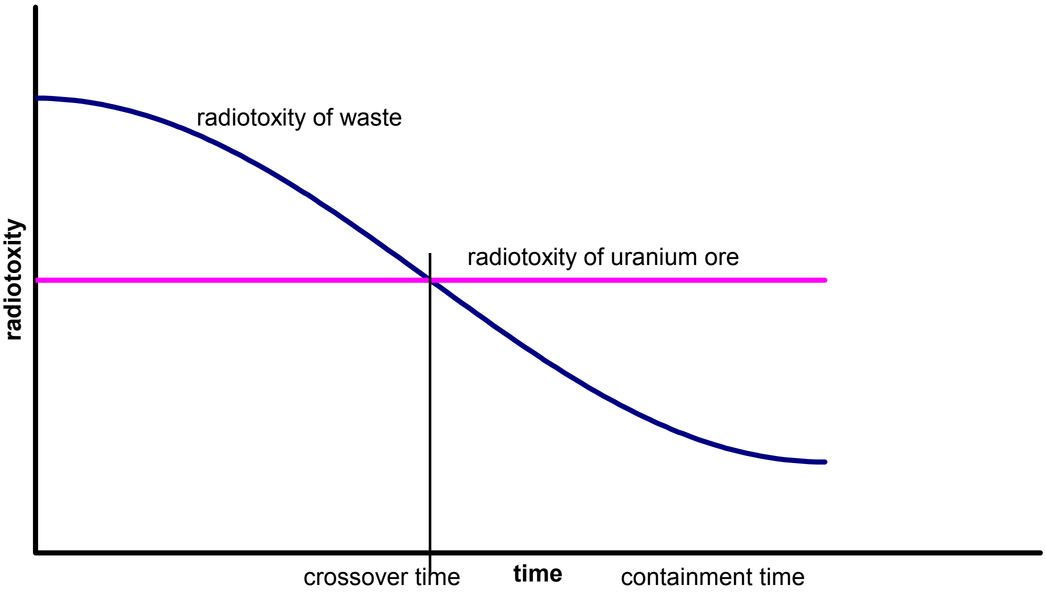

FIG. 1. Illustration of the containment time as a safety indicator, and 'crossover time' as a yardstick for comparison.

Note: The concepts of 'radiotoxicity' and 'crossover time' are described in more detail in Section 6.

2.4. OVERVIEW OF PERFORMANCE AND SAFETY INDICATORS

Table 1 provides an overview of performance and safety indicators, including the complementary safety indicators discussed in the present report. The table lists individual indicators, their 'sources' (i.e. the type of measurement or calculation used to quantify the indicator), the location within the disposal system to which the indicator applies and the yardstick against which the value assigned to the indicator may be judged.

The proposed system of indicators shown in Table 1 is not to be interpreted as a rigid structure; it implies neither that all indicators must be developed nor that additional indicators should be identified. The proposed system is meant to help in placing the various indicators in a logical relationship with the various elements of a safety case. The most useful application of the proposed indicators will need to be determined on a case by case basis. In particular, it must be determined which indicators are expected to be most beneficial, considering both the specific features of the waste isolation system and the audience to which the safety case is to be presented.

TABLE 1. EXAMPLES OF PERFORMANCE AND SAFETY INDICATORS

General performance indicators			
Indicator	**Source**	**Application**	**'Yardstick'**
Radionuclide transfer times	Quantitative evaluations of parts of total system	Engineered barriers (e.g. clay backfill) or geosphere	Radionuclide half-lives
Radionuclide concentrations in the near field	Assessment model results	Engineered barrier system	Subsystem criteria derived from sensitivity analyses ('relative' comparisons between different analyses may also be of value - see main text)
Radionuclide fluxes in the near field	Assessment model results	Engineered barrier system	Subsystem criteria derived from sensitivity analyses ('relative' comparisons between different analyses may also be of value - see main text)
Characteristics that control 'dilution' in time and space (e.g. waste-form dissolution or release rates, canister failure rate, porosities)	Experiments, technical specifications, and/or process model calculations	Engineered barriers or geosphere	Criteria derived from total system performance-assessment calculations
Age profile of groundwater	Site characterisation, paleohydrogeology	Geosphere	Time-scale of assessment
Other physico-chemical properties of the disposal system (e.g. waste package loading, buffer composition and density, fracture frequency, lack of exploitable mineral resources)	Experiments, technical specifications, and/or process model calculations	Engineered barriers or geosphere	Subsystem criteria developed by the regulatory authority or by the operator
Safety indicators (see also the Note, below)			
Risk	Assessment model results	Human beings	Risk limit or constraint
Dose	Assessment model results	Human beings	Dose limit or constraint
Environmental impact	Assessment model results	Other species	Environmental protection standards
Complementary safety indicators			
Radionuclide concentrations outside the near field	Assessment model results	Accessible environment	Levels of corresponding natural concentrations
Radionuclide fluxes outside the near field	Assessment model results	Accessible environment; geosphere-biosphere interface	Corresponding natural fluxes
Containment times	Experiments, technical specifications, and/or process model calculations	Canisters/ containers Engineered barriers or geosphere	'Crossover times' for hazard indices

3. THE NEED FOR COMPLEMENTARY SAFETY INDICATORS

3.1. EVALUATING DOSE AND RISK

In general, the safety case for a disposal system should provide a reasonable assurance that the consequences of any radionuclide migration to the accessible environment are in compliance with relevant safety criteria [2, 3].

Estimates of dose or risk are based on values, either calculated or measured, of waste derived concentrations of radionuclides in the accessible environment, for example in soils and sediments, and in surface waters such as rivers, lakes and the sea. In a safety case, these estimates are generally of a bounding nature. In order to calculate the environmental concentrations of waste derived substances, the fluxes between the disposal facility and the relevant compartments of the accessible environment also need to be estimated. For the additional conversion of the environmental values to dose or risk (for human beings and/or other organisms), assumptions have to be made about the evolution of the biosphere (including exposure pathways, the habits of relevant human population groups and the presence and behaviour of other living species).

3.2. LIMITATIONS OF DOSE AND RISK AS SAFETY INDICATORS

The use of dose or risk as safety indicators has one main limitation, associated with the uncertainty surrounding their estimation. Biosphere modelling is an integral part of dose and risk evaluation, and uncertainties associated with biosphere modelling increase considerably with the time-scale under consideration [12], in particular with regard to human habits, but also with regard to the nature and distribution of other organisms. The engineered barriers of a disposal system and the geosphere are expected to be characterised, in general, by greater long term stability.

A particular limitation with the use of risk as a safety indicator is that risk values are not necessarily useful in communicating with the public and in illustrating the safety of disposal facilities. Risk can be 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 [1].

Possible ways to deal with the uncertainties inherent in biosphere modelling include making use of stylised approaches (e.g. one or more reference biospheres [17]) and complementary safety indicators, such as those listed in Table 1. Combinations of these approaches are also possible in a safety case. The concentrations of waste derived radionuclides (and possibly of other pollutants) in the accessible environment and fluxes across the geosphere-biosphere interface are, for example, often readily available as intermediate results of the safety/performance assessment calculations. The containment times in canisters or containers are generally deduced from experimental and modelling studies.

It should be pointed out that safety assessments making use of either one of the two possibilities outlined above are conceptually similar as they both deal with the biosphere-related uncertainties in the analysis although in different ways. The choice of the method will then depend on what is believed to be most effective in presenting the safety case. These considerations also imply that all safety assessment results, when they refer to a time sufficiently far in the future, cannot be considered as actual predictions of impacts, but are, instead, indicators of safety.

3.3. BENEFITS OF COMPLEMENTARY SAFETY INDICATORS

Complementary safety indicators may go some way to overcome the limitations of dose and risk discussed in the previous section. Their main potential benefit is that they are derived, in most cases, from calculations of radionuclide migration and distribution in the relatively stable medium of the geosphere, eliminating from the assessment the part of the system (the biosphere) characterised by the most intractable uncertainty.

There are, however, other potential benefits to using complementary safety indicators over and above the fact that they avoid the need to make assumptions about future biospheric and demographic conditions in estimating the values of the indicators themselves. The yardsticks against which complementary indicators are compared may also be based on observations of natural systems generally characterised by long term stability. Complementary safety indicators could also assist with some of the issues associated with the application of radiation protection principles to the impacts of radioactive waste disposal in the remote future, such as uncertainty about the future validity of the assumed relationship between dose and detriment [18].

Complementary indicators provide for flexibility, diversity and transparency for a wide range of stakeholders (technical and non-technical). They provide numbers to compare with items which may be more easily understood by these stakeholders, for example, background radiation levels, fluxes and concentrations of naturally occurring radionuclides and other natural or man-made hazards.

Nonetheless, although complementary safety indicators offer a number of benefits, they also have some limitations, the most obvious of which is the lack of international consensus on how to apply them to safety cases. Other practical problems relate to the availability of information on natural radionuclide concentrations and fluxes, and their variability, for use in the development of yardsticks. This problem is, however, being addressed by ongoing projects to quantify more accurately natural radionuclide abundances and distributions. It is recommended that a variety of safety indicators are used in a safety case so that the limitations of one are balanced by the benefits of another.

Specific complementary safety indicators, and yardsticks against which they are measured, are discussed in the following sections.

4. USE OF RADIONUCLIDE CONCENTRATION AS AN INDICATOR

4.1. GENERAL CONSIDERATIONS

Depending on system-specific features, a number of conceptual compartments may be defined between the waste and the accessible environment. The concentrations of radionuclides derived from a disposal system within these various compartments may be evaluated in the course of assessing system performance.

4.2. USE AS A COMPLEMENTARY SAFETY INDICATOR

Not all calculated waste derived concentrations can be directly interpreted in terms of safety, and independent and meaningful yardsticks may not be available for comparison purposes. This is often the case for the engineered barriers, although, in the particular case where arguments can be made for complete containment of radionuclides in the engineered barriers for very long times, then concentrations within the engineered barriers (or hazard indices, as discussed in Section 6), could be compared to concentrations (or hazard indices) of naturally occurring radioactive materials, such as uranium ores. Such a comparison might, for example, be useful in a discussion of the rates of uplift/erosion processes that have the potential to reduce the depth of a disposal facility for long lived waste over time. More generally however, radionuclide concentrations at other locations (e.g. the host rock, overlying strata and the surface environment) have greater potential for use as meaningful safety indicators to complement dose and risk.

Slow moving groundwater, which is expected to be the normal condition for groundwater in a repository host rock (with the exception of rock salt, which generally has no moving groundwater at all), is usually in geochemical equilibrium with the rock in which it is found. Any groundwater entering the disposal system and contacting the waste is likely to move towards a different chemical equilibrium. The migration of contaminated groundwater away from the disposal system may eventually lead to concentrations of waste derived radionuclides, or other toxic chemicals, in parts of the geosphere characterised by lower isolation from the surface environment.

In general, the potentially more accessible sections of the geosphere are aquifers, adjacent to the host rock, with sufficient hydraulic conductivity to permit natural outflows of groundwater or to justify drilling wells, or relatively shallow layers where the waste derived substances can be accumulated by sorption, deposition or crystallisation. It is in these near-surface parts of the geosphere, and in the surface environment, that radionuclide concentrations are likely to be of most use as a complementary safety indicator.

4.3. YARDSTICKS FOR COMPARISON

Environmental concentrations of radionuclides migrated from a disposal facility should be assessed against the corresponding values for naturally occurring radionuclides. The values of naturally occurring concentrations would constitute the references for comparing with those derived from the waste and for defining the safety criteria.

Average concentrations and fluxes of naturally occurring radionuclides (and toxic elements) in surface and near surface media are relatively well known for a wide range of different environmental conditions and with a good geographical coverage [19–22]. Within the field of geochemical knowledge, the database on naturally occurring radioactive elements is particularly well developed [23–25]. Ongoing international geochemical projects are expected to lead to further improvements in the availability of reliable geochemical data, both in general and specific to radioactive isotopes [26]. Potentially, anthropogenic contamination at some locations may mean that it is difficult to establish true ‘natural’ concentrations and, thus, care is necessary to ensure that reliable data are adopted for use in the definition of yardsticks.

In using environmental concentrations of naturally occurring radionuclides as yardsticks against which to compare concentrations of nuclides originating from a disposal facility, two difficulties have to be overcome:

- some radionuclides originating from a disposal facility will have no natural counterpart, and a means of comparison of concentrations must be developed that reflects the different potential risks to human health and harm to the environment of different radionuclides; and
- it is necessary to establish which particular natural concentrations should be used as a yardstick (e.g. local values, regional range, global range).

Possible solutions to these difficulties are discussed in Section 7.

5. USE OF RADIONUCLIDE FLUX AS AN INDICATOR

5.1. GENERAL CONSIDERATIONS

The fluxes of radionuclides originating from a disposal system, across various real or hypothetical boundaries, i.e. the amounts (expressed as mass or activity) crossing a unit area per unit of time, may, as in the case of concentrations, be evaluated in the course of assessing system performance.

5.2. USE AS A COMPLEMENTARY SAFETY INDICATOR

As is the case with concentrations within compartments, only a subset of calculated fluxes between compartments can be directly interpreted in terms of safety by comparison with independent and meaningful yardsticks. Fluxes of radionuclides across boundaries within and around the engineered barriers can only be estimated on the basis of models of the barrier system in advance of the implementation of the disposal system. Radionuclide fluxes across the geosphere-biosphere interface, and within the biosphere, do, however, have potential for use as meaningful safety indicators.

5.3. YARDSTICKS FOR COMPARISON

Environmental fluxes of radionuclides originating from a disposal facility should also be assessed, if possible, against the corresponding values for naturally occurring radionuclides. While environmental concentrations are relatively straightforward to measure, fluxes cannot, in general, be measured directly. Rather, they are usually calculated on the basis of other parameters, and are significantly more complex to determine.

Natural processes, such as erosion, weathering and groundwater transport, cause a continuous transfer of material derived from the earth’s crust to the surface environment where it is then removed mainly by surface water and wind. During their migration, these substances become available for uptake in biological processes, and a small fraction is actually taken up by living organisms. Eventually, most materials migrating from the geosphere will reach the sea or a limited number of inland basins. The total flux leaving the geosphere contains naturally occurring radionuclides and other toxic elements. The fluxes of natural species leaving the geosphere are often dominated by erosion processes, with the flux due to groundwater discharge sometimes being of only minor importance, although this is dependent on the geological environment and climate. It is therefore possible, in principle, to define a range of fluxes for particular elements or naturally occurring radionuclides released from the geosphere due to different processes and at different locations, and thus to provide alternative yardsticks for safety comparisons (e.g. total natural radioactive flux due to all processes or only the fluxes due to groundwater discharge). This may introduce problems in determining which is the most relevant yardstick to adopt. Such decisions will need to be made on a case by case basis.

Furthermore, in using environmental fluxes of naturally occurring radionuclides as yardsticks against which to compare fluxes of nuclides originating from a disposal facility, the same difficulties have to be overcome that were mentioned in Section 4 in the context of concentrations. Possible solutions to these problems are discussed in Section 7.

6. USE OF TIME-SCALES AS INDICATORS

6.1. GENERAL CONSIDERATIONS

Safety relevant processes affecting a disposal system are generally characterised by a range of time-scales. Their relevant durations may be obtained from experiments, technical specifications and modelling calculations as, for example, in the cases of canister containment periods and waste-form dissolution times (or rates). These are often used as input parameters in performance assessment calculations. Others may be evaluated in the course of assessing overall disposal system performance, as in the case of radionuclide transfer times across different system components (backfill, host rock, etc.).

Containment times, waste-form dissolution times and transfer times often take the form of ranges, reflecting uncertainties in the rates of processes and, in the case of transfer times, heterogeneities in the media under consideration. Furthermore, in the case of diffusive transport, the transfer time should be regarded as a typical time-scale characterising the process (and somewhat arbitrarily defined), rather than as the time taken for a particle to migrate from one point to another.

6.2. USE AS COMPLEMENTARY SAFETY INDICATORS

As mentioned in Section 2, in disposal systems that include very long lived containers, the containment time may be viewed as a complementary safety indicator. If the containment time is sufficiently long, then the radiotoxicity of the waste could eventually decay to a level that may be judged as safe, without any release of radionuclides to the environment.

In principle, the same may be said of the time-scale for waste-form dissolution[3] and of transfer times through the different system components. In practice, however, in the case of waste-form dissolution, some slow release of radionuclides cannot be excluded following access of water to waste surfaces. Similarly, in the case of transfer times, the possibility that some radionuclides, especially long lived and/or highly mobile radionuclides and their decay products, may eventually migrate through these components is difficult to exclude. Safety of the disposal system then also depends on processes that ensure the low concentrations of these radionuclides within and around the disposal system, in the geosphere, or in the surface environment. Thus, in disposal systems for which containment in canisters, where slow waste form dissolution or long transfer times are expected to ensure the decay of only shorter lived nuclides or less mobile radionuclides, these time-scales should be viewed as indicators of subsystem performance for specific radionuclides, rather than as complementary safety indicators.

6.3. YARDSTICK FOR COMPARISON

An important feature of radioactivity is that it decreases with time. This is true, in the long term, for all classes of radioactive wastes. Even if particular isotopic compositions can result in a temporary increase of activity due to the ingrowth of radioactive decay products, sooner or later, the activity of the waste will decrease to levels that are comparable to those found in natural materials. Such levels in a man-made facility underground may be judged by society to be of no great concern, since they are also present in nature. The 'crossover time' is a measure of the time taken for these low values of radioactivity to be attained. The crossover time is

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[3] If radionuclide release is congruent with dissolution and the time scale for dissolution is very long, as in the cases of vitrified high level waste and synthetic rock materials.

generally significantly shorter than the half-lives of the longest lived radionuclides, since these have relatively low activities. In using containment time (or other time-scales) as safety indicators, the 'crossover time' provides a suitable yardstick for comparison.

In order to evaluate a crossover time, a quantitative measure of the hazard associated with the radioactivity of the waste (and of the natural material to which it is being compared) must be defined, and calculated as a function of time. The situation is complicated by the fact that individual radionuclides vary in:

- total inventory (or activity) and concentration;
- radiotoxicity per unit activity; and
- mobility in the engineered barriers, the geosphere and the surface environment (although this is not usually taken into account in quantitative measures of hazard[4]).

Hazard may be expressed in terms of a number of possible indices, based on various radiological parameters[5]. Hazard indices and their historical development have been reviewed [27]. Indices may include total activity and activity concentration. Alternatively, a measure of total radiotoxicity of waste can be obtained by summing the ratios of the activities of the various radionuclides to some measure of specific radiotoxicity, for example the respective annual limits on intake by ingestion or by inhalation (ALIs). This then yields the number of annual limits on intake present in a given quantity of waste or reference material.

Such hazard indices are widely used to illustrate the intrinsic hazard of radioactive materials, describe the reduction in radiological hazard with time, indicate the need for isolation of the waste from the biosphere for a certain time (e.g. until the radiotoxicity approaches that of naturally occurring radioactive materials, such as uranium ores) and, more specifically, evaluate crossover times.

The crossover time is the time at which a chosen hazard index declines to a level equal to some chosen reference value, such as:

- (for vitrified high level waste and spent fuel) the activity or radiotoxicity of the mass of ore or natural uranium used to produce the waste or of the mass of fissile material consumed by the nuclear reactions which have generated the waste;
- the toxicity of ashes from coal burning and other non-radioactive wastes [28].

The crossover times evaluated in different studies vary over several orders of magnitude, even for waste of similar origin and composition (such as high level waste and spent nuclear fuel). This is due not only to the choice of different reference values, but also to the use of different radiological hazard indices, and to the fact that some radiological parameters have been changed during the last 25 years; for example, radiation limits, biological models and, consequently, values of ALIs. This observation indicates that further consideration is needed in this area.

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[4] It is thus emphasised that hazard indices may not represent the actual risk associated with radioactive waste (although the total activity of radionuclides in a disposal system has been occasionally used as a measure of the intrinsic capacity of the waste to cause radiation exposures). For evaluation and assessment of the actual risk, or any other measure of safety, there is no substitute for a proper safety assessment that takes into account the performance of engineered and natural barriers, as well as other factors based on the mobility and biological availability of the pollutants.

[5] The discussion of different management options for spent nuclear fuel has been often based on hazard indices [28, 29]. Some hazard indices are currently obsolete in radiation protection, such as the number of maximum permissible body burdens (MPBBs) and the water volume needed to dilute the activity to the maximum permissible concentration in potable water (MPC_W).

7. PRACTICAL USE OF COMPLEMENTARY SAFETY INDICATORS

7.1. GENERAL CONSIDERATIONS

It is important to reiterate here that the indicators discussed in Sections 4 to 6 (i.e. concentrations, fluxes and containment times) are *complementary* to dose and risk. No single safety indicator is fully effective for presenting all aspects of disposal facility safety to all audiences and, thus, there may be benefits to presenting together a number of different indicators, such that the limitations of any one indicator can be offset by the benefits of another. This is consistent with the concept of applying multiple lines of reasoning in the safety case. Ideally the presentation of complementary safety indicators would be integral to the full safety case, not restricted to a separate Section at the end of the assessment document and isolated from the presentation of dose and risk.

Complementary safety indicators are valuable inputs to the decision making process, for operators, regulators and other groups, and their presentation should be relevant to all readers of the safety case. In this regard it is useful for the operators to set-out in their presentation which indicators they considered to be most valuable for aiding any decisions they have made on the basis of the outcome of the safety case. Such decisions might relate to design optimisation or, ultimately, affect the decision to proceed with an application for a licence to operate a disposal facility. On the other hand, the content of the safety case will be used by other groups as part of their decision making activities (formal or otherwise) with regard to the operator's application. The presentation of safety indicators in the safety case should not prejudge which indicators would be most useful to particular readers and, thus, this provides a further reason for the complete and unbiased presentation of a range of indicators throughout the safety case documentation.

With these thoughts in mind, the following text describes a suggestion for the presentation of complementary safety indicators in a safety case. It could and should be modified to take account of the specific characteristics of any particular disposal facility design, waste form, site location, etc. When presenting complementary safety indicators in a safety case, the choice of safety indicators and the presentational method adopted should also be consistent with the assessment context, in relation to the purpose of the assessment (e.g. to compare design options or to support an application for an operational licence) and the anticipated audience (e.g. a specific technical group or wider stakeholder groups).

The presentation suggested here assumes that the safety case will have a wide potential readership. It takes the form of a number of logical steps that correspond to specific 'questions' a reader of a safety case might ask and consider relevant, and for which coherent answers might increase their confidence in the overall safety case and the disposal facility system. The presentation begins by using complementary safety indicators quite simply to 'set the scene' for the magnitude of the waste disposal problem by comparing masses of waste to masses of naturally-occurring radioactive material in the environment. The complexity of the presentation is then built up to deal with the radiotoxilogical hazard associated with the release of waste-derived non-natural radionuclides and fluxes across the geosphere-biosphere interface. The reason for this approach is that, by starting simply, readers could follow the presentation from any point appropriate to their level of technical understanding or appropriate to an issue of personal interest.

7.2. DEFINING THE NATURAL SYSTEM

The starting point for using naturally-occurring concentrations and fluxes as yardsticks for safety indicators is an understanding of the natural elemental distributions and abundances in rocks, soils, waters, etc. and of the processes that cause their mobility. Essentially, what is required is a comprehensive description of the behaviour of the natural concentrations and fluxes (expressed in terms of mass and activity) both in general and in the environment which will host the disposal facility, so that any perturbations to that natural system arising from disposal facility-derived releases can be evaluated in a natural context.

When describing the behaviour of the natural concentrations and fluxes, the following questions need to be considered:

- What elements to consider?
- What processes (fluxes) to consider?
- What spatial scales to consider?

The answers to these questions are specific to the disposal system under investigation and the relevant assessment context. As a consequence, no single or generic description of ‘the natural system’ would be appropriate as a source of yardsticks for comparison with the safety indicators.

7.2.1. What elements to consider?

It is possible to measure concentrations in natural materials and to derive natural fluxes for all elements occurring at abundances above analytical detection limits but only a few of these would provide information that can be directly used in the assessment of health and environmental impact of a disposal facility. Given that the primary concern in a safety assessment is to evaluate the radiological impacts of the radionuclides from the disposal facility on humans and the environment, it is logical to focus on the naturally-occurring radioactive elements that control the natural series decay chains (uranium and thorium) and the dominant natural non-chain radionuclides (^{40}K and ^{87}Rb). If data permit, it may be useful to measure independently the abundance of other radionuclides in the natural series decay chains (for example radium and radon) to provide information on the state of secular equilibrium in the decay chains at the sampling locations.

It may also be interesting to determine the abundances of a number of other elements that may occur in the waste, including some heavy metals that may pose a chemotoxic risk (for example cadmium and lead). The importance of assessing the chemotoxic risk of both natural and disposal facility-derived fluxes will depend on the objectives of the safety assessment. In assessments undertaken at a late stage in a disposal facility development programme, it may be appropriate to consider the chemotoxic hazards associated with migrating chemicals as the wider environmental impacts of the disposal facility need to be evaluated.

Average concentrations of many naturally-occurring elements and radionuclides in surface and near surface media are relatively well known for a wide range of different environmental conditions and with a good geographical coverage, at least for certain countries [19-22, 30]. Within the field of geochemical knowledge, the database on naturally-occurring radioelements is particularly well developed [23-25]. Ongoing international geochemical projects are expected to lead to further improvements in the availability of reliable geochemical data, both in general and specific to certain radionuclides [26]. Many of these data relate to wide spatial averages and, thus, when looking at a specific candidate disposal facility site, pre-existing geochemical data may not be adequate or sufficiently abundant either for the site itself or the surrounding area. In this case, the site-specific geochemical data will need to be obtained from the disposal facility site characterization programme.

7.2.2. What processes to consider?

Elemental and radionuclide fluxes are caused by natural processes that result in mass movement of materials. For most potential disposal facility sites, it is likely that several processes will be operating that generate fluxes of naturally occurring elements. These processes may be site specific, depending on the local geology, hydrogeology, geochemistry, geomorphology, climate and topography. Possible processes include physical erosion (of which glacial erosion is a subset), chemical weathering, groundwater flow, rock-groundwater interactions and surface water flow.

Not all fluxes are relevant to disposal facility safety assessment and, consequently, some care should be given to determining the appropriate fluxes to calculate. What constitutes an appropriate flux largely relates to the characteristics of the site and the assessment context, although perceptions of the readers and expectations of the safety case may also affect the choice of fluxes. As a general rule, the most useful natural fluxes are those that cause a transfer across the geosphere-biosphere interface (usually groundwater discharge and erosion), although transfers across other subsurface boundaries, or boundaries within the biosphere, may also be examined in certain cases, for example during assessments to compare design concepts, host rock types or sites.

Theoretically, natural fluxes could be calculated for any mass movement process, provided sufficient data exist to allow their calculation. Basically, two types of data are required:

1. concentrations of the elements and radionuclides of interest in the rocks, soils, water, etc.; and
2. the rates of the relevant geological processes such as erosion, groundwater flow, river flow, etc.

There are, however, many practical problems associated with the derivation of natural fluxes that relate to the complexity and variability of natural systems. A particular problem is that, in contrast to geochemical data, published process rate data are less widely available and can be difficult to quantify, meaning that some can be subject to fairly large uncertainties, for example long term erosion rates. Furthermore, published process rate data have poor geographical coverage and, thus, when looking at a specific candidate disposal facility site, pre-existing data may not be adequate or abundant either for the site itself or the surrounding catchment. In this case, the necessary process rate data will need to be obtained from the disposal facility site characterization programme. Various suggestions for how to calculate fluxes are given in the Appendix.

7.2.3. What spatial scales to consider?

A presentation on complementary safety indicators would probably be most comprehensible to the widest range of audiences if made within the context of the proposed disposal facility system and local environment. Thus, the catchment area containing the disposal facility would appear to be a sensible framework in which to set the complementary safety indicators. In many countries, a typical catchment which might host a disposal facility would be likely to have an extension of some hundreds of square kilometres (although they may be larger or smaller). Such a size is consistent with the region in which the present-day local population lives. The local population is a natural audience for the safety case and will be most concerned with the area that it identifies as its own ‘backyard’. In generic safety cases undertaken early in a disposal facility development programme, no candidate disposal facility sites may yet have been identified. In this case, it would be appropriate to present the complementary safety indicators within the framework of either a hypothetical site or an actual proxy site. This would clearly need to be consistent with the system description adopted in the assessment calculations.

Although the catchment scale is most generally appropriate, it is also sensible to consider larger spatial scales to place the disposal facility site itself (and the concentrations and fluxes it contains) in a wider geographical context. For example, once the elemental abundances in the rocks, soils and waters at the catchment area have been determined, it is useful to know whether this range is typical or atypical of the ranges to be found elsewhere in the country, region or even globally. Likewise, once a particular flux has been determined (e.g. erosional flux) this also can be given added context by indicating whether it is particularly high or low. The point of providing a wider geographical context to the elemental abundances is that the radionuclide migration from the disposal facility can also be put in the widest natural context, which would highlight any potential bias that might result from any unusual geochemical conditions at the proposed disposal facility site. For example, if a disposal facility was located at a site with generally low natural elemental concentrations and fluxes, the additional input from the disposal facility would be proportionately higher than at another site with higher natural concentrations and fluxes, but, of course, the associated hazard would be unchanged.

7.3. THE SAFETY HAZARDS ASSOCIATED WITH THE NATURAL SYSTEM

The fundamental concept behind using natural concentrations and fluxes to evaluate disposal facility safety is that, by showing that disposal facility-derived releases represent only a fraction of their natural equivalents, the associated hazards must also be small. As part of the justification for this approach, it is sensible for a safety case to address the question ‘Is the natural environment safe?’ when adopting complementary safety indicators.

An approach to considering this question is to present the ranges of concentrations for the elements of concern that occur naturally in rocks, soils, sediments and waters (e.g. as a frequency curve), and then to evaluate the potential hazard associated with the highest concentrations. This can be done in several ways. For example, the concentrations of the most significant naturally-occurring radioelements uranium, thorium, potassium and rubidium (or total activities) in rocks and soils can be presented graphically, with the ranges found within the catchment area distinguished from the ranges found elsewhere in the region or globally. Similar illustrations could also be made for elemental concentrations in waters (surface and underground). On the same illustration, appropriate safety limits (drinking water standards, etc.) can be given.

Such an approach may also be used to evaluate the chemotoxic hazards of both the natural materials and the disposal facility-derived radionuclides because a comprehensive safety case, in addition to the radiological hazard, may also address this issue.

7.4. COMPARING THE DISPOSAL FACILITY WITH NATURE

Once the natural system has been described in terms of the natural concentrations and fluxes, and their associated hazards, a comprehensive picture of the natural system can be constructed. This is a key part of the presentation of the complementary safety indicators because then the incremental changes to the hazards (concentrations and fluxes) arising from perturbations to the natural system due to the addition of the disposal facility can be evaluated in a natural context. Various comparisons between the disposal facility impacts and nature are possible, with varying levels of complexity.

The following discussion presents some of the possibilities, together with some discussion of their benefits and limitations. These suggestions are intended to be sufficiently generic that they could be applied in assessments for various waste types and disposal facility designs, including near surface disposal facilities for low and intermediate level waste. These suggestions are not intended to be either restrictive or prescriptive, and appropriate disposal facility-to-nature comparisons should be developed to take account of the particular characteristics of specific safety cases.

7.4.1. Comparisons of mass

As a first step in the presentation of complementary safety indicators, it may be useful to define the magnitude of the waste inventory in the context of the amount of naturally-occurring radioelement in the environment. There are various ways this could be accomplished and the appropriateness of any particular method would be defined by the characteristics of the waste, the disposal facility design and the wider geological environment. Considering a spent fuel disposal facility for which the waste form is nominally UO_2, for example, it could be interesting to some audiences to contrast the mass of uranium in the spent fuel with the mass of uranium contained in the host rock within the catchment or the mass of rock lying directly above the disposal facility, or some other identifiable volume of rock. A similar approach was taken in the Finnish TILA-99 assessment, where the mass of uranium in a single spent fuel canister was compared to the uranium content of potential Finnish host rocks [31]. Elemental concentrations for many rock types can be found in the published literature and these may be appropriate to use in generic safety cases. Once a candidate site has been identified, it would be more appropriate to use site-specific data.

As an example, consider a hypothetical spent fuel disposal facility at a depth of 800 m with a ‘footprint’ area of 5 km^2 located in granite. Assuming a density for the granite of 2750 kg/m^3 and a uranium content of 10 mg/kg, the granite in the column of rock directly above the disposal facility would contain 1.1×10^8 kg of uranium. As a comparison, the proposed Swedish spent fuel disposal facility is likely to contain 8×10^6 kg of spent fuel [32].

Such a simple mass comparison has no direct safety significance, and the mass of uranium in the disposal facility is strictly neither a safety nor a performance indicator, because the mass of radioelement by itself is not a measure of its potential radiological or environmental hazard. In addition, the chemical forms and isotopic ratios of the element in the disposal facility system may be different to those in nature. For this reason, a simple mass comparison must be presented honestly, without over-interpretation or misrepresentation. Nonetheless, such a simple comparison may still have value because it can be used to ‘set the scene’ for non-technical audiences familiar with the concept and units of mass but not of radioactivity or dose.

7.4.2. Comparisons of total activity

A next step might be to recognise the radioactive nature of the waste and, thus, to compare the inventory activity of the waste at disposal facility closure with the activity from the naturally-occurring radionuclides contained in the host rock. Again, there are a number of ways this might be done but an appropriate way would be to link the comparison of activity to the comparison of mass (described above) and, thus, to present both the activity and radionuclide mass for the same rock volume, such as the volume of host rock within the catchment or in the column of rock directly above the disposal facility. The total natural inventory in the rock volume may be calculated on the basis of the activity of ^{238}U and ^{232}Th (or the total of all the long lived nuclides in their decay chains) plus ^{40}K and ^{87}Rb, which are the most significant non-chain radionuclides. Activities for many rock types can be found in the published literature and these may be appropriate to use for generic safety cases. Once a candidate site has been identified, it would be more appropriate to use site-specific data.

As an example, considering the hypothetical spent fuel disposal facility discussed above, the 1.1×10^8 kg of uranium contained in the granite in the column of rock directly above the disposal facility would be associated with a ^{238}U activity of 1.4×10^{15} Bq. As a comparison, the proposed Swedish spent fuel disposal facility is likely to contain 5.7×10^{19} Bq of total activity at the time of closure [33].

As with comparisons of mass, this comparison of total activity also has no direct safety significance and thus the radioactivity of the waste is not a safety indicator, because the total activity of a mass of radionuclide by itself is not a measure of its potential health or environmental hazard. Therefore, as with the mass comparison, the activity comparison must be presented honestly, without over-interpretation or misrepresentation, but it still has value because it helps to build in a step-wise manner the logical comparison between the disposal facility and nature for non-technical audiences.

7.4.3. Comparisons of potential radiological hazard

Building on the initial comparison of mass and total activity, a next step may be to consider the actual potential health and environmental hazard posed by the waste and to compare this with a similar measure of the potential hazard posed by the radionuclide content of the host rock. Again for consistency, the volume of host rock considered should be the same as that considered in the comparisons of mass and total activity, i.e. the volume of host rock within the catchment or in the column of rock directly above the disposal facility.

The hazards presented both by the radionuclides in the waste and the radionuclides in the rock can be expressed in terms of hazard indices and, as discussed in Section 6, the radiotoxicity of waste can be compared to a range of natural materials, such as the mass of ore or natural uranium used to produce the original fuel and ashes from coal burning. For continuity of presentation in the safety case, the most useful reference is the radiotoxicity of the radionuclide content of the same rock volume used in the mass and activity comparisons, such as the volume of host rock within the catchment or in the column of rock directly above the disposal facility.

The comparison of radiotoxicity between the disposal facility and nature has more direct safety significance than comparisons with hazard indices based solely on mass or total activity. It is, however, intrinsically more difficult to present and comprehend because of its reliance on specialist radiological terms and concepts. Nonetheless, it continues to build the step-wise logical comparison between the disposal facility and nature.

7.4.4. Cross-over times

To show that radioactive decay is working in the direction of reducing potential radiological hazard over time, it is possible also to indicate the evolving inventory activity of the waste over time, assuming it was totally contained within the disposal facility. Thus a simple cross-over time for when the radiological hazard associated with the waste decays to equal the hazard associated with a similar volume (or mass) of host rock, or other suitable references, can be calculated.

In itself, a cross-over time is not a measure of safety. Rather, as discussed in Section 6, cross-over time can be used as a yardstick to compare with canister lifetimes or with transfer times within specific sections of the multibarrier isolation system. When a safety case can show that anticipated containment times provided by the canisters or by a combination of engineered barriers are long in comparison to the cross-over time for the waste, then this provides a useful argument in support of safety for some audiences.

7.4.5. Concentrations and fluxes across the geosphere-biosphere interface

To some extent, the safety of a disposal system can be estimated by the fluxes of disposal facility-derived contaminants across the geosphere-biosphere interface and the resulting concentrations in appropriate environmental compartments, provided appropriate yardsticks for comparison are used. An obvious approach is to compare the concentrations in the biosphere and fluxes of disposal facility-derived contaminants crossing the geosphere-biosphere interface with their natural equivalents. In order to make these comparisons, it would be necessary for assessment results to be expressed in the form of time-dependent concentrations and activities of disposal facility-derived radionuclides in near-surface and surface compartments (e.g. soils, surface waters, etc.) and their associated fluxes. Standard assessment codes may implicitly track these values, although they may not be routinely reported.

These calculated disposal facility-derived releases could then be compared with the measured natural concentrations and derived natural fluxes for the same materials, in the same compartments at the same site. Direct comparisons are possible only for the natural series radionuclides and for parameters such as total activity because some of the disposal facility radionuclides do not occur in nature. For parameters where direct like-for-like comparisons are possible, various alternatives can be considered, including:

- natural and disposal facility-derived elemental concentrations in soils and sediments, and near-surface and surface waters;
- natural and disposal facility-derived total activities in soils and sediments, and near-surface and surface waters;
- natural and disposal facility-derived elemental fluxes from shallow rock to the soil horizon;
- natural and disposal facility-derived elemental flux discharges to surface water bodies;
- natural and disposal facility-derived activity fluxes from shallow rock to the soil horizon; and
- natural and disposal facility-derived activity flux discharges to surface water bodies.

These are only intended as examples and specific comparisons would need to be determined for individual safety cases on the basis of the climate, geology, geomorphology and vegetation in the disposal facility catchment area.

Concentration comparisons can be made graphically by reference to the natural concentration ranges of the elements of concern that occur in rocks, soils, sediments and waters, etc., as described earlier to evaluate their associated natural hazard. On such a graph, the natural concentration ranges found within the catchment area can be distinguished from the ranges found elsewhere in the region or globally. If it is then shown that the disposal facility site contains rocks and groundwaters from the median and lower ends of the concentration scales (as may be expected by siting a disposal facility away from potential resources) and that the incremental rise to the environmental concentrations due to the maximum rates of migration from the disposal facility is small, then, to a first approximation, the hazard associated with those releases is also likely to be small. Such an argument, in order to be convincing, needs to be supported by evidence that the highest natural concentrations cause no detriment to the health of local populations and that the maximum migration from the disposal facility is smaller than these.

Generally, such comparisons could be used to show that the assessment calculations of disposal facility concentrations and fluxes (by mass or activity) in the surface environment would be lower than their natural counterparts. Additionally, the increases to the concentrations, fluxes and activities in the surface materials arising from the additional input of the disposal facility-derived migration can be given. In this manner, it could be shown that these anticipated increases will have a small impact. In particular, it could be shown that the impacts will be sufficiently small so as not to increase significantly the natural radiation environment.

In many geological environments, the dominant natural radionuclide flux across the geosphere-biosphere interface will arise from erosional processes. This is in contrast to the dominant transport pathway for radionuclide migration from the disposal facility which is groundwater flow and discharge. When comparing the disposal facility-derived flux with natural ones, therefore, it is possible to compare with either the total natural flux or only that proportion associated with groundwater, provided sufficient data exist to differentiate the latter.

An additional problem arises when considering the migration from the disposal facility of non-natural radionuclides across the geosphere-biosphere interface because these cannot be compared directly with any natural counterpart. Examples of such long lived radionuclides are ^{59}Ni, ^{99}Tc, ^{129}I, ^{135}Cs, ^{237}Np and a few other transuranium radionuclides. However, a number of other approaches may be adopted.

In Finland, the Radiation and Nuclear Safety Authority (STUK) has considered these problems and has recently issued a guide for the long-term safety of spent fuel disposal which includes constraints based on activity releases to the environment expressed as nuclide specific activity fluxes across the geosphere-biosphere interface dissolved in groundwater [8]. The derivation of the flux constraints was based, in part, on consideration of the estimated present-day fluxes of naturally occurring radionuclides in Finnish rivers and occurring as a consequence of human practices, such as mining and agriculture.

Another possibility would be to make the comparisons based on radiotoxicity, as discussed in Section 6. In this case, it is possible to present the concentrations and fluxes of natural and disposal facility-derived species in terms of radiotoxicity (e.g. as number of ALIs) and then to compare the natural radiotoxicity flux crossing the geosphere-biosphere interface with the additional radiotoxicity flux derived from the disposal facility. Furthermore, these radiotoxicity fluxes may be normalised per unit area of the catchment (e.g. to compare disposal facility-derived fluxes with natural fluxes in terms of number of ALIs/km^2). Alternatively, to give additional present-day context, a simple ingestion model could be adopted, such as a person drinking two litres of groundwater per day, to determine the radiotoxicity ingested per person in the catchment (e.g. to compare ingestion of disposal facility-derived species with ingestion of natural species in terms of ALIs/person). Thus it would be possible both to quantify the incremental rise in radiotoxicity crossing the geosphere-biosphere interface as well as a conservative estimate of the incremental exposure of the local population. An example of this approach in the context of radioactive waste disposal in the UK is given in [34].

7.5. COMPLEMENTARY SAFETY INDICATORS IN DIFFERENT TIME FRAMES

Assessment time periods are generally determined by taking account of the waste type, the facility design and the assessment context. Most directly, the assessment time period needs to be consistent with the duration of the hazard associated with the particular type of waste. Cross-over times may be used as an input to defining a rational assessment time period, in addition to their use as a yardstick against which to compare time-scales as safety indicators, as discussed in Section 6. Some discussion on cut-off times is relevant in a safety case because current assessments are sometimes vague as to why specific cut-off times are adopted and what the implications are for safety beyond these times.

The assessment time period may be more readily comprehended by some audiences if presented as time intervals, rather than as a continuum. Clearly the number and length of intervals used in the presentation would be dependent also on the nature of the waste and the assessment context. Some sectors of the public may be interested mainly in relatively short time periods of, at most, a few generations (e.g. decades to a few hundred years). Although this is not a time frame traditionally of interest in performance assessments of geological disposal facilities, it may be relevant in safety assessments for near surface disposal facilities. In the context of safety cases for near surface disposal facilities a time period of a few hundred years would be relevant also because it coincides with the duration of institutional controls assumed in some instances. Other intervals may be defined in a number of ways, for example they might relate to uncertainty over the timing of events in the disposal facility evolution (the periods in which canisters might fail, the period during which transport through the far-field might be most likely to occur, etc.) or they might be defined with relation to a historical perspective (e.g. time period equal to modern civilisation, time period since last glaciation, time period equivalent to the existence of *Homo Sapiens*, etc.) or using some other approach.

Such a presentation can be particularly useful for non-technical audiences because it allows attention to be focussed on the time-scales of most interest to them. The approach may, however, also be useful to performance assessors because it is consistent with their understanding that certain safety indicators may be more appropriate for certain time frames than for others. For example, it is generally agreed that the reliability of dose and risk estimates decreases for increasing assessment times as the uncertainty about predicted future human behaviour becomes larger. It has been suggested that, in the far future, dose and risk targets should be considered only as indicative reference values, and that calculated doses and risks should be considered only as qualitative indicators [34]. Nonetheless, many national licensing authorities apply no time cut-off to the quantitative application of dose and risk in their regulations. For time periods far in the future, other indicators are thus often seen as becoming more meaningful and necessary to complement dose and risk.

In this way, the presentation of the complementary safety indicators can be linked to the discussion of the assessment time periods. It is inappropriate, however, to prejudge the value to be placed on the different indicators by different audiences. Therefore a range of safety indicators could be presented for each time period, rather than just the single indicator which the assessors consider to be most appropriate. The readers of the safety cases can then make their own value judgement as to the significance of each indicator. It may well be sensible for the proponents of the safety case to state which indicators they consider to be most meaningful for each interval, to allow their safety arguments to be independently evaluated.

An example figure for the presentation of indicators is given below. Values for dose, risk, flux and concentration may be given in actual units but this may be confusing for some non-technical readers unused to radiological concepts. An alternative may be to express the disposal facility values as a proportion of the natural values as indicated in the figure.

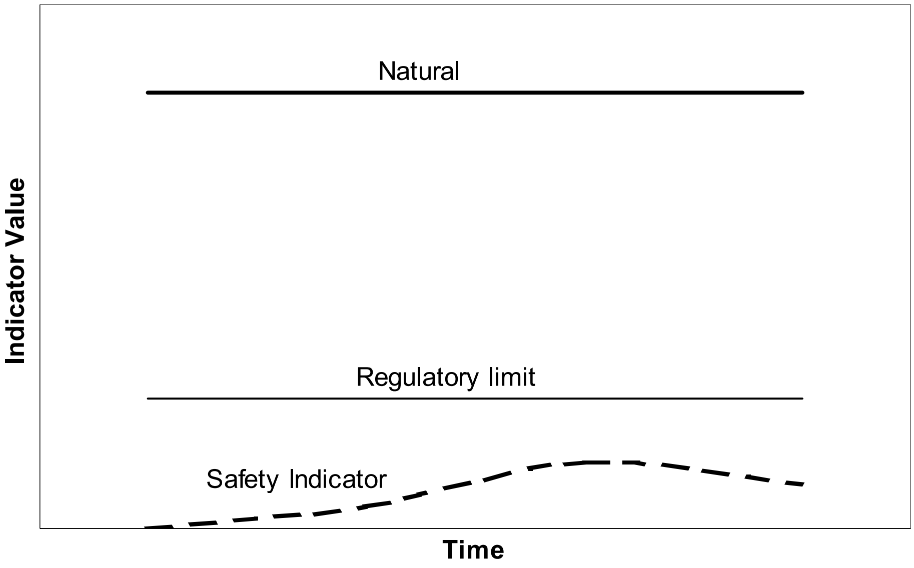

FIG. 2. Relative value of safety indicators in different time frames.

This figure highlights a further issue with respect to the behaviour of the natural system: namely its variability over time. Clearly, given future climate change and other possible environmental variations, some natural concentrations (e.g. in soils and other near surface materials) and fluxes may be expected to change over the assessment time period. Some of these changes may be estimated and the resulting time-dependent values compared with the equally time-dependent values for disposal facility-derived releases. Alternatively, the impact of future changes to the natural system may be ignored and calculated rates of radionuclide migration from the disposal facility may be compared to the present-day natural values, assumed to remain constant for the time period of the assessment. The reasoning for this approach is that the present-day system is obviously well known and, thus, provides the maximum potential for providing context to the rates of radionuclide migration.

This example and the figure given above are most relevant to geological disposal facilities, for which assessment time periods are very long. In principle, there is no reason why the complementary safety-indicators approach could not be applied in safety cases for other disposal facilities, including shallow facilities for low and intermediate level waste. In this case the duration of the assessment time period would be much shorter, and, thus, it would be appropriate to divide it into different time intervals. In the case of near surface disposal of long lived, low level waste containing naturally occurring radioactive materials, consideration of time periods separated by the expected end of institutional controls would appear to be logical. Nonetheless, the option of comparing the calculated environmental concentrations and fluxes resulting from waste-derived releases with natural counterparts is equally valid. Differences in the approach may be required to take account of, for example, the smaller spatial scales over which the relevant fluxes are expected to operate in comparison to those from deeper disposal facilities. The general consideration still stands that the application of the complementary safety-indicators approach must be carefully examined and shown to be consistent with the waste and disposal concept, the assessment basis and the requirements and expectations of the potential audiences for the safety case.

8. CONCLUSIONS AND CONSIDERATIONS

This report discusses the development and application of safety indicators, in particular indicators that can be employed, in addition to dose and risk, in developing the safety case for facilities for radioactive waste disposal. The focus of the report has been on the application of such complementary safety indicators to geological disposal facilities. Their applicability to other types of disposal facilities has not been analysed in detail. Preliminary considerations do not, however, reveal any substantial obstacle to the application of at least some complementary indicators to, for example, near surface accumulations of long lived radioactive materials such as uranium and thorium mining and milling tailings and other waste containing elevated levels of naturally occurring radionuclides.

Conclusions of the report, in relation to the objectives stated in Section 1, are:

(i) Indicators, together with appropriate yardsticks, can be used to provide arguments for the acceptability, in terms of safety, of the evaluated performance of a disposal system, and the quality and reliability of its various components, including the suitability of a chosen site and design to provide long term isolation.

When making a safety case, a primary objective is to provide arguments that build confidence in the disposal system, the assessment procedure and its findings amongst all readers. The role of performance and safety indicators is to help build this confidence by providing indications that future disposal facility behaviour will be safe in terms that are relevant to the interests and expectations of the different reader groups. In some cases, performance and safety indicators may be judged against formal licensing criteria. Other indicators may be evaluated in a less formal or qualitative approach by comparison with less well defined yardsticks.

(ii) Among the variety of potential indicators discussed, concentrations and fluxes in the geosphere and surface environment, and containment time-scale appear to have a considerable potential as complementary indicators of overall system safety.

Dose and risk remain the most important safety indicators for a disposal facility because they relate directly to regulatory criteria and, over short and perhaps medium term time frames, can be considered quantitative measures of human health detriments and environmental impacts arising from the facility. Over the longer term, uncertainties in the calculation of dose and risk may suggest that they should be used in a more qualitative manner, although many national regulations apply no time cut-off for their quantitative application as safety indicators in assessments.

Among the various complementary safety indicators discussed in this report, concentrations, fluxes and time-scale of containment are considered to be the most meaningful over a wide range of time frames, although their application to safety cases will need to be determined on a case by case basis. Concentrations, fluxes and time-scales can potentially be used as performance indicators to measure the behaviour of disposal facility subsystems or as safety indicators to measure the overall safety of the disposal system. Their application as complementary safety indicators is, however, restricted by the availability of meaningful yardsticks against which to evaluate them. Reference values from natural systems provide sensible yardsticks for disposal facility-derived concentrations and fluxes, while time-scales as a measure of engineered barrier performance can be evaluated against the yardstick of a cross-over time.

> *(iii) Safety indicators other than dose and risk complement, rather than supplant, the use of dose and risk; they can be of use, in terms that they avoid sources of uncertainty related to future human behaviour and for communicating to wide audiences.*

Although the behaviour of a disposal facility may be judged to be safe on the basis of dose and risk alone, considerable benefit may be gained by consideration of a range of other complementary indicators. This is consistent with the concept of enhancing confidence in the safety case by using ‘multiple lines of reasoning’. The benefit is further enhanced by adopting safety indicators that can be evaluated against a variety of different types of yardstick (e.g. dose limits, natural radionuclide abundance, cross-over times) to provide independent measures of safety for the disposal facility. In particular, the use of safety indicators, complementary to dose or risk, that do not rely on highly uncertain assumptions about the future evolution of society and, to some extent, the biosphere, can strengthen the arguments supporting the long term safety of radioactive waste disposal facilities.

An additional benefit of some complementary safety indicators is that they may be more easily comprehended by non-technical audiences of a safety case because they need not necessarily be couched in terms of unfamiliar radiological concepts and units. Even though simple comparisons between nature and the disposal facility might not provide a quantitative evaluation of the potential radiological hazard posed by the waste, they still may be more convincing to some audiences, particularly when combined with other arguments, e.g. considerations based on the study of natural analogues.

> *(iv) In applying, in practice, complementary safety indicators to a safety case, the key consideration at the outset is that the suite of indicators selected must be consistent with the waste and disposal concept, the assessment basis and the requirements and expectations of the potential audiences for the safety case.*

In a safety case that is likely to be read by non-technical audiences, it is possible to use complementary safety indicators in a step-wise manner to build-up the comparison of the disposal facility system with nature. Simple comparisons of mass and total activity can ‘set the scene’ for some readers but need to be presented carefully to avoid misrepresenting the hazard associated with the waste.

Presentations comparing the concentrations and fluxes of disposal facility-derived contaminants crossing the geosphere-biosphere interface with their natural counterparts can be made. The most challenging aspect of using complementary safety indicators, however, is to put the releases of non-natural disposal facility-derived radionuclides in a natural perspective. This can be most usefully done by presenting the concentrations and fluxes of natural and disposal facility-derived species in terms of radiotoxicity and then comparing the natural radiotoxicity flux crossing the geosphere-biosphere interface with the additional radiotoxicity flux due to disposal facility-derived releases. Such comparisons can show the impacts of disposal facility-derived radionuclide migration to be of no major significance.

A useful approach to the presentation of complementary safety indicators may be to divide the total assessment time period into a number of intervals, and to provide for each a range of indicators. The readers of the safety case can then make their own value judgement as to the significance of each indicator for the intervals of most concern to themselves. It would be sensible for the developers of the safety case to state which indicators they consider to be most meaningful for each interval, to allow their safety arguments to be evaluated.

It is worth stressing that it is not the intention of these proposals to require that standard methodologies for performance assessment be significantly changed, although additional reporting of intermediate quantities such as disposal facility-derived concentrations in near-surface environmental media may be required. Instead, it is recommended that any additional safety indicators be expressed in a form that is readily comparable to safety assessment outputs, so as to allow them to be easily evaluated.

In view of these conclusions, it is suggested that additional work be carried out on at least the most potentially useful of the discussed indicators. In particular, in relation to yardsticks against which to compare complementary safety indicators, reference levels for fluxes leaving the geosphere and concentrations in particular compartments of the accessible environment could be defined on the basis of average, worldwide values or of regional data. This should be done within an international co-operation framework.

APPENDIX
DERIVING NATURAL FLUXES

The discussion in this document indicates that the fluxes of disposal facility-derived contaminants across the geosphere–biosphere interface can be useful safety indicators, provided appropriate yardsticks for comparison can be determined. An obvious approach is to compare the fluxes of disposal facility-derived contaminants crossing the geosphere–biosphere interface with their natural equivalents. In order to make these comparisons, it is necessary to quantify these natural fluxes. Basically, two types of data are required to do this:

1. concentrations of the elements and radionuclides of interest in the rocks, soils, water, etc.; and
2. the rates of the relevant geological processes such as erosion, groundwater flow, river flow, etc. that cause mass movement.

The concentrations of many naturally-occurring elements and radionuclides in surface and near surface media are relatively well known for a wide range of different environmental conditions and with a good geographical coverage. Ongoing international geochemical projects are expected to lead to further improvements in the availability of reliable geochemical data.

Nonetheless, there are many practical problems associated with the derivation of natural fluxes that relate to the complexity and variability of natural systems, and the fact that fluxes cannot be directly measured and need to be inferred from other information, such as the mass of sediment transported in rivers. A further problem is that, in contrast to geochemical data, published process rate data are less widely available and can be difficult to quantify, meaning that some can be subject to fairly large uncertainties, for example long term erosion rates. Furthermore, published process rate data have poor geographical coverage and, thus, when looking at a specific candidate disposal facility site, pre-existing data may not be adequate or abundant either for the site itself or the surrounding catchment..

It is useful to consider natural fluxes over different spatial scales in order to be able to place the disposal facility site values in a wider geographical context, as discussed in Section 7. This Appendix discusses how fluxes may be determined over large scales, equivalent to the size of river basins, and over smaller, disposal facility site, scales. The fact that process rates data have poor geographical coverage, however, means that it may be difficult to obtain reliable data from the published literature alone and site characterisation programmes may need to be modified to acquire the necessary information.

Large scale fluxes

It is likely that the establishment of regional or even global variability in natural fluxes will be undertaken using quite a broad-brush approach. One suggested methodology to do this is to use data on suspended and dissolved elemental loads in river basins. Rivers can be seen to be long term integrators of all fluxes operating in the basin, thus providing long term, large scale average flux values. This approach has merit in that river transport data are available for many of the world rivers, although the quality of the data is highly variable. In addition, comparing disposal facility-derived values with a range of fluxes determined for a variety of geological, morphological and climatic conditions, and their natural variability, eliminates the risk of reaching misleading conclusions in the event that the candidate disposal facility site were located in an area characterized by anomalous geochemical conditions.

There are also drawbacks associated with this approach. Firstly, river transport loads can be easily affected by anthropogenic factors, such as discharge of effluents, enhanced erosion due to deforestation, agriculture and mining, construction of dams, etc. Care needs to be taken, therefore, to determine how closely measured river transport data reflect natural processes. It is believed that most current river flow data are affected by human activity and may not be easy to interpret as indicators of long term natural processes. Secondly, because rivers integrate all fluxes in the basin, information is lost on the relative importance of individual processes generating fluxes - notably the relative importance of fluxes derived from the outflow of groundwater. One possibility to circumvent this difficulty might be to assume that the dissolved load is mostly generated by groundwater discharge and the suspended load from mass movement of eroded solid material. This neglects, however, the effects of elemental partitioning between the liquid and solid phases, which is especially important for redox sensitive elements such as uranium. Thirdly, the river data mask the natural flux variations within the catchment, which can be quite large, especially if the basin includes outcrops of different rock types, variable topographic relief and variations in soil development and land use.

A number of studies have addressed the mass fluxes of a number of elements for large rivers. Notably, Fyfe has calculated the long term global (geological) fluxes of uranium from basement rock to the ocean sediments [35]. This long term average value could be interpreted as the simplest reference for the comparison with disposal facility derived fluxes/concentrations.

In another study [30], average elemental abundances and process rate data were compiled and used to determine indicative elemental fluxes for a number of generic environments which potentially may host disposal facilities, including an inland pluton, sedimentary basin and crystalline basement under sedimentary cover. Part of the calculations included estimates of the elemental fluxes in suspended and dissolved loads in world rivers, as well as calculations of the fluxes derived from other processes such as average global erosion and groundwater flow. These calculations showed that, in general, the largest elemental fluxes crossing the geosphere-biosphere interface are due to physical weathering of rock, with those due to groundwater discharge being notably smaller. Obviously, this has an important bearing on deciding what are the appropriate comparisons to make between the disposal facility impacts and natural systems. It should be noted, however, that this general observation does not hold for all geographical locations and climatic conditions.

Site-specific fluxes

Disposal facility-derived fluxes determined by assessment calculations can be compared with the fluxes occurring at the same site, or in the same general locality, as the proposed disposal facility. The benefit of the site-specific approach is that the most direct comparisons are made, since it should be possible to compare natural and disposal facility-derived fluxes in the same rock and water compartments, crossing the same geological boundaries and under the same physico-chemical conditions. On this basis, reliable evaluations could be made of the impact of the disposal facility-derived releases on the natural geochemical system.

In theory, site-specific comparisons between natural and disposal facility-derived fluxes should be possible to a greater level of detail than comparisons with natural fluxes at other locations but this is dependent on there being adequate site-specific information. Much of the relevant information may be acquired from the disposal facility site characterization programme. If site characterization data were not yet available or were incomplete, it might be justifiable to use proxy data from other locations with similar geology and surface conditions.

Where there is a detailed body of geological and geochemical data for a site, it should be possible to calculate the natural elemental and radionuclide fluxes produced by each of the dominant geological processes operating in the vicinity of the disposal facility site, rather than relying on an integrated average flux provided by stream water data. This site-specific flux comparison methodology has been demonstrated for the Äspö site in Sweden, using information derived from investigations carried out in the underground research laboratory (URL) [5, 36].

A further possible refinement to the methodology would be to scale the natural fluxes calculated for the disposal facility site from unit area/volume values to the geometry and dimensions of the proposed disposal facility, i.e. to calculate the natural fluxes derived from the volume of rock that would hold the proposed disposal facility. In fact, this methodology was adopted for the flux calculations mentioned above for the Äspö site using the concept of the Repository Equivalent Rock Volume (RERV). The potential advantage of scaling the natural elemental and radioactive fluxes to the dimensions of the RERV is that comparison of the repository and natural fluxes are made for systems with identical size and geometry. The most relevant scale to consider would be the catchment in which the disposal facility is located because this largely defines the areal extent of both the disposal facility and natural fluxes, their rates and variability.

Elemental mass and radionuclide fluxes

For fluxes calculated at any scale, the initial fluxes are likely to be derived in terms of elemental masses, given that the input geochemical data are usually expressed in mass concentrations (for example mg/kg or mg/L) which, however, can be easily converted to radioactive fluxes (for example in units of Bq/year or ALI/year). Depending on the input data and the objectives of the safety assessment, it may be possible to calculate separately the radioactive fluxes due to each geological process for both the alpha (natural decay series) and non-alpha emitters (predominantly ^{40}K). In the case of the alpha emitters, if only concentrations of uranium are known, then the radioactive flux from the long lived components of the decay chain can be estimated, if secular equilibrium in the decay chains is assumed. An example of this approach in the context of radioactive waste disposal in the UK is given in Ref. [33].

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Meeting of the Working Group on Principles and Criteria for Radioactive Waste Disposal
Vienna, 13–15 March 2001

Consultants Meetings
Vienna, 30 October – 3 November 2000 and 26–30 November 2001

Final review by Working Group of Principles and Criteria for Radioactive Waste Disposal
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