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Indicators in the Safety Case

A report of the Integrated Group on the Safety Case (IGSC)

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Radioactive Waste Management Committee

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EXECUTIVE SUMMARY

The last several years have seen a number of important developments in the use of indicators in safety cases for geological disposal. The NEA has reviewed these developments within the scope of its Methods for Safety Assessment (MeSA) project, and this Status Report presents the findings of that review.

This review began by evaluating relevant aspects of previous NEA initiatives into safety cases, in particular the International Experience in Safety Cases (INTESC), Long-Term Safety Criteria (LTSC) and Timescales initiatives, as well as key publications from other international agencies such as the IAEA and EC. That evaluation confirmed the growing international interest in the subject but also highlighted a clear lack of consistency in the terminology, characteristics and methods of application of the indicators used by different organisations. To understand the situation better, a questionnaire was developed that included a number of questions grouped under the headings of (i) regulatory context and guidance, (ii) status of repository development programme, (iii) use of complementary indicators, and (iv) areas of uncertainty and future development. The Indicators Questionnaire was circulated to implementing organisations and regulatory agencies in Member States in February 2010, and twenty one separate responses were received that covered a range of experiences from developing assessment programmes just beginning to consider how to use indicators, to mature programmes that have already performed detailed site-specific assessments.

The responses to the Indicators Questionnaire provided the primary source material for this Status Report, together with the outcomes from comparable international work, in particular relevant IAEA Technical Reports and the EC's SPIN and PAMINA Project reports.

The main purpose of this Status Report is to increase awareness and understanding of the potential applications of indicators in the safety case, and provide support for further development in the area. Some guidance on the possible use of indicators is given but it is not the objective to seek to propose a 'standard' approach or terminology. This would be neither sensible nor possible given the differences in national regulations concerning their requirements for how indicators should be applied. For the sake of clarity, however, in this report an important distinction is made between primary and complementary indicators. A *primary indicator* (typically annual dose or risk) is one that is compared to a legally or regulatory defined radiological constraint, whilst all other indicators that may be used in a safety case are referred to in this report as *complementary indicators*.

This Status Report is intended to be useful to anyone engaged in the planning, preparation and review of safety cases for radioactive waste repositories. It is, however, focussed on providing advice to developers of deep geological repositories with programmes at an early stage of development (e.g. pre-site selection), rather than those that are more mature and which have already defined their assessment methodologies and end-points. This report may also be useful to regulators and those engaged in peer review of safety assessments, particularly in regimes where regulators may choose to stipulate the use of specific indicators in addition to dose or risk in formal safety cases that are submitted to them.

The first important observation that was made from the responses to the Indicators Questionnaire is that complementary indicators are now accepted by the majority of implementers and regulators as an important component of a safety case. This is a markedly different position from a decade ago, when the potential for complementary indicators was still under investigation. This shift in approach is consistent with the development of safety cases using multiple lines of reasoning which require the mechanics of repository evolution to be understood at the sub-system and component or process level.

Whilst there is almost universal acceptance of the potential benefits of using complementary indicators, there are significant differences in the types of indicators that are used or proposed, and the methods for their application in safety cases. Over 100 separate indicators were reported in the responses to the Indicators Questionnaire, illustrating their growing relevance within assessment programmes. On inspection, however, many of the reported indicators are shown to be broadly the same or variants of each other, but they are often differently named, described or categorised. In simple terms, the most commonly reported indicators fall into three main groups, as follows:

- ‘Content and concentration’ related indicators, such as:
  - Radioactivity/toxicity concentration in the wasteform
  - Radioactivity/toxicity concentration in the engineered barrier system components
  - Radioactivity/toxicity concentration in the geosphere (particularly in groundwater)
  - Radioactivity/toxicity concentration in the biosphere (particularly in surface waters)
  - Power density in groundwater
- ‘Flux’ related indicators, such as:
  - Radioactivity/toxicity flux from the engineered barriers to the geosphere
  - Radioactivity/toxicity flux from the geosphere to the biosphere
  - Integrated radioactivity/toxicity flux from the geosphere to the biosphere over time
  - Radionuclide molar flow (mass over the assessment period)
- ‘Status of barriers’ related indicators, such as:
  - Groundwater age
  - Container lifetime
  - Transport times through the engineered barrier system components and the geosphere
  - State of stress in the near-field rock (containment zone)
  - Swelling pressure (buffer and backfill)
  - Ionic strength (geosphere groundwater)

The grouping shown above has been derived within the scope of developing this Status Report, based on the types of indicators reported to have been used to date. This simple grouping is considered to be useful because it does not suggest any relative importance or hierarchy between the various indicators that may be used in a safety case. Many (but not all) organisations, however, make a distinction between *safety indicators* and *performance indicators*, following the recommendations of the IAEA made in 2003.

In very broad terms, a safety indicator provides a measure of the overall safety of the entire repository system. Safety indicators are usually compared with quantities, known as *reference values*, which represent some minimum measure of safety that is generally considered to be acceptable. At the simplest level, calculated repository releases may be compared with the equivalent abundances of naturally occurring radionuclides measured in the rocks and groundwaters at the repository site, on the basis that the natural environment is generally considered to be safe. This simple approach to using safety indicators is consistent with early suggestions that the impact of a repository should not lead to a significant increase in the radiation environment. The approach can be refined by making more specific comparisons between particular transport pathways (e.g. groundwater discharge), and abundances can be defined for either concentrations or fluxes of all radionuclides or just for specific nuclides of interest. The approach is also well suited for comparing the chemotoxic hazard associated with repository releases and natural systems.

A difficulty with the use of safety indicators lies in the derivation of appropriate reference values. There is a small number of universally applicable reference values that may be used in all safety cases, such as internationally agreed drinking water standards, and these can provide a means for comparing between different assessments. There is a trend, however, towards using site-specific reference values, such as local or regional groundwater concentrations, because these are often considered to provide the most relevant situational context. Several national repository development organisations anticipate deriving site-specific reference values from characterisation studies, once sites have been chosen.

In comparison to a safety indicator, a performance indicator provides a measure of the behaviour of an individual repository component or sub-system. For this reason, performance indicators are usually more concept or site-specific than safety indicators. Multiple performance indicators may be applied in a safety case and they could be used to evaluate performance of the disposal system barrier-by-barrier, and to determine what redundancy and performance ‘head room’ is available in the repository design. Various performance indicators have been used or proposed, and they typically relate to such things as the containment times provided by individual barriers or the migration rate (flux) of radionuclides across them.

One newly identified potential application of performance indicators is their use in site selection and design optimisation. Performance indicators allow the relative containment provided by different host rocks, geological environments and engineered barrier materials to be quantified and compared in a structured manner. They may, therefore, be used to select and optimise the design against known subsurface conditions (e.g. the best buffer material given known groundwater composition), and to ensure the overall cost and effort for constructing the repository are not excessive.

Performance indicators may be compared with independent quantities, known as *indicator criteria*, although these are not essential and not available for comparison with all performance indicators. Where they are available, indicator criteria may be derived from independent modelling, laboratory studies or, occasionally, natural analogue studies (e.g. to provide a measure of long-term metal corrosion rates).

More recently, a number of organisations have begun to define explicit safety functions for some individual repository components. It is possible to derive indicators from these safety functions, sometimes called *safety function indicators,* which are measurable or calculable properties that indicate the extent to which the system components achieve their safety function. For example, a metal waste canister may be assigned the safety function of ‘physical containment’ in which case an appropriate safety function indicator may be the redox condition of the groundwater because, if it is too oxidising, the metal may corrode rapidly causing it to lose its containment function. Safety function indicators are usually compared with indicator criteria which define the quantitative limits (maximum or minimum conditions) that are the boundary conditions under which the matching safety function may be maintained. These will generally be derived from independent studies.

It is clear that safety function indicators have quite a lot in common with performance indicators in so far as they both relate to the evaluation of system components and sub-systems. The key difference between them lies in the requirement for a safety function indicator to be compared with a corresponding indicator criterion, whereas a performance indicator need not always have a matching criterion for comparison. Given their similarity, safety function indicators can be considered as a special case and application of performance indicators.

The concept of safety function indicators has been developed further by SKB in its recent safety cases for spent fuel disposal in Sweden, in which safety function indicators were used to identify scenarios and to derive calculation cases for the safety assessment. In SKB's methodology, when an assessment showed that a safety function indicator may not achieve its matching indicator criterion, then additional calculations were performed to evaluate the consequences of the associated safety function being lost.

Although many organisations stated in their responses to the Indicators Questionnaire that they do explicitly categorise indicators as either safety, performance or safety function indicators, several other organisations deliberately do not apply any defined categorisation scheme and prefer to use more general terminology that does not suggest any hierarchy amongst the complementary indicators they use. This is due, in part, to differences in the regulatory regimes and safety assessment methodologies adopted in different countries.

There is increasing recognition of complementary indicators within national regulations. In many countries, the regulatory regimes are non-prescriptive and complementary indicators are featured in non-statutory guidance documents but, nonetheless, the language used in them often makes it evident that the regulator has a strong expectation that the repository developer *will* use complementary indicators to support their safety case, even if there is no formal requirement in law to do so. At the present time, however, new regulations have been produced in final or draft form in several countries (e.g. Finland and Germany) and these include formal requirements to use complementary indicators, although these regulations vary considerably in how the regulator expects them to be applied. These variations are driven, in part, by differences in the repository design and safety concepts in each country. For example, the Finnish regulations are expressed in terms of maximum allowable concentrations of repository releases in groundwater (a form of safety indicator), whereas the German regulations are expressed in terms of the functional requirements for the containment providing rock zone (a form of performance indicator or safety function indicator).

Irrespective of what classification scheme or terminology may be adopted, it is clear that complementary indicators may have multiple but related applications within a safety case. Those identified from the responses to the Indicators Questionnaire include:

- supporting the safety case structure and applying multiple lines of reasoning;
- increasing the transparency of safety case arguments;
- assessment of repository safety and presenting impacts in the content of the natural environment;
- assessment of repository safety in different timeframes;
- addressing uncertainty in dose and risk calculations;
- assessment of sub-system performance;
- assessment of safety functions;

- scenario identification; and
- helping with communication, especially to non-technical audiences.

Not all of these applications are appropriate in all circumstances. Whilst it is recommended that complementary indicators should feature in all safety cases, the safety case developer is encouraged to give careful thought to choosing and applying appropriate indicators so that they are consistent with:

- the regulatory context;
- the assessment context;
- the assessment methodology;
- the stage in the repository development programmes; and
- the intended audiences for the safety case.

In this Status Report, we provide examples of the many different indicators that have been proposed, and their methods of application, that are intended to be useful to programmes beginning to consider how to apply them in their own safety cases.

In addition to choosing appropriate indicators, the way in which they are presented in a safety case is also important. One of the primary drivers behind the use of complementary indicators is that they can offset some of the drawbacks associated with the calculation of dose and risk. In particular, they do not require assumptions to be made about future human behaviour; they allow the performance of the repository to be disaggregated rather than presented as a single parameter (e.g. dose) thus enabling the performance and safety functions of individual barriers to be assessed; and they provide site-specific context to repository releases and so can be more readily comprehended by non-technical audiences.

Of these points, the first is perhaps the most important and this has led several national regulators to require repository developers to place greater emphasis on complementary indicators in far-future assessment times, beyond the period when radiation exposure to humans can be reliably assessed, and especially after significant climate change may have occurred. When presenting indicators in a safety case, therefore, there is significant benefit to be gained from using different indicators in different assessment timeframes, so that the advantages of one can clearly be seen to be balancing the disadvantages associated with another. In this way, using a suite of different indicators will help to address uncertainty and to increase confidence in the safety case.

In the coming years, it is likely that further developments in the use of complementary indicators will occur, particularly in the context of safety cases produced to support repository siting and implementation decisions. This Status Report presents 'best case' examples of how indicators may be used in safety cases but does not propose that a standardised approach to their application should be promoted. One of the strengths of complementary indicators is that they can be applied flexibly in safety cases to provide a number of benefits, and to align with the particular circumstances at the time. Nonetheless, there may be some benefit from a focussed international effort to identify and collate appropriate reference values and indicator criteria that could be compared to different indicators. Having a common set of values would aid intercomparison exercises between safety cases, and support future repository design optimisation studies.

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1. INTRODUCTION

1.1 Background to the present report

In light of the substantial developments over the past 20 years, the NEA Integration Group for the Safety Case (IGSC) organised in 2008 a project examining and documenting Methods for Safety Assessment for long-term safety of geological repositories for the disposal of radioactive waste (MeSA: NEA, 2011). As one important aspect of the MeSA project, the current status about the use of indicators complementary to dose and risk was compiled using existing information from national and international projects, and information available from previous NEA initiatives, particularly from the International Experience in Safety Cases (INTESC: NEA, 2009a), the Long Term Safety Criteria (LTSC: NEA, 2007) and the Timescales Initiative (NEA, 2009b).

It became clear that there is a strong diversity in the terminology, definitions and characteristics of the indicators used by different organisations. Differences in the underlying safety and repository concepts, and the assessment strategy applied in each country lead to significant variations in the way indicators were identified and developed. Furthermore it was shown that the use of indicators depends, to some extent, on the geological formation, the system design and the stage of development of the repository programme. To better understand these diversities, a survey about the use of indicators by organisations from different NEA member countries was performed during the MeSA project.

From the review and survey work, as well as from the outputs from other recent international projects, such as the EC PAMINA Project, a large amount of detailed information about the application of indicators in safety cases and the experiences in various countries became available. This included a comprehensive list of the indicators and reference values used. The evaluation of all this information showed that there is a clear tendency for indicators to be used not only as part of the safety assessment but also increasingly to contribute more broadly to different elements of a safety case. It was decided by the IGSC to evaluate and integrate this information in a Status Report, so as to increase understanding with regards to the diversity of terminology, definitions and characteristics of indicators used.

One objective of this Status Report is to increase transparency and traceability in the use of indicators, provide support for further development in the area and to promote mutual understanding. Some guidance on the possible use of complementary indicators and reference values in the safety case is given but it is not the objective to seek to develop a standard approach or terminology due to the differences in national regulatory requirements, as discussed later.

1.2 Overview of indicators in the safety case

Repositories for the final disposal of radioactive wastes need adequately to isolate and contain the waste to ensure the long-term safety of people and protection of the environment. There are many different designs for repositories but containment is generally provided by a series of man-made (engineered) and natural (geological) barriers that rely on combinations of physical and chemical processes to isolate the waste and to minimise any radionuclide migration that may occur, and to do so robustly in response to natural changes in climatic and geological conditions.

In a safety assessment, the long-term evolution of the waste, the barriers and the natural environment are modelled to analyse and quantify barrier performance as well as any future release of radionuclides that may occur back to the surface. Conservative assumptions are also made for how humans may be exposed to these releases (e.g. in food and drink), and the resulting radiological dose and associated risk are then calculated. In all safety assessments, annual dose or risk are the final end-points for the calculations and 'safety' is ultimately determined by comparing the calculated dose and risk quantities with internationally recognised limits that are considered to be safe. This approach to repository safety assessment is well developed and universally applied, but is not without its drawbacks such as:

- radiological dose and risk are conceptually difficult quantities for non-technical audiences to understand and contextualise;
- assumptions for future human behaviour which need to be made when calculating dose and risk become increasingly difficult to justify with increasing assessment time periods, particularly after climate change will significantly change the surface environment; and
- dose and risk both provide aggregated measures of safety performance for the combined engineered and geological barrier system, and do not indicate which barrier(s) contribute most to safety.

For these and other reasons, there has been a move to develop safety cases which encompass multiple and independent lines of reasoning, both qualitative and quantitative, to provide additional reassurance that a repository will be safe. The safety assessment calculation of dose and risk is one line of reasoning within the safety case, albeit a very important one, but others are varied and can be chosen to reflect the specific interests and concerns of different audiences, including local public and stakeholders. The concept of a safety case based on multiple lines of reasoning has been promoted by the NEA in various recent reports (e.g. NEA, 2004).

The use of indicators that are complementary to dose and risk is one of the possible independent lines of reasoning that can contribute to a safety case. Such complementary indicators are often divided into *safety indicators* and *performance indicators*.

In very broad terms, a safety indicator provides an alternative measure for the overall safety of the entire repository system. Safety indicators must be compared with independent quantities, known as *reference values*, that represent some minimum measure of safety that is generally considered to be acceptable (e.g. drinking water standards).

Used in the simplest manner, the radionuclide releases from the repository, calculated in the safety assessment, can be compared with equivalent abundances of naturally occurring radionuclides measured in the rocks and groundwaters at the repository site. Given that all areas of the earth are variably radioactive due to the presence of naturally occurring uranium and its decay chain products (e.g. radon), this comparison can provide a measure for how much extra radioactivity, and associated radiological hazard, is added to the environment by the repository over and above that occurring naturally. This approach can be refined by making more specific comparisons between particular transport pathways in the geosphere or releases to the surface environment (e.g. by groundwater discharge, erosion or river flow), and abundances can be defined for either concentrations or fluxes of all radionuclides or just for specific nuclides of interest. The approach is also well suited for comparing the chemotoxic hazard associated with repository releases and natural systems.

In equally broad terms, a performance indicator provides a measure for the performance of a repository component or sub-system. For example, by calculating the proportion of repository releases that occur through successive nested barriers, it is possible to determine which barrier(s) contribute most to the overall containment capacity of the repository, and whether that is due largely to physical processes (e.g. containment within a waste container) or chemical processes (e.g. limiting radionuclide solubilities in groundwater).

Performance indicators may be compared with independent quantities, known as *indicator criteria*, although these are not essential and not available for comparison with all performance indicators. Where they are available, indicator criteria may be derived from independent modelling, laboratory studies or, occasionally, natural analogue studies (e.g. to provide a measure of long-term metal corrosion rates). In some cases, they may also be compared to design criteria such as the expected length of time a waste container will remain intact.

More recently, a number of organisations have begun to define explicit safety functions for some individual repository components, and to use *safety function indicators* in safety cases to evaluate them. These indicators are measurable or calculable properties that indicate the extent to which the components may achieve their safety function. For example, a steel waste canister may be assigned the safety function of 'physical containment' in which case an appropriate safety function indicator may be the redox condition of the groundwater because, if it is too oxidising, the steel canister may corrode rapidly causing it to lose its containment function. Safety function indicators may also be compared with indicator criteria which define the quantitative limits (maximum or minimum conditions) that are the boundary conditions under which the matching safety function may be maintained.

Within a safety case, complementary indicators may be used to make simple illustrations for how the repository is expected to evolve over time, and how this compares to the evolution of the natural system that contains the repository. Such illustrations and comparisons may be particularly useful for explaining to non-technical audiences the expected long-term performance of the repository and setting it in a natural (and local) context.

Alternatively (or additionally), complementary indicators may be used in a rigorous and quantitative manner to provide a set of interim calculation end-points that demonstrate the performance of the repository system component-by-component, and thus explain how overall safety is derived, and what redundancy and safety 'head room' is available within the repository system.

Not all safety cases use the terms safety, performance or safety function indicators, but most of the safety cases published in recent years have used complementary indicators in some form or other. Different approaches to the use of indicators may be most appropriate for different purposes, dictated by the context for a safety assessment or safety case, the stage in the repository development programme, and the intended audience for the assessment. As such there is no single 'best' or recommended approach to the use of indicators in safety cases, and this report discusses how they may be applied in specific circumstances. As safety case methodologies evolve and mature as more repository programmes reach site selection, it is to be expected that the application of complementary indicators will also expand and evolve, and this report is intended to provide a basis for how this may happen with international consensus.

1.3 Aims and intended audience

This report is intended to be useful to anyone engaged in the planning, preparation and review of safety cases for radioactive waste repositories. It is, however, focussed on providing advice to those assessment programmes at an early stage of development (e.g.

pre-site selection), rather than those that are more mature. This is because the more advanced programmes have generally already defined their assessment methodologies and end-points, and have decided how they intend to integrate different indicators in their safety cases. It is not the intention of this report to cause any of the advanced assessment programmes to change their approach, although some mature programmes may find certain aspects of this report useful when planning future iterations of their existing safety cases. On the other hand, is clear that developing programmes can benefit from the experiences of the advanced programmes, and this report is intended to provide a distillation of lessons learned from them (good and bad) and to offer recommendations for the use of indicators in future safety cases.

This report is aimed predominantly at repository developers and their technical support and research organisations that perform safety assessments. It will, however, also be useful to regulators and those engaged in peer review of safety assessments, particularly in regimes where regulators may wish to mandate the use of specific indicators or methods for their application.

1.4 Mode of operation

This Status Report is the culmination of a step-wise process, performed within the scope of the NEA's Methods for Safety Assessment (MeSA) project, that was intended to examine and document the current status of methods for safety assessment for long-term safety of geological repositories for disposal of radioactive waste. One aspect of the MeSA project was to review and evaluate international experience in the use of indicators in safety assessment.

The first step involved a review of previous related NEA work and, in particular, an evaluation of the responses received to questionnaires distributed to national organisations as part of earlier NEA initiatives related to safety cases:

- International Experience in Safety Cases [INTESC] Initiative (NEA, 2009a),
- Long-Term Safety Criteria [LTSC] Initiative (NEA, 2007), and
- Timescales Initiative (NEA, 2009b).

Each of these initiatives included some coverage of indicators within their wider scopes of interest. The outcomes from these initiatives were evaluated to gain a comprehensive picture of the then known recent and planned uses of indicators in different countries and programmes. That evaluation also identified a number of key issues that were thought to require further consideration, and information gaps to be filled.

The second step involved distributing a new questionnaire that was intended specifically to address the issues and information gaps identified in the first step, and to canvas attitudes and experiences from applying indicators within the most recently completed safety cases. That Indicators Questionnaire (Appendix A2) included a number of questions grouped under the headings of (i) regulatory context and guidance, (ii) status of repository development programme, (iii) use of complementary indicators, and (iv) areas of uncertainty and future development. In addition to answering the questions, each organisation was asked to complete a table that detailed their specific use of indicators, and any corresponding reference values or criteria, in safety assessments.

The Indicators Questionnaire was sent to implementing organisations and regulatory agencies in Member States in February 2010, and twenty one separate responses were received that covered a range of experiences from developing assessment programmes just beginning to consider how to use indicators, to mature programmes that have already performed detailed site-specific assessments. The various responses were evaluated and the results compiled (Appendix A3). One output from the compilation was a fully populated table of indicators which identified over 100 separate indicators that had been used, or planned to be used, by the organisations who responded to the questionnaire (Table 2). Overall the responses were detailed and informative, and enabled a comprehensive picture of the use of indicators to be formed.

The third step involved sending a short follow-up question list to those organisations that responded to the Indicators Questionnaire. This question list was intended to delve deeper into a few key issues that were identified from the evaluation of the questionnaire responses (e.g. derivation of reference values), and to clarify with each organisation a few specific questions of detail and understanding.

The responses to the Indicators Questionnaire and to the follow-up question list provide the primary source material for this Status Report, together with relevant information from other NEA initiatives and comparable international work, in particular relevant IAEA Technical Reports and the EC's SPIN and PAMINA project reports.

1.5 Report structure

The following section provides an overview and discusses some general considerations on the use of indicators in the safety case, and introduces the concept of reference values and indicator criteria to compare with calculated indicators. Section 3 then presents the different types of indicators that have been proposed and used in previous studies, and also addresses the related issues of the classification and terminology for indicators. The regulatory position in different countries is then reviewed in Section 4, considering the role of indicators in statutory requirements and non-statutory guidance. Section 5 is the largest section of the report, and it addresses in detail the various different applications of indicators in safety cases, and related applications within a repository development programme. In this section, 'best case' examples of the use of indicators are presented. Section 6 then considers the various sources of reference values and indicator criteria, and provides a summary of the different reference values that have been used in previous studies. Lastly, Section 7 provides an overall summary and the conclusions from this work.

There is a set of appendices at the end of this report. These include a number of 'case studies' on the application of indicators in some of the more recent national programmes and published safety cases. In addition, the appendices also include the 'Indicators Questionnaire' and a compilation of the responses to it from the various national agencies that participated.

2. GENERAL CONSIDERATIONS ON THE USE OF INDICATORS IN THE SAFETY CASE

2.1 The history and development of indicators

It is difficult to pin-point the first published reference to complementary indicators but the concept of comparing repository releases to (or limiting them to) some fraction of the naturally occurring radiation field has been considered for several decades. For example, in the UK, a criterion of this type was expressed explicitly in the UK Principles Document with regard to setting requirements for radioactive waste disposal (DoE, 1984):

"*Future movement of radioactivity from a facility should not lead to a significant increase in the radioactivity naturally occurring in the general locality of the facility.*"

This general concept was developed further, particularly in Nordic countries through their collaboration in the field of radiation protection that led to the publication of a series of Nordic 'Flag Books'. The first of these was published in 1976 on the subject of radiation protection norms and was followed by others, dealing with more specific issues, in particular basic criteria for high level radioactive waste disposal (Nordic Radiation Protection and Nuclear Safety Authorities, 1993) that set the following basic requirement:

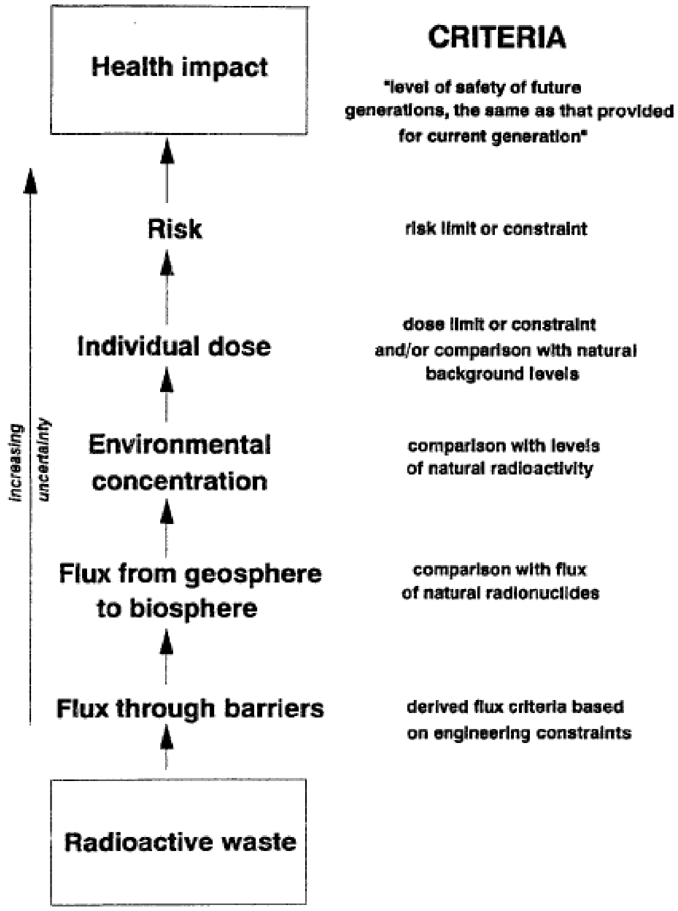
"Applied Principle 3; Long-Term Environmental Protection: The radionuclides released from the repository shall not lead to any significant changes in the radiation environment. This implies that the inflows of the disposed radionuclides into the biosphere, averaged over long time periods, shall be low in comparison with the respective inflows of natural alpha emitters."

Around the same time, the IAEA began to take an active interest in the development of complementary indicators as it became increasingly understood that dose and risk cannot be assessed with certainty, particularly in the far future. The first report of the IAEA's International Radioactive Waste Management Advisory Committee (INWAC) proposed that dose and risk should be *"supplemented with other types of safety indicator which rely less on assumptions about future conditions"* (IAEA, 1994). This report introduced the concept of 'radiological safety indicators' (meaning dose and risk) and 'other safety indicators' which included discussion on concentrations, fluxes through barriers and the biosphere, radiotoxicity and time. The report went on to present the various indicators in a hierarchy corresponding to increasing levels of uncertainty and also explained that the emphasis in a safety assessment should shift towards the use of 'other' indicators for longer assessment timeframes of the order of one million years, as shown in Figure 1.

The IAEA developed its thinking on indicators and introduced the distinction between safety and performance indicators in the sixth report of the IAEA's Working Group on Principles and Criteria for Radioactive Waste Disposal (IAEA, 2003). That report discussed practical issues associated with the application of concentrations and fluxes as indicators in safety assessment, such as how to identify the relevant elements and radionuclides to compare between repository releases and nature, and how to derive spatial and temporal averages. The report also discussed the difficulty in identifying appropriate 'yardsticks' to compare with the indicators, particularly safety indicators. The general lack of reliable information on the abundances of naturally occurring geochemical species to compare with safety and performance indicators was subsequently addressed by the IAEA in a Co-ordinated Research Project. That project compiled a database of national, regional and global averages and variations in measured elemental and radionuclide concentrations and fluxes, and assessed the ranges that could be independently be considered to be safe (IAEA, 2005).

Figure 1: Hierarchy of indicators suggested by the IAEA (1994).

In parallel with, and complementary to, the IAEA initiatives, the EC sponsored the international Testing of Safety and Performance Indicators (SPIN) Project that had the



objective of identifying and assessing potential complementary indicators that may be applied in a safety case. This project eventually identified 21 separate indicators that were considered to be useful, including 7 safety indicators that are intended to help assess the global performance of geological repositories in terms of their impact on human health, and 14 performance indicators concerned with how geological repositories and their individual components work to contain the waste (Becker *et al.*, 2003). The SPIN project also discussed the need for safety-relevant reference values to which safety indicators may be compared, and concluded that some values may already have been determined by regulatory authorities, for instance dose constraints, and others may be derived from nature, applying the premise that natural values in general can be considered to be safe.

The SPIN project was followed by the EC sponsored Performance Assessment Methodologies in Application to Guide the Development of the Safety Case (PAMINA) Project that included, in its wide scope, an assessment of safety and performance indicators (Becker *et al.*, 2009). As part of that project, safety and performance indicators were defined and tested for repository designs in three host rock types (clay, granite, and rock salt). The focus of the work was on 4 safety indicators (effective dose rate, radiotoxicity concentration in the biosphere water, radiotoxicity flux from the geosphere and power density in groundwater) plus a range of performance indicators based on inventories or concentrations, fluxes, safety functions and transport times. All were found to give useful results, although each indicator had specific advantages for illustrating the properties of a repository system. The project concluded that, when used in a complementary fashion, the proposed indicators are effective communication tools to present the results of a safety assessment and to explain the functioning of the repository system and the contribution of its safety functions and components.

The definitions of the terms safety and performance indicators developed within the PAMINA Project were the ones most referenced in the responses to the Indicators Questionnaire (Appendix A3), and are the definitions used in this report.

The growing awareness of, and interest in, the potential use of complementary indicators seen in the SPIN and PAMINA projects was driven, in part, by a move to develop safety cases with a wider scope than traditional safety assessments which have a narrow radiological protection focus. The impetus behind the development of safety cases was largely the work of the NEA and its Integration Group for the Safety Case (IGSC) which promoted a structured approach to the planning and implementation of safety cases, using a variety of evidences, analyses and arguments (NEA, 2004). The use of a safety case based on multiple lines of reasoning is now enshrined in international guidance with the publication of the IAEA's Specific Safety Requirements for the Disposal of Radioactive Waste (IAEA, 2011).

Complementary indicators are referred to in the IAEA Safety Requirements document as one of the lines of reasoning that may be applied in safety cases. The others mentioned include palaeohydrogeological and natural analogue studies that are both based on a similar philosophy of using relevant natural (and archaeological) systems to draw conclusions about the likely processes and rates controlling the long-term evolution of a repository system.

The recent focus on repository safety functions has been the impetus for a number of organisations to consider safety function indicators in their safety cases. At the time of writing, safety function indicators have been most used by SKB in their SR-Site safety case (SKB, 2011) but similar approaches are being considered in a number of other national programmes, such as in Belgium and France.

With growing recognition of the value complementary indicators can add to a safety case, both in terms of enhancing scientific rigour and for engaging with stakeholders, a number of national regulators have begun to make explicit mention of them in their regulatory documents. As discussed in Section 4, regulators often provide non-statutory guidance suggesting that complementary indicators should form part of a safety case but a few regulators have gone further and now mandate their use.

This emphasises that the initial concept of complementary safety indicators has matured over the last few decades and is now an internationally acknowledged method for assessing repository safety by providing additional robustness to radiological dose and risk calculations.

2.2 Safety case methodologies

The safety case, with respect to long-term post-closure safety for a geological repository, is an integration of arguments and evidence that describe, quantify and substantiate the safety of the facility, and the associated level of confidence. In a safety case, the results of safety assessment (i.e. the calculated numerical results for the safety indicators) are supplemented by a broader range of evidence that gives context to the conclusions or provides complementary safety arguments, either quantitative or qualitative. A safety case is the compilation of underlying evidence, models, designs and methods that give confidence in the quality of the scientific and institutional processes as well as the resulting information and analyses that support safety (NEA, 2011).

Most national regulations relating to repositories for radioactive waste give safety criteria in terms of dose or risk (or sometimes both), and these indicators are evaluated for a range of evolution scenarios for the disposal system using quantitative analyses. In recent years it has become evident that this comparison for an overall system safety assessment can be augmented with additional analyses and indicators in the safety case. It is now internationally accepted that the robustness of the safety case and the resulting confidence in the repository concept is strengthened by the use of multiple lines of evidence which includes complementary (also qualitative) safety arguments that can compensate for shortcomings in any single argument. One type of evidence and argument in support of a safety case is the use of complementary indicators (NEA, 2004).

Such complementary indicators can avoid, to some extent, the difficulties faced in evaluating and interpreting dose and risk that are expected to occur in the far future. In particular, individual human behaviour and near-surface processes, which are important factors in the calculation of dose and risk, are difficult or impossible to predict over long timescales. In contrast the possible evolutions of a well-chosen host rock and geological site can be bounded with reasonable confidence over much longer timescales of up to about one million years into the future (depending on the site). Hence, there is a trend in some recent safety cases towards evaluating indicators in addition to dose and risk, which show more clearly the repository's intrinsic performance without requiring any assumptions concerning the surface environment and the biosphere. The use of such indicators may support the statement that radionuclide release to the surface environment will be minor and of low consequence and, thereby, increase the robustness of the safety case.

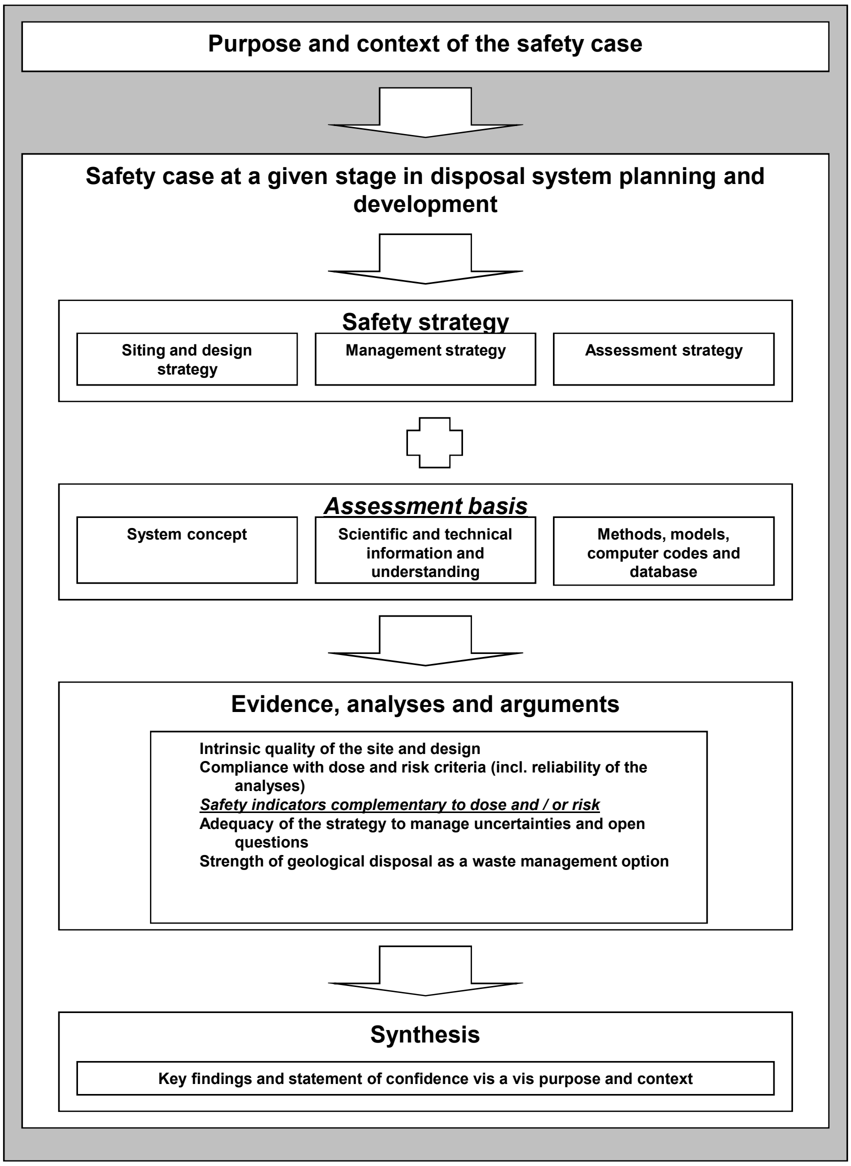
The NEA Safety Case Brochure (NEA, 2004) described the essential elements of a safety case as follows, and as shown in Figure 2:

- A clear *statement of purpose* provides context for the safety case.
- The *safety strategy* is the high-level approach adopted for achieving safe disposal, including an overall management strategy, a siting and design strategy and an assessment strategy. It incorporates good management and engineering practice, and provides sufficient flexibility to cope with new information and technical advances. Strategies favour robustness and minimise uncertainty by selecting a site with assessable features and by tailoring repository design to its geological setting.
- The *assessment strategy* ensures that events and processes relevant to safety are identified and guides how their consequences will be quantified. The assessment strategy involves the definition of conceptual models and mathematical approaches to be used to evaluate them.
- The *assessment basis* is the collection of information and analysis tools supporting the safety assessment. This includes an overall description of the disposal system that consists of the chosen repository design and its geological setting; the scientific and technical data and understanding relevant to the assessment of safety; and the assessment methods, models, computer codes and databases for analysing system performance. The quality and reliability of a safety assessment depends on the quality and reliability of the assessment basis.
- *Evidence, analyses and arguments for safety* must be compiled into a safety case. Results of analyses are typically compared against safety criteria, often in terms of radiological dose and risk, but there may also be other performance measures applied either for regulatory compliance or as indicators of performance that provide insights into system behaviour. The evaluation of these performance measures or indicators,

using mathematical analyses is typically accompanied by more qualitative arguments that provide a context or support for the performance calculation results.

- The *synthesis* of available evidence, arguments and analyses, supported by the quality and reliability of the assessment basis, supports a *statement of confidence* in the safety case, which is typically made by the implementer. This should explicitly state that sufficient confidence exists in the safety of the system to justify a positive decision to proceed to the next stage of planning or implementation of a disposal system.

Figure 2: An overview of the elements of a safety case. From NEA (2004).



Based on this presentation, the most important input of indicators concerns the element *evidence, analyses and arguments*, where safety indicators complementary to dose and risk are directly mentioned as one relevant component. This is of course the most frequent application of complementary indicators, either as additional statements of safety or as indicators illustrating the performance of the entire repository system or subsystems of it.

More recently, however, the use of complementary indicators has been widened and they have been increasingly applied to other elements of the safety case. The application of safety function indicators is directly connected to the increased use of safety functions in the safety case (Section 2.3). Their adoption for scenario identification and selection is one example of complementary indicators contributing to the *assessment strategy*, i.e. ensuring that events and processes relevant to safety are identified and contributing to the strategy for how their consequences will be quantified.

Other new applications like the growing use of complementary indicators in a design and engineering context (e.g. to evaluate the performance of design variants) contribute to some extent to the *siting and design strategy*. They might flow into the definition of criteria for design optimisation or site selection. There is, to date, only limited experience in applying complementary indicators to these issues but this is likely to be an area where further development is required as an increasing number of countries move from generic design to implementation.

In a way, the potential use of indicators for performance confirmation monitoring will support the *assessment basis*, particularly to the component scientific and technical information and understanding. Once waste has been emplaced, predicted performance can be compared with actual measured performance for certain indicators. These results might then be used to underpin or modify approaches and data used in process-level or even integrated models.

Finally, the use of indicators contributes to the overall safety case principle of transparency, i.e. to present results in ways that are both clear and understandable to the intended audience. Here, particularly the use of performance indicators is meaningful, e.g. illustrating how the repository system is expected to work and how different components (sub-systems) contribute to the overall safety of the repository.

2.3 Safety functions

During the development of the defence-in-depth concept for nuclear power plants (IAEA, 1996), the multi-barrier concept for a reactor was complemented with an approach to safety based on three fundamental safety functions: controlling the power, cooling the fuel and confining radioactive material. At around the same time, the possibility of applying the defence-in-depth concept to geological disposal was examined by SKB within the Swedish radioactive waste management programme. It was felt necessary to complement the multi-barrier concept for a repository with a set of safety functions that are provided by diverse mechanisms and components.

Early applications of the safety functions concept to safety evaluations of radioactive waste disposal can be found in the Swedish (SKB, 1999), Belgian (De Preter *et al*., 1999) and French (Andra, 2001) radioactive waste management programmes. Meanwhile, safety functions have now been introduced in most geological disposal programmes and their use is recommended in documents prepared by international agencies, such as the NEA Safety Case brochure (NEA, 2004), the NEA MeSA Initiative (NEA, 2011) and the IAEA Safety Standards on Disposal of Radioactive Waste (IAEA, 2011).

The IAEA Safety Glossary (IAEA, 2007) defines a safety function as "*a specific purpose that must be accomplished for safety*" but this definition is given in the context of reactor safety. In the context of radioactive waste disposal, however, SKB (2006) give the following definition "*the role through which a component contributes to safety*". Although different sets of safety functions have been developed in national radioactive waste programmes, three main high level safety functions can be distinguished: isolation, containment and retardation.

Isolation: "*The disposal facility shall be sited, designed and operated to provide features that are aimed at isolation of the radioactive waste from people and from the accessible biosphere*" (IAEA, 2011). For this safety function it is possible to distinguish two lower level functions:

- the first (sometimes called *stability*) is related to isolating the waste from future surface events and climate change, and so contribute to the stability of the repository near-field conditions and to the longevity of the natural barriers; this function forms a boundary condition that ensures that the other safety functions can fulfil their role over long periods of time;
- the second is related to reducing the probability that future human actions might result in an inadvertent intrusion into the sealed repository.

Containment: "*The engineered barriers, including the waste form and packaging, shall be designed, and the host environment shall be selected, so as to provide containment of the radionuclides associated with the waste. Containment shall be provided until radioactive decay has significantly reduced the hazard posed by the waste*" (IAEA, 2011). It should be noticed that IAEA applies the term containment in a wide sense "*to avoid or minimize the release of radionuclides*" so, from this point-of-view, various engineered and natural barriers, including the waste matrix, the buffer and the host formation, contribute to this safety function. Many radioactive waste management programmes, however, use the term containment in the stricter sense of physical containment provided by the waste container or the near-field rock, which prevents groundwater from coming into contact with the waste. In this case, a third safety function retardation is often considered.

Retardation: "*The disposal facility is also designed to retard the dispersion of radionuclides in the geosphere and biosphere…*" (IAEA, 2011). After failure of the containment function, the retardation safety function will play an important role to limit the migration of radionuclides through the geosphere and so delay their release to the surface environment. This function is essentially provided by diffusive transport through, and possible sorption on, the buffer and host rock formation.

The importance that is given to a specific safety function and the further differentiation into sub-functions strongly depends on the nature of the host rock formation and the repository design. In the case of disposal in hard rock or salt formations, containment may be the primary safety function considered whereas, in the case of disposal in argillaceous formations, the retardation safety function may have the same level of importance as the containment safety function.

Safety functions were initially introduced in safety cases for implementing the defence-in-depth principle. Therefore, the functioning of the repository system is often analysed by identifying the role of the main components and processes of the system. As safety functions often explain the functioning of the repository system in easily understandable terms, they soon appeared to be a very useful tool for communication to non-technical audiences. In some recent safety cases, safety functions play a central role and they are now used for various applications such as determination of the safety strategy and safety concept, development of the repository concept, structuring the safety case and identification of a representative set of altered evolution scenarios.

As safety functions are now increasingly playing a central role in safety cases, indicators have been introduced that illustrate how the main components of the repository system contribute to the fulfilment of those safety functions. For example, in Belgium, SCK•CEN has developed indicators that quantify the contribution of the effective safety functions to overall safety (Weetjens *et al.*, 2010). Similarly, in Sweden, SKB distinguish between the high-level safety functions assigned to the main components of the repository (e.g. canister, buffer, host rock) and lower level safety functions used to assess whether the main safety function can be maintained for very long periods of time. Corresponding safety function indicators are defined for each safety function (see Appendix A1.2).

2.4 Indicators and assessment timeframes

The original intent of using complementary indicators was to avoid some of the uncertainty inherent in calculations of dose and risk based on assumptions for human behaviour and climatic conditions in the very far future. As such there was anticipation that complementary indicators, particularly those that can be considered as safety indicators, would be most usefully applied to very long assessment time periods. This concept was reinforced by the IAEA (2003, 2005).

Considering the application of complementary indicators in different time periods, the SPIN Project (Becker *et al.*, 2003), concluded that the effective dose rate is especially suitable for the timeframe only up to a few ten thousands of years. Afterwards its application is restricted because of the uncertainties of biosphere parameters. The radiotoxicity concentration in biosphere water is a more robust indicator for longer timeframes than the dose rate and potentially applicable in a timeframe of up to 100,000 years. The radiotoxicity flux from the geosphere is not directly correlated to human habits and, therefore, it is more suitable for very long timeframes beyond 100,000 years.

The preferential application of complementary indicators to different time periods is also supported by the most recent NEA report considering timescales in safety assessment (NEA, 2009b) which noted that that the types of argument, and indicators of performance and safety used or emphasised, may vary between timeframes.

This timeframes approach is, however, only to a limited extent reflected in existing regulatory guidance documents which are mostly non-prescriptive, although some do provide suggestions of the type of calculations that could be made using complementary indicators. Nonetheless, a few regulations do explicitly address the issue. In Finland, for example, the regulations require dose constraints to be applied for the initial adequately predictable time period but, after the onset of glaciation and permafrost conditions, constraints on the activity release rates to the environment (a flux based complementary indicator) are applied in preference to dose (STUK, 2009). In other countries that adopt a prescriptive approach to regulation, the timeframes over which specific indicators need to be calculated are pre-defined. In the USA, for example, regulations applicable to the Yucca Mountain Project required that doses are calculated out to 1 million years (NRC, 2004) but environmental groundwater standards apply only to the first 10 000 years (EPA, 2001).

Another aspect relevant to time is that complementary indicators can be used to justify the cut-off time for the assessment by explicit comparison of the changing hazard posed by the waste (due to radioactive decay) with the hazard due to naturally occurring materials and, in particular, uranium orebodies. This approach was used in the Swiss Opalinus Clay safety assessment (Nagra, 2002).

Despite the advantages of complementary indicators in assessments of far-future impacts, the responses to the Indicators Questionnaire show, however, that most organisations calculate all indicators (both primary and complementary indicators) for all assessment time periods, and do not apply any preferred bias or weighting. There may be a number of reasons for this, but primarily the growing interest in using complementary indicators to evaluate sub-system performance and the evolving status of barriers over time (expressed as performance indicators or safety function indicators) means that they add value to the assessment at all time periods and not just in the far future.

2.5 Summary of the purposes of using indicators in safety cases

As the concept of complementary indicators has matured over the last few years, a number of different but related purposes for using indicators in safety cases have been identified. These are:

- supporting safety case structure and multiple lines of reasoning;
- increasing the transparency of safety case arguments;
- assessment of repository safety and presenting impacts in the content of the natural environment;
- assessment of sub-system performance;
- assessment of safety functions;
- scenario identification;
- addressing uncertainty and the assessment of repository safety in different timeframes; and
- helping with communication, especially to non-technical audiences.

In addition to the use of indicators in safety cases, there are other uses in the wider scope of repository development programmes that have only recently being identified:

- supporting site selection;
- aiding selection of the repository design options and engineering optimisation; and
- repository monitoring and performance confirmation.

Each of these uses is summarised briefly below to provide an overview of the multiple potential benefits from using indicators in a repository development and safety assessment programme, and further details and specific examples of their use are provided in Section 5.

Supporting safety case structure and multiple lines of reasoning

Modern safety cases are based on the use of ‘multiple lines of reasoning’, rather than solely on quantitative radiological safety assessment. The idea is that by using parallel and independent sets of arguments, the relative advantages of one can offset the disadvantages of another. Complementary indicators are one of the most useful multiple lines of reasoning in a safety case because they can provide an independent measure of repository safety over the very long-term, that can offset the uncertainties associated with conventional dose and risk calculations that are due to the need to make assumptions for future human behaviours. Furthermore, complementary indicators can be presented in terms of engineering and geological language and concepts, rather than radiological ones, making the safety case more understandable to a wider range of readers.

Increasing the transparency of safety case arguments

Increasing transparency in the safety case is linked to the use of safety and performance indicators because they allow for a better and more structured approach to illustrating the overall behaviour of the entire repository system. If a series of complementary indicators is developed that relates to each of the key components of the repository, then ultimately a hierarchy of arguments can be developed to support an overarching statement that a repository is considered to be safe. The combination of primary and complementary indicators, and other multiple lines of reasoning, is intended to build confidence that the processes and rates controlling the long-term evolution of the repository are understood, and their consequences evaluated, so that the contributing parameters to the overarching dose and risk impacts are known and can be independently demonstrated.

Assessment of repository safety and presenting impacts in the content of the natural environment

One of the primary uses of complementary indicators, and the first use identified, is that the calculated releases from the repository can be compared to the abundance of naturally occurring radionuclides (and chemotoxic elements) in the vicinity of the repository to provide an alternative measure of safety that is independent of assumptions about exposure pathways to humans. In simple terms, if the natural radiation environment is considered to be safe, and the repository releases contribute only a very small increase to the total radiation in the environment, then the repository releases may also be judged to be safe. There are, of course, complexities associated with making such comparisons, particularly in relation to the radiological hazard associated with transuranic nuclides that do not occur in nature, but provided that comparisons are expressed transparently and are not 'over interpreted' they can be very useful for explaining the impacts to readers who do not have a background in radiological assessments.

Assessment of sub-system performance

A primary drawback of conventional dose and risk calculations is that they provide no information on what part(s) of the repository system most contribute to its overall isolation and containment capacity. As such, dose and risk calculations cannot be used to assess engineering robustness and the performance of individual barriers in a multiple barrier design. Performance indicators, on the other hand, can be defined specifically to assess how individual components (and sub-systems) behave and contribute to the overall safety performance of a repository design. For example, calculated radionuclide fluxes through barriers over time can be used to determine whether long-term containment of the waste is provided predominantly by the physical engineered barriers or hydrogeochemical conditions in the rock. Similar calculations of concentration can be used to develop a detailed picture for how the inventory becomes distributed over time in the repository system due to transport and retardation processes.

Assessment of safety functions

A safety function may be defined as the specific role or purpose of an individual repository component (or sub-system) that contributes to safety. In some safety cases, particular emphasis is placed on the evaluation of these safety functions, and their evolution over time, to determine whether the repository will perform as anticipated. Specific safety function indicators may be derived to allow the status of the various safety functions to be assessed. Often a single safety function may be correlated directly or indirectly with multiple safety function indicators to provide an assessment of whether the safety function is maintained. So, for example, if the safety function of a cementitious buffer is to provide for low radionuclide solubility under alkaline conditions, appropriate safety function indicators may relate to parameters associated with the rock-water interactions that control groundwater pH. To date, only a few safety cases have applied safety function indicators in a rigorous manner but there appears to be considerable benefit to using them to provide a robust evaluation of repository evolution.

Scenario identification

Most of the recently published safety cases are based on calculation of the impacts that may result in a range of different expected ('normal') or altered evolution scenarios for the repository. Usually, scenarios are identified using expert judgement and an audit of various features, events and processes (FEPs) that are relevant to the repository design and site conditions. An alternative way to identify scenarios and calculation cases has, however, been developed in conjunction with the application of safety function indicators. In this approach, a number of safety function indicators for the repository system are identified (e.g. buffer swelling pressure) and criteria defined, where possible.

The safety function indicators are then quantified in the assessment for the base scenario and, if any criteria are not fulfilled, then a further set of calculations are performed to analyse the consequences of the scenario that results from the situation. A chain of assessment calculations relating to different evolution scenarios may, thus, be initiated by consideration of safety function indicators.

Addressing uncertainty and the assessment of repository safety in different timeframes

Radiological dose and risk calculations are robust over the period during which the natural system and human behaviour patterns can be expected to remain largely unchanged. As the assessment time periods increase, however, the dose and risk calculations become progressively more uncertain, particularly once climate change processes will cause significant perturbations to the surface environment. For this reason, different indicators may be used in different assessment timeframes. In the early time periods, when there is high confidence in the engineered barriers, a set of performance or safety function indicators may be used to assess the containment function provided by the wasteform, canister and other man-made barrier systems. As assessment timescales increase, greater emphasis may be placed on performance indicators that evaluate the retardation function provided by the geosphere. At very long assessment timeframes, safety indicators are likely to provide the most suitable measure of total system safety because they avoid much of the uncertainty inherent in calculations of dose and risk based on assumptions for human behaviour and climatic conditions. As a consequence, complementary indicators become the most reliable and certain measure of repository behaviour for assessment time periods beyond several thousands of years.

Helping with communication, especially to non-technical audiences

Complementary indicators have a significant benefit in that many of them can be used to explain the potential impacts of a repository using language and concepts that are understandable to a wide range of audiences. For example, fluxes can be explained in terms of everyday units of mass or volume (e.g. kilograms and litres) which are broadly understood by most people, whereas the units and language of radiological protection are largely unintelligible to anyone who is not a trained expert. Furthermore, complementary indicators can readily be expressed in relation to the local environment around a site (e.g. radionuclide concentrations in a river), in a way that is not easily done using dose and risk. Combined, these benefits mean that complementary indicators provide significant opportunity for engaging and communicating with non-technical audiences, which is particularly important for local communities around potential host sites.

Supporting site selection

A repository site will be chosen on the balance of many technical and non-technical attributes but considerable weighting must be given to the ability of the geological conditions to ensure long-term isolation and containment of the waste. Although geological conditions have always been taken into account during site selection, the explicit use of complementary indicators to assess and compare alternative sites and geological environments has only recently been considered in a detailed manner. By using relevant safety and performance indicators, both the transport and retardation capacity of the rock mass and its ability to provide stable conditions to protect the engineered barriers can be quantified. Importantly, by applying indicators in a structured manner, the process becomes more transparent and auditable, so that is possible to explain how the various natural attributes of alternative sites are balanced against each other to choose a preferred site.

Aiding selection of the repository design options and engineering optimisation

In a similar manner to comparing potential repository sites, performance indicators can be used to compare the long-term integrity of alternative wasteforms and engineered barrier design options (e.g. steel or copper canisters) in a structured manner. Once a preferred design has been chosen and the site is characterised, performance indicators may also be used to optimise the design against known subsurface conditions and to ensure the overall cost and effort for constructing the repository are not excessive. The comparison of alternative design options is routinely done as part of a repository development programme, and may continue iteratively throughout a programme. To date, however, indicators have rarely been explicitly used in such comparisons. As more repository development programmes move towards practical implementation, however, there is likely to be increasing emphasis on design optimisation and, therefore, this is likely to be an application of performance indicators that will grow in importance.

Repository monitoring and performance confirmation

Post-closure repository monitoring is of interest to many stakeholders, particularly for designs where waste retrieval may be considered. Performance indicators can be used to predict the behaviour of certain barrier functions and, under certain circumstances, the actual post-emplacement behaviour may subsequently be monitored and compared with the predictions. Such performance confirmation monitoring concepts have been investigated for some repository designs but the link to complementary indicators has yet to be fully investigated. There is an obvious potential link with performance indicators that could be used explicitly to help define the expected performance envelopes and likely threshold levels against which monitoring results may be compared. Significantly, this application of indicators is characterised by the use of measured (observed) quantities rather than calculated ones, which is the case in all other applications of indicators. This application has not, so far, been tested but there appears to be some potential to be explored. There are, however, practical limits to how far this approach may be developed for certain repository designs due to the inevitable difficulties associated with monitoring closed facilities and the slow evolution of the system.

2.6 Yardsticks and comparisons

When applying measurable or calculable quantities such as indicators for an evaluation of safety relevant aspects of repository systems, it is often useful to compare these indicators to appropriate 'yardsticks' to help judge whether those safety relevant aspects have been met (e.g. to judge the effectiveness of barrier performance or the acceptability of calculated safety levels). Such 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 (IAEA, 2003).

Different types of yardsticks may be used, depending on the objective of an assessment. When considering performance indicators, an appropriate yardstick can be used to provide an assessment scale. Such yardsticks can be derived from technical data, expert judgement or laboratory experiments. They do not necessarily separate 'good' from 'bad' values, but allow the modeller to assess the performance of the component by ranging the calculated values.

In the concept introduced by SKB, individual components of the system are supposed to fulfil specific safety functions, which are judged using safety function indicators (SKB, 2006). These values are compared with individual criteria that define the expected level of performance for each component. Such criteria are stricter than simple yardsticks, but failure to meet the required level of performance for an individual barrier does not necessarily mean that the system as a whole is unsafe because of the redundancy inherent in the multi-barrier repository concept.

A third type of indicator yardsticks is needed for safety indicators. A safety indicator is meant to provide a statement about the safety of the total system with respect to some aspect. Such a statement can only be made if a unique criterion is given, which is defined by a reference value for the indicator. Reference values for safety indicators should define a level that can be considered safe regarding the aspect under consideration, and this should be well substantiated. The safety statement is then derived by comparing the calculated indicator value with the reference value.

3. TYPES OF INDICATOR AND TERMINOLOGY

3.1 The possible ways to categorise indicators

For the sake of clarity, in this report an important distinction is made between primary and complementary indicators. A *primary indicator* (typically annual dose or risk) is one that is compared to a legally or regulatory defined radiological constraint, whilst all other indicators that may be used in a safety case are referred to as *complementary indicators*.

As the different applications of complementary indicators to safety cases have been progressively developed over the last several years, a number of systematic classification schemes and formal definitions have been proposed for them, and these are discussed below. None of these have been universally adopted, however, in part because they are not consistent with the regulatory regimes and assessment methodologies applied in all national disposal programmes.

Whilst many organisations do apply a clearly defined classification scheme, several others do not and deliberately use more general terminology when discussing indicators. This is often the case with regulators who do wish to prescribe or suggest how developers should apply complementary indicators within their own safety cases, as discussed in Section 4. Furthermore, many developers who are still at the generic or early planning stages of their repository programmes have not yet finalised their approach to using indicators.

3.1.1 Safety and performance indicators

In an early report on the potential uses of indicators by the IAEA (1994) a simple distinction was made between 'radiological safety indicators' (i.e. dose and risk) and 'complementary indicators' which encompassed all other forms of indicators, including comparisons with natural fluxes and concentrations. In a later report, the IAEA (2003) further developed its thinking on the complementary indicators and introduced a distinction between 'safety indicators' and 'performance indicators' as follows:

> *"A <u>performance indicator</u> 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 <u>safety indicator</u>, which may be regarded as a special type of performance indicator, is used to assess calculated performance in terms of overall safety."*

The distinction between safety and performance indicators has since been commonly (but not universally) adopted by several other organisations. In particular, it was adopted in the EC's SPIN project (Becker *et al*., 2003) which made efforts to provide further clarification on the distinction and application of these two types of indicators:

> *"In this context, safety and performance indicators are magnitudes following from numerical performance assessment calculations.*
>
> *A <u>safety indicator</u> of the considered type must:*
>
> - *provide a statement on the safety of the whole system;*

- *provide an integrated measure describing the effects of the whole nuclide spectrum;*
- *be a calculable, time-dependent parameter;*
- *allow comparison with safety-related reference values.*

A performance indicator of the considered type must:

- *provide a statement on the performance of the whole system, a subsystem or a single barrier;*
- *provide a nuclide-specific or integral measure;*
- *be a calculable, time-dependent or absolute parameter;*
- *allow comparison between different options or with technical criteria."*

An important aspect of these definitions is that both safety and performance indicators must be amenable to calculation as part of the safety assessment. In other words, they are integral to the safety assessment and are not separate from it.

In later work, the EC's PAMINA project (Becker *et al.*, 2009) built on the outcome of the SPIN project and also accepted the distinction between safety and performance indicators, but recommended slightly different definitions of the terms:

"A safety indicator is a quantity, calculable by means of suitable models, that provides a measure for the total system performance with respect to a specific safety aspect, in comparison with a reference value quantifying a global or local level that can be proven, or is at least commonly considered, to be safe.

A performance indicator is a quantity, calculable by means of appropriate models, that provides a measure for the performance of a system component, several components or the whole system."

As with the SPIN definition, the PAMINA definition requires that both safety and performance indicators must be amenable to calculation as part of the safety assessment. What is added to the PAMINA definition is the explicit requirement that, for a safety indicator, a relevant reference value must be identified to allow safety to be evaluated by means of comparison. This requirement is challenging and, as discussed in Section 6, it may be difficult to define the reference values that can be applied.

3.1.2 Safety function indicators

A few developers who are more advanced in their programmes and are performing site or concept-specific safety cases (notably SKB) have taken the concept of safety and performance indicators one stage further and have introduced an additional category of indicator, the 'safety function indicator' which is intended for evaluating the integrity of specific repository components and systems against predefined safety functions. This is defined by SKB (2006) as follows:

"A safety function is a role through which a repository component contributes to safety. A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled. A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained."

According to this definition, a safety function indicator has quite a lot in common with a performance indicator in so far as they both relate to the evaluation of system components and sub-systems. The key difference between them lies in the quantitative requirement for the safety function indicator to be compared with a specific criterion (reference value) whereas performance indicators need not always have a matching reference value for comparison. Given this, safety function indicators could be considered as a special case and application of performance indicators.

3.1.3 *Alternative ways to categorise indicators*

Whilst defining complementary indicators as either safety or performance indicators is the most widely adopted categorisation scheme, it is not the only possible one. Looking at the application of indicators in safety cases at a generic level, it is clear that they can roughly be divided into three groups on the basis of their nature and the information they provide:

- *concentration and content related indicators*, that provide information on the radionuclide inventory and its distribution within compartments of the repository and the environment, and the evolution of the inventory distribution over time (e.g. total radioactivity content of the wasteform or radiotoxicity concentration in groundwater);
- *flux related indicators*, that provide information on the flux of radionuclides between compartments of the repository and their release to the accessible environment (e.g. radioactivity flux from the engineered barriers to the geosphere or total integrated radiotoxicity flux from the geosphere to the biosphere over time); and
- *status of barriers related indicators*, that provide information on the functioning and containment capability of the barriers in the repository system (e.g. container life time or buffer swelling pressure).

These three groups are not fully independent. In particular, the status of a barrier could have a significant impact on the flux of radionuclides across it and, consequently, the content of radionuclides in the compartments on either side.

Categorising indicators in this way means that their definitions must be strongly dependent on the geometry of the repository system, for example the compartments must be clearly distinguished and described to allow the concentrations in them, and the fluxes between them, to be calculated. At a generic level, it is possible to relate these three groups of indicators to the main compartments in a typical repository concept, as illustrated in Table 1.

Table 1: An alternative approach to classifying indicators.

	Compartment			
Indicator Type	Wasteform	Engineered barriers	Geosphere	Biosphere
Concentration and content indicators	✓	✓	✓	✓
Flux indicators				
Status of barrier indicators	✓	✓	✓	

3.2 Previous uses and names for different indicators

As with the proposed categorisation schemes discussed above, there is no universally accepted terminology for individual indicators. Over 100 individual complementary indicators were reported in the responses to the Indicators Questionnaire, and these are all listed in Table 2. The organisations were asked to state whether they considered each indicator to be a safety, performance or safety function indicator, and the type is also shown in Table 2 (when a category was provided).

This table provides an illustration of how widely complementary indicators have been considered in different national disposal programmes. All organisations who responded to the Indicators Questionnaire reported that they have used, or planned to use, multiple complementary indicators in their safety cases. The level of detail to which the reported indicators are specified and described varies between organisations and, to a certain extent, this reflects the status of the different national programmes.

Table 2: The complete list of complementary indicators reported in responses to the NEA Indicators Questionnaire, and their type as provided by the responding organisations. SI = safety indicator, PI = performance indicator, SFI = safety function indicator, NC = not categorised.

Indicator	Description	Type
SCK•CEN (Belgium)		
Concentration in groundwater	Aquifer above host clay formation	SI
Flux out of host formation	Aquifer above host clay formation	SI
Containment factor	Ratio of released radiotoxicity (up to 1 Ma) / initial radiotoxicity at time of disposal	PI (SI)
Transport time through clay barrier	-	PI
Evolution of radiotoxicity inventory in compartments	-	PI
Flux from compartments	-	PI
Time-integrated flux from compartments	-	PI
Time-integrated flux related to safety functions	-	PI
FANC (Belgium)		
Extent of the potentially contaminated zone	In the biosphere and the part of the geosphere located outside the disposal system	NC
Activity and radiotoxicity concentration in the liquid and solid phases	In the biosphere and the part of the geosphere located outside the disposal system	NC
Flux of activity/radiotoxicity released out of the disposal system	At the boundaries of the disposal system	NC
Total activity/radiotoxicity released out of the disposal system	At the boundaries of the disposal system	NC
NWMO (Canada)		
Radiotoxicity concentration in surface waters	Current reference lake above repository	NC
Radiotoxicity flux to surface	100 km^2 watershed-scale	NC
Total waste radioactivity	Repository (neglects losses other than decay)	NC
Nuclide flow rate across various boundaries	Repository barrier / site boundary	NC
Dose rate	Repository / site	NC
Age of groundwater	Site	NC
RAWRA (Czech Republic)		
Source term	Water activity on the interface repository/host structure	SI
Groundwater activity	Activity of groundwater on the interface host structure/biosphere	SI
Container lifetime / future version	Probable durability	PI
NRI (Czech Republic)		
Concentration of radionuclides in water	PA	SI
Posiva (Finland)		
Complementary safety indicator I	-	-
Complementary safety indicator II	-	-
Andra (France)		
Advection / diffusion	Host rock, waste disposal tunnels, galleries, shaft	PI
Radionuclide mass transport rock v. shafts	Host rock, waste disposal tunnels, shaft	PI
Diffusion process in rock and seals	Host rock, waste disposal tunnels, galleries, shaft and access ramp	PI
Radionuclide molar flux (maximum)	Host rock, waste disposal tunnels, galleries, shaft and access ramp	PI
Radionuclide molar flow (mass over assessment period)	-	PI
Radionuclide molar flow (time of maximum flow)	-	PI
Distribution of activity concentration	-	PI
BGR (Germany)		

Indicator	Description	Type
State of stress (dilatancy criterion)	Containment providing rock zone*	SFI
State of stress (fluid pressure criterion)	Containment providing rock zone*	SFI
GRS-K (Germany)		
Alternative indicator (no specific term)	Outer border of containment providing rock zone*	SI
Stress (implicitly required)	Within containment providing rock zone*	PI
Fluid pressure (implicitly required)	Within containment providing rock zone*	PI
Temperature (implicitly required)	Within containment providing rock zone*	PI
GRS-B (Germany)		
Radiotoxicity concentration in biosphere water	Near surface groundwater	SI
Power density in groundwater	Near surface groundwater	SI
Radiotoxicity flux from the geosphere	Interface host rock/overburden	SI
Radiotoxicity in compartments	Waste segment, repository, overlying rock, total	PI
Radiotoxicity flux from compartment	Fluxes out of compartments above	PI
Integrated radiotoxicity flux from compartments	Fluxes out of compartments above	PI
Radiotoxicity flux from geosphere	Near-surface groundwater	SI
Radiotoxicity inventory in compartments	System compartments	PI
Relative integrated radiotoxicity flux from compartments	System compartments	PI
Index of Radiological Insignificance (RGI)	Barrier system within and including the containment providing rock zone*	SI
VerSi I1	Barrier system within and including the containment providing rock zone*	PI
VerSi I2	Barrier system within and including the containment providing rock zone*	PI
VerSi I3	Containment providing rock zone*	PI
JAEA (Japan)		
Radionuclide concentrations in groundwater	Generic site in Japan	SI/PI
Equivalent fluxes of ^{238}U	Generic site in Japan	PI
NRG (The Netherlands)		
Effective dose rate	Biosphere	SI
Radiotoxicity concentration in biosphere water	Biosphere water (rivers)	SI
Power density in groundwater	Groundwater	SI
Radiotoxicity flux from geosphere	Flux from geosphere to biosphere	SI
Relative activity concentration in biosphere water	Biosphere water	SI
Activity in compartments	Waste container, concrete buffer, gallery, clay, biosphere	PI
Activity flux from compartments	Flux from: waste container, concrete buffer, gallery, clay	PI
Time integrated activity flux from compartments	Flux from: waste container, concrete buffer, gallery, clay	PI
Radiotoxicity in compartments	Waste container, concrete buffer, gallery, clay, biosphere	PI
Radiotoxicity flux from compartments	Flux from: waste container, disposal cell, host formation	PI
Time integrated radiotoxicity flux from compartments	Flux from: waste container, disposal cell, host formation	PI
Activity concentration in compartment water	Waste container, disposal cell, gallery, biosphere	PI
Radiotoxicity concentration in compartment water	Waste container, disposal cell, gallery, biosphere	PI
Activity/radiotoxicity concentration in biosphere water divided by A/R concentration in waste package water	Biosphere / waste package	PI
Transport time through compartments	Geosphere	PI

Indicator	Description	Type
Time to plug closure	Borehole plug	PI
ENRESA (Spain)		
Radionuclide concentration in the biosphere water	In the water course used by the receptor (well or river)	SI
Radiotoxicity flux from the geosphere	At the interface between the geosphere and biosphere	SI
Power density in biosphere water	In the water course used by the receptor (well or river)	SI
Fraction of UO_2 matrix altered v. time	UO_2 becomes oxidised/altered due to the alpha radiolysis in the water in contact with it	PI
Canister failure distribution	Carbon steel canisters fail due to generalised corrosion	PI
Water travel time in the geosphere (granite)	The water travel time is calculated from the repository to the discharge point to the biosphere	PI
Solute transport time through the near-field	A measure of the time necessary for a given solute to move from the inner surface of the bentonite barrier to the bentonite-granite interface	PI
Solute transport time through the geosphere	A measure of the time necessary for a given solute to cross the geosphere from the outer surface of the near-field to the biosphere	PI
Inventory of radionuclides in each compartment	The inventories present in each compartment are calculated	PI
Radionuclide fluxes between compartments	Fluxes are calculated at the interfaces between compartments	PI
Time-integrated radionuclide flux from compartments	Time-integrated fluxes are calculated at the interfaces between compartments	PI
Time-integrated molar flux from compartments	Time-integrated fluxes are calculated at the interfaces between compartments	PI
Radionuclide inventory outside compartments	The system is divided into a set of consecutive compartments, from the waste to the biosphere. This indicator provides the inventory that has moved beyond a given compartment.	PI
SKB (Sweden)		
Minimum copper thickness	Canister	SFI
Ionic strength of groundwater	Geosphere, near-field	SFI
A range in addition to the two above (see SR-Can report)	Either canister, buffer, deposition tunnel, geosphere	SFI
Finnish activity constraint	Geosphere/biosphere interface	NC
Natural content	Biosphere	NC
Natural activity fluxes	Geosphere/biosphere interface	NC
Natural toxicity fluxes	Geosphere/biosphere interface	NC
Nagra (Switzerland)		
RTI of waste on ingestion	Throughout the system (once the waste starts to disperse)	SI/PI
RTI flux to biosphere	Geosphere/biosphere interface	SI/PI
RTI concentration at top of host rock	Top of host rock	SI/PI
RTI distribution	Within each of the main system compartments	SI/PI
Diffusive transport time through host rock: half life	Outer boundary of host rock	SI/PI
Steady state transport distance	Across buffer and host rock	SI/PI
RWMD (UK)		
Concentration of radiotoxic or chemically toxic elements in the biosphere over time	Biosphere	SI
Radiotoxicity flux from the geosphere to the biosphere over time	Geosphere	SI
Radiotoxicity inventory over time in components of the geological disposal system	Not defined at the present time and could be all components	PI

Indicator	Description	Type
Radiotoxicity flux over time from components of the geological disposal system	Geosphere / Near-field	PI
Cumulative radiotoxicity flux up to given times from components of the geological disposal system	Not defined at the present time and could be all components	PI
Containment factor defined as the activity released from the GDF divided by activity disposed of, over time	Not defined at the present time	PI
Transport time through components of the geological disposal facility	Not defined at the present time	PI
*DOE/EPA/NRC (USA) ** *		
Flux across defined accessible environment boundary	≤ 5 km from repository (accessible environment)	SI
Radionuclide concentration in groundwater	≤ 5 km from repository (accessible environment)	SI
Radionuclide concentration in groundwater	≤ 18 km from repository (accessible environment)	SI
Engineered barrier containment time requirement	-	PI
Post-containment engineered barrier release rate limit	-	PI

*Note: the German regulations define this zone as the 'isolating rock zone' but to be consistent with the content of this report the term 'containment providing rock zone' is used instead to illustrate that it refers to the safety function of 'containment'.

**Note: the DOE, EPA and NRC collectively provided a single response to the Indicators Questionnaire.

It is evident from the many complementary indicators reported in the Indicators Questionnaire that many of them are broadly similar to each other, although the exact names and descriptions used vary between the organisations. For example, the following reported indicators can all be considered as variants of the same generic indicator related to *concentration in the geosphere*:

- Concentration in groundwater
- Activity and radiotoxicity concentration in the liquid phases
- Concentration of radionuclides in water
- Radionuclide concentration in groundwater
- Activity concentration in compartment water

A couple of observations are evident from this list that reflect, to some extent, the differences in maturity of the various national disposal and assessment programmes, with some working with generic descriptions of indicators and others at a more defined level.

1. There are different degrees of specificity when defining the compartment volume and spatial scale in which concentration may be measured (liquid phases, groundwater, compartment water etc). The same is true for the other reported indicators related to the engineered barriers and biosphere components of the repository system.
2. Concentration may refer to different physicochemical parameters and these may be variably defined (radionuclides, radiotoxicity, radioactivity). In general terms, there is a separation between organisations that use the parameter radio<u>activity</u> and those that use radio<u>toxicity</u>. In some cases the distinction is clearly intended whereas, in other cases, the terminology may have been used loosely.

The SPIN Project attempted to rationalise and define a set of specific indicators that may be most usefully applied in a safety case but this list has been adopted mostly by only those organisations that participated in that project. A comparison of the individual indicators reported in the responses to the Indicators Questionnaire showed that there are, in fact, only around 15 that appear to be generic and conceptually different to each other, and these can all be related to the alternative categorisation scheme discussed earlier. Most of these generic forms of indicator can be mapped to the specific indicators recommended in the SPIN project, as shown in Table 3.

Table 3: Comparison of the generic indicators identified from the Indicators Questionnaire and the indicators recommended in the SPIN Project.

Generic indicators derived from the Indicators Questionnaire	SPIN Project indicators
'Content and concentration' related indicators	
Radioactivity/toxicity concentration in the wasteform	Activity in compartments Activity concentration in compartment water Activity outside compartment Radiotoxicity in compartments Radiotoxicity concentration in compartment water Radiotoxicity outside compartments
Radioactivity/toxicity concentration in the engineered barrier system components	Activity in compartments Activity concentration in compartment water Activity outside compartment Radiotoxicity in compartments Radiotoxicity concentration in compartment water Radiotoxicity outside compartments
Radioactivity/toxicity concentration in the geosphere (particularly in groundwater)	Activity in compartments Activity concentration in compartment water Activity outside compartment Radiotoxicity in compartments Radiotoxicity concentration in compartment water Radiotoxicity outside compartments
Radioactivity/toxicity concentration in the biosphere (particularly in surface waters)	Relative activity concentration in biosphere water Radiotoxicity concentration in biosphere water Radiotoxicity outside geosphere Concentration in biosphere water/waste package water
Power density in groundwater	No direct equivalent
'Flux' related indicators	
Radioactivity/toxicity flux from the engineered barrier system components to the geosphere	Activity flux from compartments Radiotoxicity flux from compartments
Radioactivity/toxicity flux from the geosphere to the biosphere	Relative activity flux from geosphere Radiotoxicity flux from geosphere
Integrated radioactivity/toxicity flux from the geosphere to the biosphere over time	Time-integrated activity flux from compartments Time-integrated flux from geosphere/initial inventory
Radionuclide molar flow (mass over the assessment period)	No direct equivalent
'Status of barriers' related indicators	
Groundwater age	No direct equivalent
Container lifetime	No direct equivalent
Transport times through the engineered barrier system components and the geosphere	Transport time through compartments
State of stress in the containment providing rock zone	No direct equivalent
No direct equivalent	Portion of not totally isolated waste
Minimum copper thickness (canister)	No direct equivalent
Strength and rupture limit (canister)	No direct equivalent
Hydraulic conductivity (buffer and backfill)	No direct equivalent
Swelling pressure (buffer and backfill)	No direct equivalent
Ionic strength (geosphere groundwater)	No direct equivalent
pH and Eh (geosphere groundwater)	No direct equivalent

3.3 Terminology used in this report

For the remainder of this report, when referring to safety and performance indicators, we have adopted the definitions derived in the PAMINA Project (Becker *et al*., 2009). Similarly, when referring to safety function indicators, we use the definition provided by SKB (2006). This is because these definitions are based on thorough analysis, and are already widely used by many in the assessment community.

It is not, however, the intention of this report to recommend that any particular classification scheme or set of definitions should be universally applied in all safety cases. This would not be appropriate because, as explained in the next section, there are considerable differences in the regulatory regimes that apply in different countries.

It is most important that indicators are chosen and used in a manner that is consistent with the applicable regulatory regime and the assessment context, and that all indicators are clearly defined and described in the safety case documents.

4. REGULATORY REQUIREMENTS AND GUIDANCE

4.1 Prescriptive and non-prescriptive regulatory regimes

Any safety indicator compared to legally or regulatory defined radiological constraints (e.g. an annual dose constraint of 0.3 mSv/a) is called a *primary indicator*, whilst all other indicators that may be used in a safety case may be referred to as *complementary indicators*.

All national regulations require dose or risk (or sometimes both) to be calculated as the primary safety indicator in safety cases. It is evident, however, that the regulatory basis for the use of complementary indicators varies from country to country. A common theme is that all regulatory systems recognise the potential value of complementary indicators but they take considerably different stances when it comes to setting requirements for their use. In the majority of countries, regulators take a 'non-prescriptive' approach, and leave it to the safety assessors to decide how to apply complementary indicators in their safety assessments and safety cases. In a few countries, the regulations are 'partially prescriptive' in so far as they define certain minimum requirements for the use of complementary indicators (e.g. specify certain calculations or comparisons that must be made). Only in the case of the USA, however, are the regulations 'fully prescriptive' and set out in precise detail the nature of all the assessment calculations that must be performed. Table 4 provides examples of some countries that take each of these regulatory approaches.

Table 4: Examples of non-prescriptive, partially prescriptive and fully prescriptive regulations with regards to the use of complementary indicators.

Non prescriptive	Partially prescriptive	Fully prescriptive
Belgium Canada Japan Switzerland UK	France Finland Germany Sweden	USA

4.1.1 *Non-prescriptive regulation*

Non-prescriptive regulation that does not mandate the use of complementary indicators (other than dose and risk), and does not specify particular indicators to use or corresponding reference values, is the most widely adopted regulatory regime. For regulators that take this stance, the reason appears to be that they take the view that it is the repository developer's responsibility to decide how to structure a safety assessment and ultimately prove that the legally defined dose or risk constraint can be met. It is common, however, for formal regulations to be accompanied by non-statutory guidance documents that set-out advice to repository developers on how the regulations may be met. In these guidance documents, complementary indicators are sometimes addressed within the wider context of 'multiple lines of reasoning' and confidence building, particularly for far-future assessment time periods, even when they are not explicitly mentioned in the regulations themselves.

By their nature, these guidance documents are non-statutory but, nonetheless, the language used in them often makes it evident that the regulator has a strong expectation that the repository developer will use complementary indicators to support their safety case, as discussed in Section 4.2. For example, in Belgium, the use of complementary indicators is described in a regulatory guide developed for surface disposal of short-lived ILW and LLW. This guide includes a list of specified indicators:

- the extent of the potentially contaminated zone;
- the radioactivity and radiotoxicity concentrations in the liquid and solid phases of the geological units located in the disposal system environment;
- the flux of radioactivity and radiotoxicity released out of the disposal system; and
- the total radioactivity and radiotoxicity released out of the disposal system.

New guidance is also under consideration for both surface and geological disposal in Belgium and it is possible that similar indicators will be included in that guidance when it is completed.

4.1.2 Partially prescriptive regulation

In the last few years, a number of regulatory authorities have decided that complementary indicators are sufficiently important for demonstrating repository safety, that they have updated their regulations to include certain minimum requirements, such as specifying that one or a few specific indicators must be calculated in a safety assessment in addition to dose and risk.

The first regulatory authority to do so was STUK in Finland that included a constraint on the amount of activity that may be released from the repository to the accessible environment. This requirement can be seen as the formal quantification of the general expectation previously expressed in the Nordic Flag Book that *"inflows of the disposed radionuclides into the biosphere, averaged over long time-periods, shall be low in comparison with the respective inflows of natural alpha emitters"* (Nordic Radiation Protection and Nuclear Safety Authorities, 1993). STUK have expressed the formal regulatory requirement in the form of the following nuclide-specific radioactivity fluxes (STUK, 2009):

- 0.03 GBq/a for the long-lived, alpha emitting Ra, Th, Pa, Pu, Am and Cm isotopes;
- 0.1 GBq/a for the nuclides ^{79}Se, ^{129}I and ^{237}Np;
- 0.3 GBq/a for the nuclides ^{14}C, ^{36}Cl and ^{135}Cs and for the long-lived U isotopes;
- 1 GBq/a for ^{94}Nb and ^{126}Sn;
- 3 GBq/a for the nuclide ^{99}Tc;
- 10 GBq/a for the nuclide ^{93}Zr;
- 30 GBq/a for the nuclide ^{59}Ni; and
- 100 GBq/a for the nuclides ^{107}Pd and ^{151}Sm.

By demonstrating that these radionuclides cover the spectrum of relevant radionuclides emanating from the repository, a safety indicator is defined in the Finnish guide by the directive that the sum of the ratios between the nuclide-specific activity releases and the respective constraints shall be less than one. These radionuclide-specific reference values were derived by STUK using, amongst other things, biosphere models. In practical terms this means that the regulator took the responsibility for the assumptions that underpin these biosphere models. This flux based indicator is intended to ensure that:

- at a maximum, the radiation impacts arising from disposal can be equivalent to those arising from natural radioactive substances in the Earth's crust; and
- on a large scale, the radiation impacts remain insignificantly low.

The Finnish regulations specify that that these fluxes apply to normal evolution scenarios, after the period when the radiation exposure to humans can be assessed with sufficient reliability (taken to be a minimum over several millennia), and that the fluxes can be averaged over 1,000 years at the most. Although they do not use the term, these Finnish regulations effectively require the application of a set of safety indicators within the safety case.

Partially prescriptive regulations have also recently been developed in Germany (BMU, 2010) but these take a significantly different approach to the Finnish regulations. Rather than apply indicators based on fluxes of radionuclides released to the environment, the German regulations apply complementary indicators (in addition to the primary indicator of radiological dose) that measure long-term containment within the engineered barriers and the surrounding block of rock that hosts the repository (referred to here as the 'containment providing rock zone[1]). These regulations require that a set of statements are provided in the safety case for the long-term integrity of the containment providing rock zone, such that:

- the formation of secondary water pathways within the containment providing rock zone which could lead to the ingress or escape of potentially contaminated aqueous solutions can be excluded, and
- any pore water that may be present in the containment providing rock zone does not participate in the hydrogeological cycle outside of the containment providing rock zone, as defined by water legislation. This requirement is considered to have been met if the dispersion of pollutants within the containment providing rock zone by advective transport processes is at best comparable with dispersion by diffusive transport processes.

In addition, specifically for rock salt and clay host rocks, statements are required that:

- the anticipated stresses should not exceed the dilatancy strength of the rock formations in the containment providing rock zone outside of the disturbed rock zone;
- the anticipated fluid pressures must not exceed the fluid pressure capacity of the rock formations in the containment providing rock zone in a manner that could lead to the increased ingress of groundwater into the containment providing rock zone; and
- the barrier effect of the containment providing rock zone must not be inadmissibly influenced by temperature development.

Although they do not use the term, these German regulations effectively require the application of a set of complementary indicators within the safety case that could be classed as either performance indicators or safety function indicators.

In the Swedish regulations, risk is the primary safety indicator (SSM, 2008) but, in its general advice on the application of the regulations, SSM also requires the use of complementary indicators to strengthen the confidence in the calculated risks for the period up to 100 000 years. For the period beyond 100 000 years the advice states that:

"A strict quantitative comparison of calculated risk with the criterion for individual risk contained in the regulations is not meaningful. The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with several

1. The German regulations, and the German organisations responding to the Indicators Questionnaire, define this zone as the 'isolating rock zone' but to be consistent with the content of this report the term 'containment providing rock zone' is used instead to illustrate that this zone refers to the safety function 'containment'.

supplementary indicators of the protective capability of the repository such as barrier functions, radionuclide fluxes and concentrations in the environment."

In the French regulations, the dose constraint is also the primary safety indicator (ASN, 2008) but the regulations require that safety is demonstrated in an iterative manner that includes the verification of the favourable performance of each component that contributes to the overall safety function of the repository. The regulations also suggest that indicators complementary to dose should be used in a safety assessment, and activity fluxes and concentrations estimated at various locations in the repository are mentioned in the regulations as examples of such indicators.

4.1.3 *Fully prescriptive regulation*

In only one country (the USA) are the regulations fully prescriptive, and set-out in precise detail what assessment calculations the repository developer must perform. Unlike in most other countries, the USA has taken the approach of developing site (facility) specific regulations and, to date, the Nuclear Regulatory Commission (NRC) has produced regulations for:

- the WIPP repository in New Mexico which is located in bedded salt and is currently operating for the disposal of TRU wastes (40 CFR Part 197 and 40 CFR Part 191); and
- the Yucca Mountain project in Nevada which is located in unsaturated volcanic tuff, and was intended for the disposal of spent fuel (10 CFR Part 63).

In both cases, in addition to dose assessment, both sets of regulations include a number of additional requirements that take the form of complementary indicators, although that term is not used in either case. In particular, the following maximum permissible concentrations have been set for the 'representative volume of groundwater' which is defined as the volume of potentially contaminated groundwater that may be extracted from an aquifer to supply a given water demand:

- combined ^{226}Ra and ^{228}Ra, < 5 pCi/L [< 0.19 Bq/L] (including background);
- gross alpha activity (including ^{226}Ra but excluding Rn and U), 15 pCi/L [< 0.56 Bq/L] (including background); and
- combined beta and photon emitting radionuclides, 0.04 mSv/a to the whole body or any organ, based on drinking 2 L/day from the representative volume.

In addition, for WIPP, there are additional performance indicator type requirements for containment that are defined as radionuclide-specific maximum permissible release rates per 1,000 MTHM of waste, that are to be calculated cumulatively over a 10,000 year period.

4.2 Regulatory guidance

As mentioned earlier, even in non-prescriptive regulatory regimes there is often a strong expectation that complementary indicators should be used in safety cases, and they are frequently mentioned in non-statutory guidance documents.

These guides, because of their nature, do not set-out formal requirements and consequently they do not always specify what indicators the regulators might expect to see in a safety case, how they should be calculated or what reference values might be compared to them. They do, however, sometimes provide clear suggestions to the developer that may take the form of practical advice.

In the UK, for instance, formal dose and risk limits applicable to nuclear operations (including radioactive waste disposals) are specified in primary legislation. There is no statutory requirement to apply any complementary indicators in addition to dose and risk. The regulator (the Environment Agency for England and Wales) has, however, recently published detailed guidance on the process for authorising a deep geological repository (EA and NIEA, 2009) and, in this, they explicitly state they expect a quantitative risk assessment would need to be supported by multiple lines of reasoning based on a variety of evidence, leading to complementary environmental safety arguments. The guidance document provides the following advice:

Examples of environmental safety indicators that might be used to strengthen the environmental safety case include radiation dose, radionuclide flux, radionuclide travel times, environmental concentration and radiotoxicity. The developer/operator should provide a wide range of information relating to such indicators, for example:

- assessments of radionuclide release characteristics from the waste and from the various barriers that make up the disposal system;
- assessments of the concentrations in the accessible environment of radionuclides released from the disposal system and comparison of these with naturally occurring levels of radioactivity in the environment;
- if appropriate, assessment of collective radiological impact (as a measure of how widespread any significant increase in risk may be as a result of radioactivity released into the accessible environment); and
- unifying statements that aim to place in context the different items of information that contribute to assuring environmental safety.

Other sets of guidance provide similar advice and recommendations. For example, a joint report by French and Belgian regulators and repository developers on approaches to repository safety assessment (FANC *et al.*, 2004) discusses the use of complementary indicators for different assessment timeframes, and also the consideration of safety functions.

Although such guidance documents are non-statutory, they do set minimum expectations for how complementary indicators should be handled in safety cases. In practical terms, therefore, there is often little distinction between regulatory expectations set out in guidance documents and the formal requirements set-out in the regulations themselves.

4.3 Other environmental regulation

It is common that a repository will be regulated under several sets of regulations (and often by multiple regulators). In particular, there may be environmental regulations that apply in addition to those specified by the nuclear regulator, and these may have relevance to complementary indicators. For example, repositories in Europe will be subject to the 2000 Water Framework Directive and the 2006 Groundwater Directive which are intended to protect groundwater from pollution from any industrial activity. National regulations that transpose these Directives are likely to set maximum permissible limits on the amount of chemical and radioactive substances in groundwater, and these may be considered as examples of complementary indicators and corresponding reference values. Alternatively, drinking water standards set by the World Health Organisation provide other global reference values for both chemical and radiological substances that could be used as comparisons (WHO, 2011).

Furthermore, there has been a growing interest in the last decade on the impacts of repository releases on non-human biota. Although models exist that relate radionuclide concentrations in the environment to dose to reference species (e.g. Beresford *et al.*, 2007; ICRP, 2008), there are clearly large uncertainties about this approach particularly regarding the correlation between dose and effect. There is potential to apply safety indicators to non-human biota so as to reduce this uncertainty, provided suitable reference values applicable to the key species of interest can be derived.

5. APPLICATION IN THE SAFETY CASE

5.1 Indicators in different stages of a repository development programme

Several safety cases are likely to be produced iteratively throughout an entire repository development programme. Some of these may be undertaken for internal purposes (e.g. to help develop system understanding) but others will mark key decision points when the developer seeks approval to move from one major stage of the programme to the next. In very simple terms, the main stages of a repository development programme are:

- concept development, and assessment of alternative conceptual designs;
- site characterisation and selection of a preferred site / host geological environment;
- construction and operation (often occurring in parallel in different parts of the facility);
- backfill and closure; and
- post-closure institutional control.

Complementary indicators can be applied in the safety cases required in each of these stages, although the nature and use of indicators is likely to become more important as the repository development programme moves towards implementation.

During the initial stage of concept development, indicators may be used to help compare alternative designs. At this time, the emphasis may be on performance indicators to help evaluate the comparative evolution of different options for the engineered barriers. A relatively small number of performance indicators may be necessary at this stage, and the most useful ones are likely to be those that provide a measure of the containment function, such as radionuclide flux through barriers over time. Safety indicators can also be applied in generic safety cases performed in the early stages of repository development but the absence of a site means that proxy reference values would need to be compared with the indicators, such as national average radioactivity concentrations in ground and river waters.

As a repository development programme moves on to site selection (or selection of a preferred host geological environment), greater emphasis may be placed on safety indicators to evaluate how the integrated engineered and natural barrier system evolves within the different sites and geological environments being compared. The final choice of site will depend on a large number of technical, socio-economic and financial factors, but safety indicators could be an important addition to the list of attributes considered. As discussed in Section 2, there is often a broad requirement that a repository should not be sited where it would cause a significant increase to the natural background radiation environment, and this requires some quantitative comparison between repository releases and the naturally occurring abundances (fluxes and concentrations) of radioactive species, which is the fundamental basis of the complementary indicators approach. This approach can be formalised, as is done in Germany in the VerSi Project discussed in Section 5.2.

Also, as sites are identified, engaging with stakeholders and the local host community becomes increasingly important. The role of indicators in communication with licensing authorities as well as with the general public, illustrating how the system behaves and impacts on the site and local area, is of increasing importance with further development of the repository programme, where confidence in the performance assessment becomes more and more relevant. This aspect is discussed in more detail in Section 5.7.

Once a preferred site(s) has been identified, a large effort will be placed on performing site characterisation, usually starting with regional surface studies and progressing to more localised and sub-surface investigations. As information on the site-specific rock and groundwater conditions becomes progressively available, the design of the repository will need to be optimised. This will involve refining the layout of tunnels to fit within significant geological features such as fractures and, perhaps, choosing the best engineered barrier materials (e.g. bentonite composition) to reflect the groundwater chemistry. Performance indicators and safety function indicators are particularly helpful tools to be used in optimising the layout and design of the repository, and could also give valuable information about properties of a suitable site.

It is important that the site characterisation studies measure the parameters that will be needed to provide the necessary site-specific and local reference values for comparison with the safety indicators used in the safety case. Where possible, these reference values should be measured during baseline studies so that the measured quantities are not affected by the sub-surface investigations themselves (e.g. deep drilling and hydrotesting) and later repository construction. This means that, ideally, the safety indicators and the matching site-specific reference values should be defined at the outset. In this way, application of indicators has a lot in common with repository monitoring because it is generally accepted that the baseline characteristics of a site should be determined before construction starts so that the perturbations caused by the facility on the natural system can be quantified. For example, the concentration and fluxes of naturally occurring radionuclides in the groundwater at a site will be affected by the hydrogeochemical changes caused by excavation of the repository and groundwater pumping.

The linkage between complementary indicators and repository monitoring has only recently been identified, and further work may be required to test the level of integration that may be needed between these two activities. During the successive phases of construction, waste emplacement and tunnel backfilling, ongoing monitoring work will record an evolution in the groundwater and rock stress systems. This information may be relevant to the derivation and application of performance indicators in subsequent safety assessments in so far as it provides additional information on the characteristics of the site which may be useful when calculating key performance indicators for the post-closure period (e.g. transport time through the rock).

Also of potential interest is the connection between complementary indicators and performance confirmation monitoring in the post-emplacement stage. Once waste has been emplaced, predicted performance can be compared with actual measured performance for certain indicators (e.g. canister corrosion rates), provided measurements are possible. If deviations are identified then further analyses and investigations would be required. In some repository concepts, there is planned to be a period of post-emplacement monitoring before the facility is finally backfilled and sealed, and this period provides greater opportunity for comparing predicted and measured performance, although even over a period of, say, one hundred years the processes that are likely to be measureable will relate to slow achievement of equilibrium rather than actual radionuclide release.

In very general terms, the most advanced repository development programmes are also the ones that have the greatest experience in using complementary indicators. This observation may also reflect a broad view that the value of complementary indicators increases significantly when a preferred site has been identified and the emphasis changes from undertaking generic safety assessments to evaluating specific impacts to a particular community and environment, and when meaningful, local reference values for comparison with safety and performance indicators can be established.

The more advanced programmes are also characterised by the most detailed and complex safety assessments that are based on site and design-specific data rather than generic information. Thus, the level of detail and the use of complementary indicators will also reflect the maturity of the scientific understanding and assessment capability, and will evolve as the repository concept and safety case are further developed.

Several of the more advanced programmes are now also using safety functions as a further analytical tool to understand the evolution of the repository system. The use of safety functions (and the emphasis that can be put on them in a safety assessment) depends on the scientific understanding of the system being analysed. The establishment of a comprehensive set of detailed safety functions and, especially, the definition of criteria for their fulfilment, relies on considerable information which typically is achieved only through dedicated and site-specific R&D efforts over time. In those programmes where safety functions are given a key role in the safety case, it has been important to demonstrate clearly how they were derived. This may explain, in part, why the use of safety functions has emerged most strongly in safety assessment for well-established concepts like the Swedish KBS-3 or the clay concepts developing in France and Belgium. Several of the more advanced programmes are now also developing their approaches to using safety function indicators to evaluate whether or not safety functions in the repository system are fulfilled. For programmes at early stages of development, the identification of safety functions may still be important and useful for structuring the development of system understanding and to identify key uncertainties and research topics (NEA, 2009a).

5.2 Assessment of overall repository safety

Providing an alternative and independent means to assess the safety of the overall repository system was the primary purpose behind the initial work to develop complementary indicators and, in particular, to overcome the uncertainty associated with evaluating safety in the very far-future using dose and risk (e.g. IAEA, 1994). This still remains an important role for complementary indicators in a safety case, although increasingly the emphasis is being placed on understanding the behaviour of the repository at a sub-system or component level.

Assessing overall repository safety essentially depends on calculating the amount of waste-derived nuclides (and their associated radioactivity) that migrates from the near-field and is released to the accessible environment, and then making an evaluation of the safety hazard associated with that release. To calculate dose or risk impacts, assumptions obviously need to be made for the exposure pathways and such assumptions become increasingly uncertain as assessment timeframes increase. Once large scale climatic changes occur, only stylised or reference future conditions can be postulated.

Complementary safety indicators seek to remove the uncertainty associated with the exposure pathway and, instead, the calculated repository releases are compared to other independent parameters. The simplest of these is the abundance of naturally occurring radioactive substances in the environment, and this argument rests on two points:

1. that the natural environment is, itself, safe which is a reasonable assumption given that there is no epidemiological evidence that people suffer an increase in the rates of cancers, even in areas with the highest natural radiation background; and

2. that if the repository releases remain only a very small fraction of the total natural background, then those releases may also be considered to be safe.

The difficultly with this approach is that it cannot readily take account of the different radionuclide inventory in the repository releases compared to the naturally occurring radionuclide abundances, and specifically the non-natural nuclides present in the releases. To address this point, other reference values may be considered, such as nuclide or element-specific maximum permissible concentrations such as are agreed internationally for drinking water standards, and other environmental and health protection guidelines.

Simply put, these complementary safety indicators move the evaluation of safety from consideration of dose to a consideration of environmental concentration.

5.2.1 Safety statements

To describe the role of safety indicators in a safety case, it is necessary to consider how ‘safety’ is addressed in a safety case. Commonly, safety cases refer to national (and international) regulations and policies. For example, in Belgium, the following top level safety statement is proposed *“the repository system and its environment (should) conform(s) to regulatory standards and guidance concerning long-term safety via the safety functions that it performs over the required timeframe”* (ONDRAF/NIRAS, 2009). Similar statements can be found in other national programmes.

In most regulations, safety is usually addressed as ‘protection of people and environment’ such as in the French regulations that state *“the protection of people and the environment in the short and long term is the basic objective assigned to a waste repository in a deep geological formation”* (ASN, 2008).

Regulations for radiological protection vary in detail between countries but they are always consistent with the ICRP’s three fundamental principles of radiological protection: (i) justification, (ii) optimisation of protection, and (iii) application of dose limits, applied according to the exposure situation being considered (ICRP, 2007). Complementary safety and performance indicators are meaningful and can be presented in the context of these ICRP Principles:

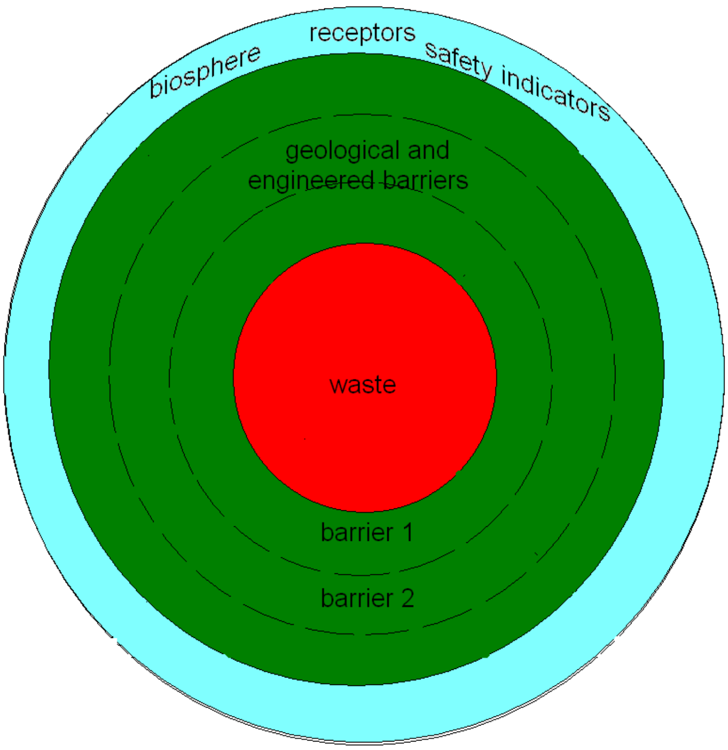
- Justification: If people feel that disposal is insufficiently justified, they may feel that a repository is unacceptable even though the predicted doses are much lower than those from other, justified practises. In a safety case, complementary indicators may be used in the context of multiple lines of reasoning to provide justification arguments for why disposal is preferable to other management options, such as indefinite storage.
- Optimisation: The use of safety indicators in combination with performance indicators (and safety function indicators), can be used as a tool to optimise the safety performance of the disposal system. For example, performance indicators can be used to assess the level of long-term containment provided by alternative engineered barrier system options, and so optimise the barrier design against the hydrogeochemical conditions of a site.
- Dose limits: Many complementary safety indicators, such as radiotoxicity, radiotoxicity flux and power concentration can be directly correlated to dose because they are direct measures of the radiological hazard presented by calculated repository releases, but without the uncertainty associated with assuming potential exposure pathways.

5.2.2 Understanding overall repository safety

Repository safety is provided jointly by the engineered and geological barriers, as illustrated in Figure 3, and the safety of the repository may be measured by the level of protection it provides to our environment, and specifically to the biosphere and its biota (including humans). Consequently, safety indicators are often strongly linked to the definition of the biosphere.

Most national legislation requires that humans and the environment are protected against the harmful effects of radiation that may be released from facilities, including a repository. To help assess the protection of the environment, the ICRP described a set of 'Reference Animals and Plants' that can serve as the default target for protection and protective actions (ICRP, 2008). The abstraction from 'humans' to 'reference animals and plants' can be taken one step further by relating 'reference animals and plants' to a 'reference biosphere'.

Figure 3: The repository system incorporates waste packages, the engineered barrier system, the host rock and its groundwaters, while the 'receptor' is the biosphere and its biota, including humans.



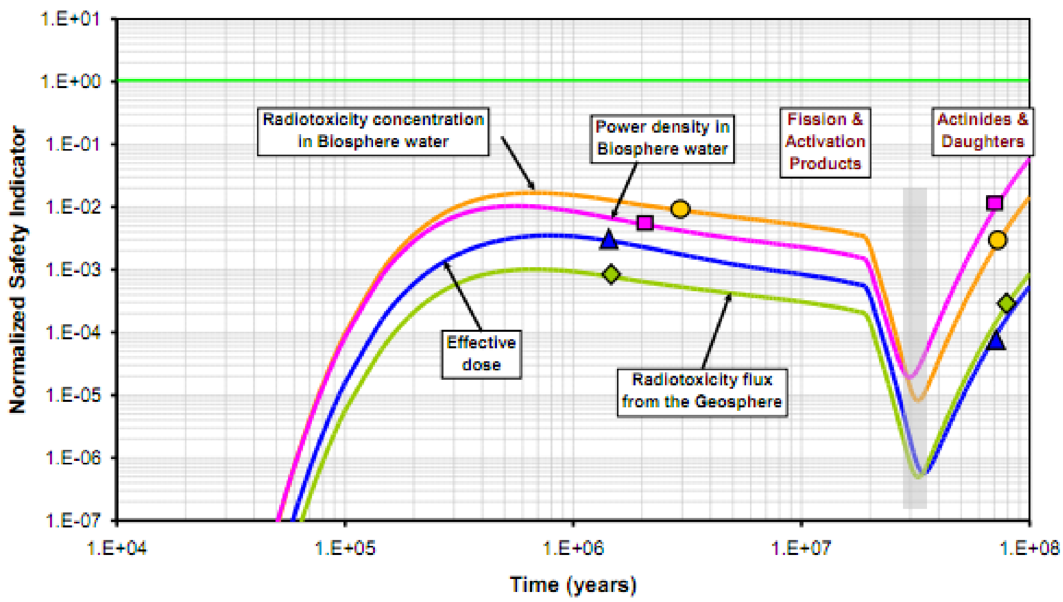
In this context, complementary safety indicators (such as those defined in the SPIN and PAMINA projects) are very useful because they can be used to assess the radionuclide fluxes and concentrations to, and within, a reference biosphere, and their potential impacts. The reason why the SPIN and PAMINA projects considered radionuclide fluxes and concentrations is that, apart from the increasing requirement to demonstrate that the environment as a whole is protected, predictions of far future radiotoxicity fluxes and concentrations are subject to much less uncertainty than dose rate predictions (see Section 5.6).

An example from the PAMINA project of calculation results using safety indicators is shown in Figure 4. In this, several safety indicators (radiotoxicity concentration, power density, radiotoxicity flux and effective dose) are presented as normalised values, divided by their respective reference values. This allows direct comparison of the safety statements about a repository system that can be derived from the different indicators.

The four curves have similar shapes, demonstrating a strong correlation between dose rate and the complementary indicators in the assumed reference biosphere system.

Complementary safety indicators are a valuable tool to help evaluate total system safety by demonstrating that the amount of radioactive material (flux and concentration) that may reach the biosphere is well within regulatory limits that are applicable to the scenario considered. It is difficult, however, to demonstrate the full protection capability of the repository system with safety indicators only. A multi-barrier system will generally show the same safety indictor results as for a single barrier system, even though it is generally agreed that a multi-barrier system offers better protection. Differences usually only show in the probability of 'high consequence scenarios' and in risk type indicators.

Figure 4: Example of normalised safety indicators. From Becker *et al.* (2009).



5.2.3 *Reference Values*

In accordance with the third ICRP Principle, dose limits (and reference values in general) should be applied according to the exposure situation being considered. The reasoning is that a reference level can only be proved, or considered, to be safe in a given context.

The ICRP recommends that a dose constraint of 0.3 mSv/a (equivalent to a risk constraint of 10^{-5}/a) should be used for potential exposures from waste disposed in a repository in an expected evolution scenario, and suggests that it is useful to disaggregate the probability and potential consequences (ICRP, 2007). If an unexpected disruptive event occurs when oversight of the disposal system has ended, and authorities eventually become aware of the disturbance, they would treat the situation as an emergency exposure situation or an existing exposure situation depending on the severity of the disturbance, and then different limits would apply:

- For emergency exposure situations, the ICRP recommends selection of a reference level in the range of 20 mSv to 100 mSv for the first year, and development of protection strategies to reduce exposures to as low as reasonably achievable (ALARA) below the reference level, taking into account economic and societal factors (ICRP, 2009a).

- For existing exposure situations where long-lasting exposures result from natural disruptive events (with or without an emergency phase), the recommended reference levels to be selected for optimising protection strategies range between 1 and 20 mSv/a, and a reference level should be selected in the lower part of that band, in the range of a few mSv/a (ICRP, 2009b).

For comparison, the reference values that were used in the PAMINA project for the calculations of the normal evolution scenario are given in Table 5. In line with ICRP Principles, reference values, including those derived from natural levels (such as applied in PAMINA) can be used only if they are suitable for the situation under consideration and must be applied according to the exposure situation (or context) considered. Even if a natural level is used for reference, a rationale must be given that explains why that reference is both appropriate and applicable.

Table 5: The set of reference values for the safety indicators used in the PAMINA project calculations. From Becker *et al.* (2009).

Safety Indicator	Range of reference values
Risk (1/a)	1×10^{-8} – 1×10^{-5}
Dose rate (mSv/a)	0.1 – 0.3
Radiotoxicity concentration in biosphere water (Sv/m^3)	2×10^{-6} – 2×10^{-5}
Radiotoxicity flux from the geosphere (Sv/a)	0.1 – 60

5.2.4 System integrity

The concept of risk and safety assessment has been evolving during the last few decades into (management) systems for risk management and system integrity. Where, in the past, a safety report would be required, nowadays regulators require that operators implement a system for risk management (e.g. in accordance with ISO 31000) or advanced standards for system integrity in the case of facility operations (e.g. in accordance with ASME 31.8S in the case of pipeline integrity management). ASME 31.8S promotes system integrity management because it *"provides the information to the operator to effectively allocate resources for appropriate prevention, detection, and mitigation activities that will result in improved safety"* (ASME, 2010)

In contrast, safety indicators for a repository will generally not show an increase in safety when (additional) options of prevention, detection, and mitigation are implemented because of the passive nature of safety provided by a closed disposal facility

5.3 Assessment of repository and sub-system performance

Performance indicators have been developed to illustrate and quantify how various sub-systems, components and processes contribute to the isolation and containment of the radionuclides in the repository system. Comprehensive sets of performance indicators were developed in the SPIN and PAMINA projects (Becker *et al.*, 2003; Becker *et al.*, 2009) and, over the last decade, various other performance indicators have successfully been applied in several published safety cases, as shown in Table 2.

The main performance indicators that were identified in the Indicators Questionnaire (that included those from the SPIN and PAMINA projects) broadly fall into the three groups that comprise the alternative classification scheme proposed in Section 3.1.3:

- *concentration and content related indicators*, that provide information on the radionuclide inventory and its distribution within compartments of the repository and the environment, and the evolution of the inventory distribution over time (e.g. total radioactivity content of the wasteform or radiotoxicity concentration in groundwater);

- *flux related indicators*, that provide information on the flux and transport of radionuclides between compartments of the repository, and their release to the accessible environment (e.g. radioactivity flux from the engineered barriers to the geosphere or total integrated radiotoxicity flux from the geosphere to the biosphere over time); and
- *status of barriers related indicators*, that provide information on the functioning and containment capability of the barriers in the repository system (e.g. container life time or buffer swelling pressure).

Most performance indicators are based on consideration of a compartmentalised repository system, which represents the division of the repository system into sub-systems, at a level of detail appropriate to the purpose of an assessment. For example, the content of a waste package compartment (inventory) can be defined as the sum of the activity still present in the waste matrix, the activity in the precipitate and the activity of the radionuclides dissolved in the water within the waste canister. Similarly, the flux from the waste package can be defined as the amount of activity transferred from the waste package compartment to the surrounding buffer compartment.

5.3.1 *Content and concentration related indicators*

Examples of the performance indicators based on content and concentration (inventory) that were identified in responses to the Indicators Questionnaire are listed in Table 6. These are presented in generic format (non-concept or site specific), although examples of specific indicators relevant to particular disposal programmes are given in Table 2. They provide information about parameters such as:

- concentrations (e.g. mass or activity concentrations) in different system compartments, showing where radionuclides are at different points in time;
- concentrations outside of the different compartments, showing the containment capability of the inner barriers; and
- concentrations in compartment waters, illustrating the dilution and dispersion in successive compartments during transport.

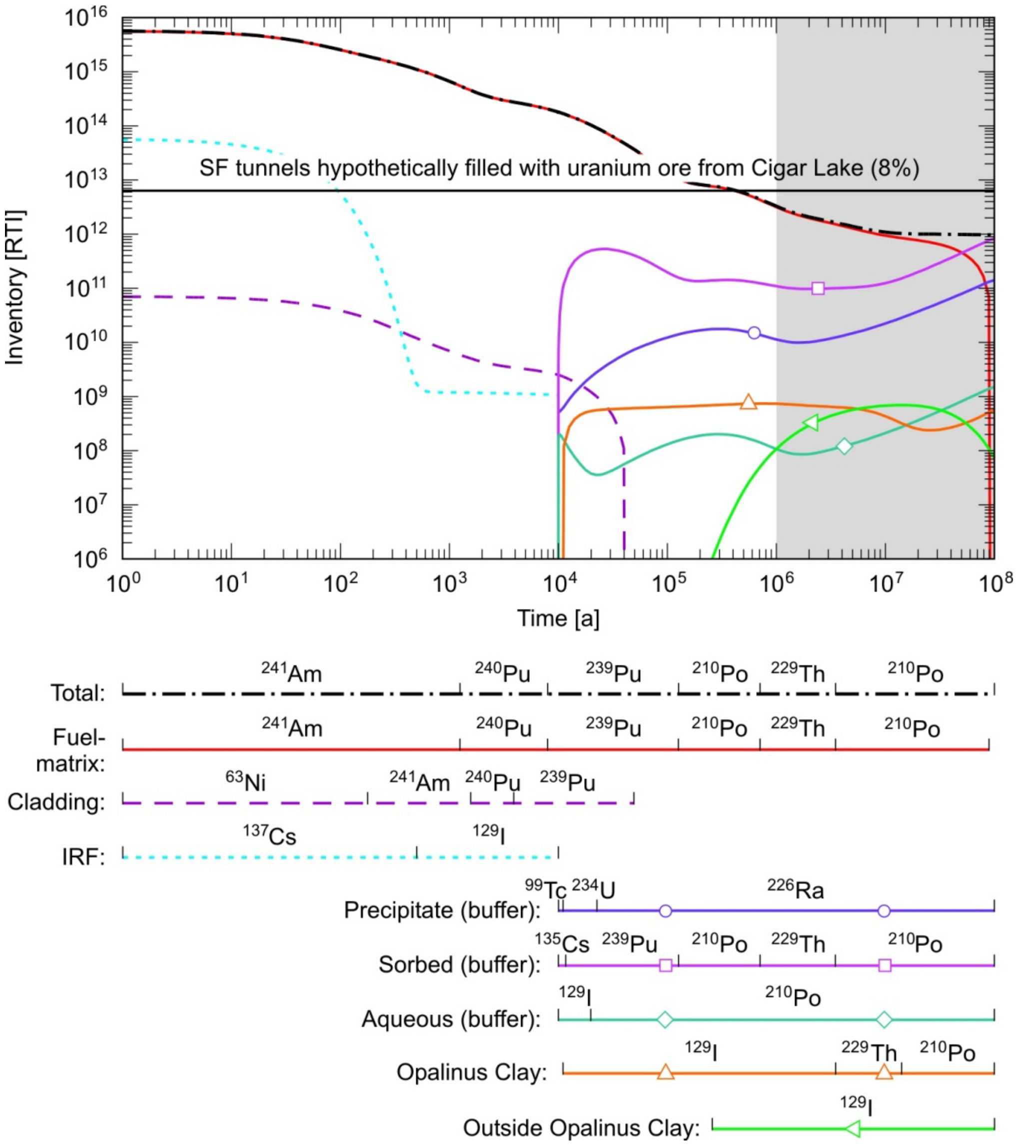
Table 6: Examples of generic performance indicators based on concentration and content that were reported in responses to the Indicators Questionnaire.

Performance indicator (content and concentration related)	Unit
Activity in compartments	Bq
Activity outside compartments	Bq
Radiotoxicity in compartments	Sv
Radiotoxicity outside compartments	Sv
Activity concentration in compartment water	Bq/m^3
Radiotoxicity concentration in compartment water	Sv/m^3
Concentration in biosphere water / waste package water	-

The use of performance indicators to illustrate how the barrier system isolates and contains radionuclides, especially by immobilisation in the waste forms and geochemical immobilisation within and around the repository, is given in Figure 5. This example is from Nagra's safety case for the disposal of spent fuel in the Opalinus Clay in Switzerland (Nagra, 2002). In this, the assessors presented various indicators that show the distribution of radiotoxicity at different times between the various components of the barrier system, and also the biosphere. An important observation from this figure is that the large majority of the total radiotoxicity, which is dominated by the actinides, is contained almost entirely within the spent fuel matrix for more than 10 million years.

Another observation from this figure is that, after about 400,000 years, the radiological significance of the spent fuel in terms of radiotoxicity is similar to that of a uranium orebody with the same volume as the spent fuel disposal tunnels. Only at the very longest assessment times is most of the radiotoxicity no longer contained within the fuel matrix, and, even then, it is still mainly contained in the near field due to sorption on to the bentonite buffer.

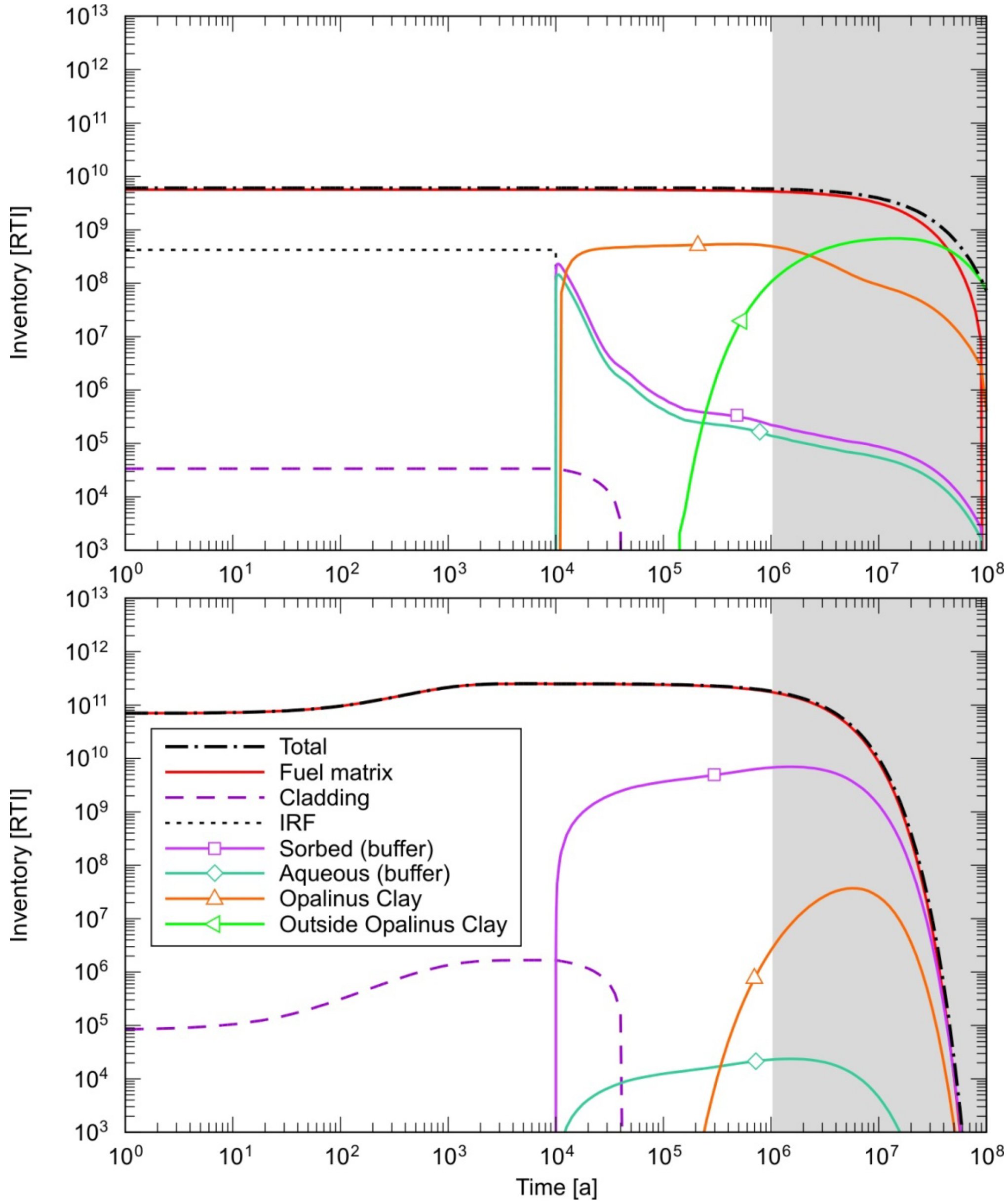
Figure 5: Evolution and distribution of the radiotoxicity from spent fuel in the different components of the disposal system and in regions outside the upper and lower boundaries of the Opalinus Clay (the bars beneath the graph indicate the successive radionuclides that make the highest contribution to radiotoxicity in the considered parts of the system. From Nagra (2002).



The radiotoxicity of radionuclides that were calculated to have migrated into the Opalinus Clay, which is dominated by the daughters of ^{238}U, is still increasing, even after 10^8 years. This can be explained in terms of the very low corrosion rate of the fuel matrix, the very long half-life of ^{238}U (4.5×10^9 years), and the strong sorption of uranium compared to that of some of its daughters (e.g. ^{226}Ra) within the bentonite and Opalinus

Clay. The very small level of radiotoxicity outside the Opalinus Clay (contained within the overlying and underlying sedimentary layers, and in the biosphere) is dominated by ^{129}I which is both long-lived and poorly sorbing. The radiotoxicity associated with ^{129}I rises to a maximum at about 10 million years due to in-growth from its parent nuclides, and then decreases due to its slow decay with a long half-life of about 16 million years. Figure 6 shows the evolution and distribution of radiotoxicity originating from spent fuel for two long-lived radionuclides with contrasting sorption properties, namely ^{129}I (a low sorbing anion) and ^{237}Np (a strongly sorbing actinide).

Figure 6: Evolution and distribution of the radiotoxicity from spent fuel due to 129I (upper figure) and 237Np (lower figure). From Nagra (2002).



The figure shows that the radiotoxicity of both radionuclides is contained predominantly in the fuel matrix for more than 10 million years. A significant part (a few per cent) of the radiotoxicity of ^{129}I is, however, contained initially in the grain boundaries of the fuel matrix, in fuel pellet cracks and in the gap between the fuel and the cladding. After failure of the canister, this instant release fraction (IRF) enters solution, and is then transported through the clay barriers (i.e. the bentonite and the Opalinus Clay), with retardation by weak sorption, before finally reaching the overlying and underlying sedimentary layers and the biosphere. Even though the maximum radiotoxicity outside the Opalinus Clay does not occur until more than 10 million years after emplacement, there is little decay of the ^{129}I inventory by this time, due to its very long half-life. By contrast, most of the ^{237}Np in spent fuel has decayed before the canister fails, and, therefore, only an insignificant proportion of the ^{237}Np inventory is ever present in the Opalinus Clay, and the amount that can reach the biosphere is too small to show in the figure.

This example from Nagra clearly demonstrates how performance indicators based on content and concentration can provide a detailed understanding of the containment performance provided by the engineered barriers, and the isolation and retardation performance provided by the host rock. Such an understanding considerably increases confidence in the associated dose and risk based safety assessment, by explaining how safety is assured by the repository design and its functioning.

5.3.2 Flux related indicators

Examples of the performance indicators based on fluxes that were identified in responses to the Indicators Questionnaire are listed in Table 7. Again, these are presented in generic format (non-concept or site specific), although examples of specific indicators relevant to particular disposal programmes are given in Table 2. These indicators show the evolution of the transport of radionuclides between successive compartments, including the effects of radioactive decay and in-growth. They are also a measure of the barrier function of the disposal system. These flux related indicators can be calculated in absolute terms or normalised to the initial inventory at the repository closure. They show the retention capabilities of each compartment of the disposal system, and are independent of any assumptions in biosphere models and exposure pathways.

Table 7: Examples of generic performance indicators based on fluxes that were reported in responses to the Indicators Questionnaire.

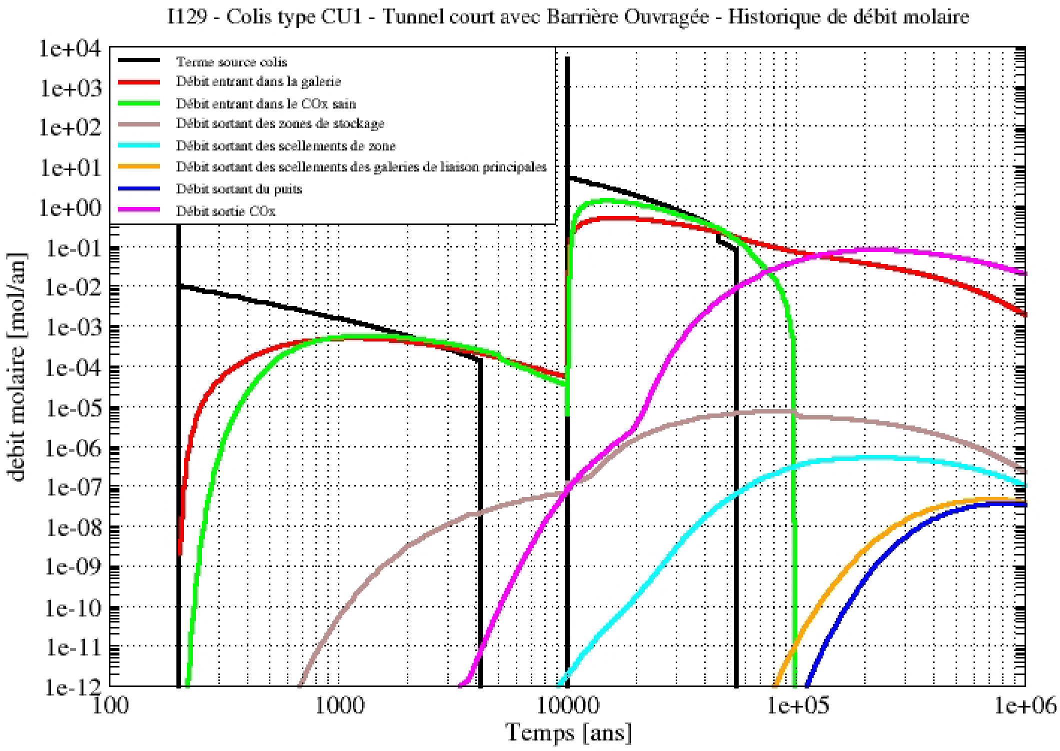
Performance indicator (flux related)	Unit
Activity flux from compartments	Bq/a
Radiotoxicity flux from compartments	Sv/a
Time-integrated activity flux from compartments	Bq
Time-integrated radiotoxicity flux from compartments	Sv

Fluxes can be presented in terms of mass, activity or radiotoxicity, depending on the purpose of the assessment, and the intended audience. From a radiation protection perspective, radiotoxicity is the most meaningful and, if this is applied as the weighted sum over all radionuclides, fluxes from inner compartments can be dominated by the contributions from the short-lived, highly mobile decay products of high activity fluxes and dose conversion factors. In this case, the sum of these indicators can exceed the total initial radiotoxicity inventory in the waste. Other indicators are based on integrated fluxes. For individual radionuclides these indicators allow the quantification of the fraction of the inventory that decays in each compartment.

Time-integrated fluxes may be used to quantify the performance of the total repository system. For example, in the Belgian case, SCK•CEN define a 'containment factor' as the fraction of the radiotoxicity present in the disposed waste that is released into the surface environment (Marivoet *et al.*, 2010). This factor is calculated by dividing the time-integrated radiotoxicity flux released from the host clay layer by the initial radiotoxicity of the disposed waste at the time of its disposal.

As an example of this approach, in its ‘Dossier 2005’ safety case for the disposal of HLW and spent fuel in the Callovo-Oxfordian Clay formation in France, Andra calculated the fluxes between the main compartments of the repository system (Andra, 2005), as illustrated in Figure 7. This shows the evolution of the fluxes between compartments in the case of the normal evolution scenario. Two peaks in the near-field fluxes can be distinguished. The first is due to releases from a small number of canisters that are assumed to fail within the first 200 years due to manufacturing defects, and the second peak is due to releases from the remaining canisters which are assumed to have a lifetime of 10,000 years. The figure clearly shows the strong retardation provided by the host clay formation. It also shows that the flux to the aquifers through the sealed access shaft is only a small fraction of the total flux migrating through the host formation.

Figure 7: Evolution of the fluxes between the main compartments of the repository system for spent fuel in the case of the normal evolution scenario. From Andra (2005).



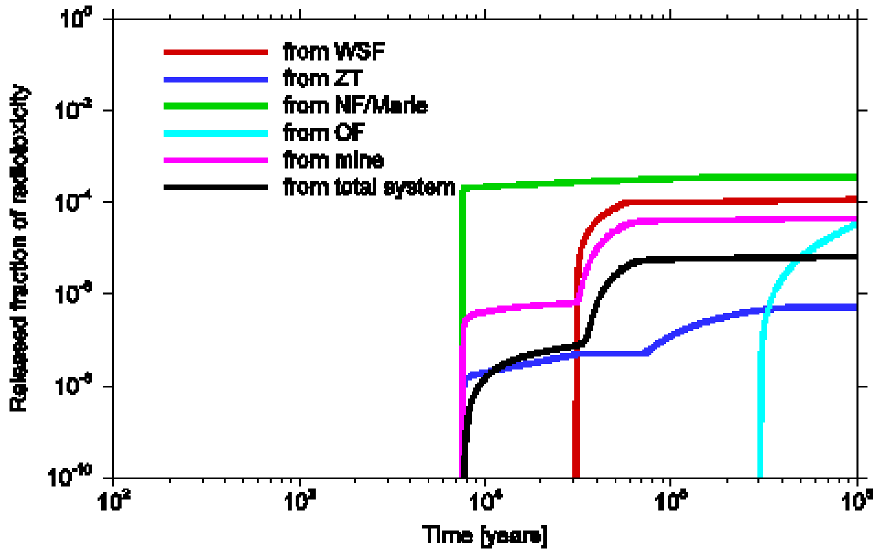
In another example, Nagra also used integrated fluxes as performance indicators to illustrate that the processes controlling radionuclide transport from its spent fuel repository are very slow, ensuring that the majority of radionuclides decay within the engineered barriers and geosphere. The extent of decay within the system components is illustrated in Table 8 that shows the proportions of the radiotoxicity due to various radionuclides that decay within different parts of the engineered barrier system. The fluxes were integrated over a 10^8 year period. The vast majority of individual nuclides decay within the engineered barriers, except for a few low-sorbing and long-lived nuclides, such as ^{129}I, ^{36}Cl and ^{79}Se, a proportion of which can migrate into the Opalinus Clay.

Table 8: The proportions of the radiotoxicity due to key radionuclides that decay within different parts of the barrier system for spent fuel. From Nagra (2002).

Nuclide	Proportion of radionuclide inventory originating in spent fuel that decays in:				
	Waste matrix	Waste matrix + immediate surroundings + precipitates	Waste matrix + immediate surroundings + precipitates + buffer	Waste matrix + immediate surroundings + precipitates + buffer + Opalinus Clay	Outside the Opalinus Clay
^{14}C (organic)	0.88	0.88	0.90	1.00	4.5×10^{-5}
^{36}Cl	0.41	0.41	0.41	0.89	0.11
^{59}Ni	0.22	0.56	0.95	1.00	0.00
^{79}Se	0.89	0.99	0.99	0.99	6.8×10^{-3}
^{99}Tc	0.96	0.96	1.00	1.00	0.00
^{129}I	0.69	0.69	0.69	0.72	0.27

In safety assessments for the Morsleben repository for L/ILW in a salt formation in Germany, GRS used the time-integrated radiotoxicity fluxes out of the different vaults (WSF, ZT, NF and OF), normalised to their initial inventories, as a performance indicator. Figure 8 shows what fraction of the initial radiotoxic inventory has migrated from the vaults over time. In the repository, only the WSF and OF vaults are sealed from the rest of the facility. Nevertheless, even for the NF vault, which has the least isolation capacity, the released fraction never exceeds 0.036 % because its inventory consists mainly of very short-lived nuclides which decay before being released. From the non-sealed ZT vault, less than 10^{-4} % of the initial radiotoxicity is released to the host rock. The calculated releases from the OF vault are still increasing at the end of the assessment time period (one million years) due to in-growth of long-lived daughter nuclides. The cumulate release fraction from the mine to the host rock is 4.6×10^{-3} %, and the total release fraction from the total system to the biosphere is only 6.5×10^{-4} % due to the high sorption capacity of the geosphere.

Figure 8: Time-integrated, relative radiotoxicity fluxes from compartments. Figure used with kind permission from BfS.



5.3.3 *Status of barriers related indicators*

Examples of the performance indicators related to the status of barriers that were identified in responses to the Indicators Questionnaire are listed in Table 9. By their nature, these status of barrier indicators tend to be very specific to individual repository concepts and designs and, consequently, they are most applicable in advanced repository programmes with a detailed system design. This also means that there are fewer examples of their use compared to the content and concentration, and flux related indicators.

Table 9: Examples of performance indicators related to the status of barriers that were reported in responses to the Indicators Questionnaire.

Performance indicator (status of barriers related)	Unit
Groundwater age at repository depth	a
Container lifetime	a
Transport times through the barrier system components and the geosphere	a
State of stress in the near-field rock	MPa
Swelling pressure (for buffer and backfill)	MPa
Ionic strength (geosphere groundwater)	mol/L

The most generic, and therefore potentially most transferrable status of barrier indicator is ‘transport times through system compartments’. In its ‘Dossier 2005’ safety case, for example, Andra calculated the time (after closure) when the maximum molar flux of certain poorly sorbing radionuclides occurred to the top of the host Callovo-Oxfordian Clay formation, assuming releases from three different types of waste package (Andra, 2005). The time of maximum flux has a direct relationship with the transfer time through the clay for these radionuclides and, therefore, is an indicator of the barrier ‘containment’ performance provided by the host rock, as shown in Table 10.

Table 10: The calculated time of maximum molar flux to the top of the Callovo-Oxfordian Clay formation for a number of radionuclides released from different waste packages in the French HLW disposal concept. Data from Andra (2005).

Reference Waste Package	Radionuclide	Time after closure to maximum molar flux (a)
CU1	^{129}I	260 000
	^{36}Cl	180 000
	^{79}Se	400 000
C1/C2	^{129}I	460 000
	^{36}Cl	380 000
	^{79}Se	750 000
B2	^{129}I	465 000
	^{36}Cl	200 000
	^{79}Se	165 000

Comparison of the indicator ‘transport times through system compartments’ with the half-life of a radionuclide provides information about how much of a radionuclide’s inventory will decay during its transit through a compartment and, therefore, indicates the importance of individual radionuclides for long-term safety. Such comparisons are often used for the selection of radionuclides for which transport calculations will be made in the safety assessment.

In simple terms, the status of barriers indicators provide information on the time-dependent processes that control the evolution of system components, such as the slow corrosion of metallic containers that ultimately will lead to failure and loss of containment. Such indicators can be useful for comparing different design alternatives. In some recent assessments, however, the status of barrier indicators have been replaced by safety function indicators because one objective of an assessment is to determine whether particular barriers meet specific requirements that underpin the safety concept for a given repository design.

5.4 Assessment of the status of repository safety functions

The performance indicators presented in Section 5.3 are intended to quantify the contribution of the main components of the repository to the containment provided by the entire disposal system and, therefore, illustrate the role and efficiency of each barrier. In recent years there has been a trend in the development of safety cases to present a geological repository as an integrated system with multiple safety functions, that are provided by the multi-barrier concept. In this context, indicators have been developed, which are intended to allow the efficiency and the status of safety functions to be quantitatively assessed by comparison with specific safety function indicator criteria.

It is clear that both safety function indicators and performance indicators relate to the evaluation of system components or sub-systems. Given their similarity, safety function indicators can be considered as a special case and application of performance indicators. The difference between them lies in the quantitative requirement for a safety function indicator to be compared with specific indicator criteria, whereas performance indicators need not always have a matching reference value for comparison.

The application of indicators related to safety functions is illustrated by the example of the Belgian safety and feasibility case ‘SFC1’ for HLW disposal in the Boom Clay. For this repository concept, a long-term safety strategy has been developed that is based on two main safety functions (ONDRAF/NIRAS, 2009):

- the safety function ‘containment’ (C) which is provided by a long-lived carbon steel overpack; and
- the safety function ‘limited and delayed release’ (R) which has three sub-safety functions of ‘slow release’ (R1), ‘limited water flow’ (R2) and ‘retardation’ (R3).

A set of indicators was also developed that quantify the contribution of the safety functions to the overall performance of the repository system (Marivoet *et al.*, 2010; Weetjens *et al.*, 2010). These safety function indicators are defined as:

- containment (PIC): the activity in each waste package at time of overpack/canister failure (t1) divided by the initial activity in the waste at the time of its disposal;
- limitation of release (PIR1): the activity released from each waste package at time t divided by the activity in the waste package at time t1;
- retardation (PIR3): the activity released from the host formation at time t divided by the activity released from waste package at time t.

The product of these 3 indicators provides a quantitative measure of the performance of the integrated repository system (IRS) which is represented by the containment factor indicator:

$$PI_{IRS}(t) = PI_{C} \times PI_{R1}(t) \times PI_{R3}(t)$$

This represents the activity released from the host formation to the biosphere at time t divided by the initial activity in the waste at the time of its disposal. The values for these indicators calculated for a number of fission and activation products are given in Table 11.

Table 11: Performance indicators of the contribution of each safety function in the Belgian HLW repository concept, calculated for a 10 million year period. From Weetjens *et al.* (2010).

Radionuclide	PI_C	PI_{R1}	PI_{R3}	PI_{IRS}
^{14}C	5.46×10^{-01}	3.48×10^{-02}	1.70×10^{-04}	3.24×10^{-06}
^{36}Cl	9.89×10^{-01}	4.93×10^{-01}	6.92×10^{-01}	3.37×10^{-01}
^{59}Ni	9.55×10^{-01}	8.36×10^{-01}	4.61×10^{-05}	3.68×10^{-05}
^{79}Se	9.88×10^{-01}	2.21×10^{-01}	7.62×10^{-01}	1.67×10^{-01}
^{93}Zr	9.98×10^{-01}	8.12×10^{-01}	1.99×10^{-03}	1.61×10^{-03}
^{94}Nb	8.43×10^{-01}	5.74×10^{-01}	2.70×10^{-09}	1.31×10^{-09}
^{99}Tc	9.84×10^{-01}	2.91×10^{-02}	6.88×10^{-01}	1.97×10^{-02}
^{107}Pd	9.99×10^{-01}	3.63×10^{-01}	6.20×10^{-01}	2.25×10^{-01}
^{126}Sn	9.83×10^{-01}	3.00×10^{-01}	3.35×10^{-02}	9.88×10^{-03}
^{129}I	1.00	9.79×10^{-01}	9.93×10^{-01}	9.72×10^{-01}
^{135}Cs	9.98×10^{-01}	8.66×10^{-01}	6.65×10^{-08}	5.75×10^{-08}

Of the radionuclides considered, only ^{14}C has undergone significant radioactive decay during the containment period. For ^{129}I, none of the three safety functions is effective in reducing its activity because of its long half-life and relatively high mobility. For ^{36}Cl the safety function 'limitation of release' (provided by the waste matrix) gives a significant contribution to the containment of this radionuclide. For ^{59}Ni, ^{93}Zr, ^{94}Nb, ^{126}Sn and ^{135}Cs the sorption on the Boom Clay ensures a high contribution to the safety function 'retardation'. For ^{79}Se, it is the safety function 'limitation of release' (provided by a combination of the waste matrix and low solubility) that gives the highest contribution to its containment. For ^{99}Tc and ^{107}Pd the safety function 'limitation of release' (mainly provided by their low solubility limits) gives the highest contribution to their containment in the repository system. In the last column, the values of the containment factor indicator for the integrated repository system clearly demonstrate for which radionuclides the repository system provides effective isolation and containment.

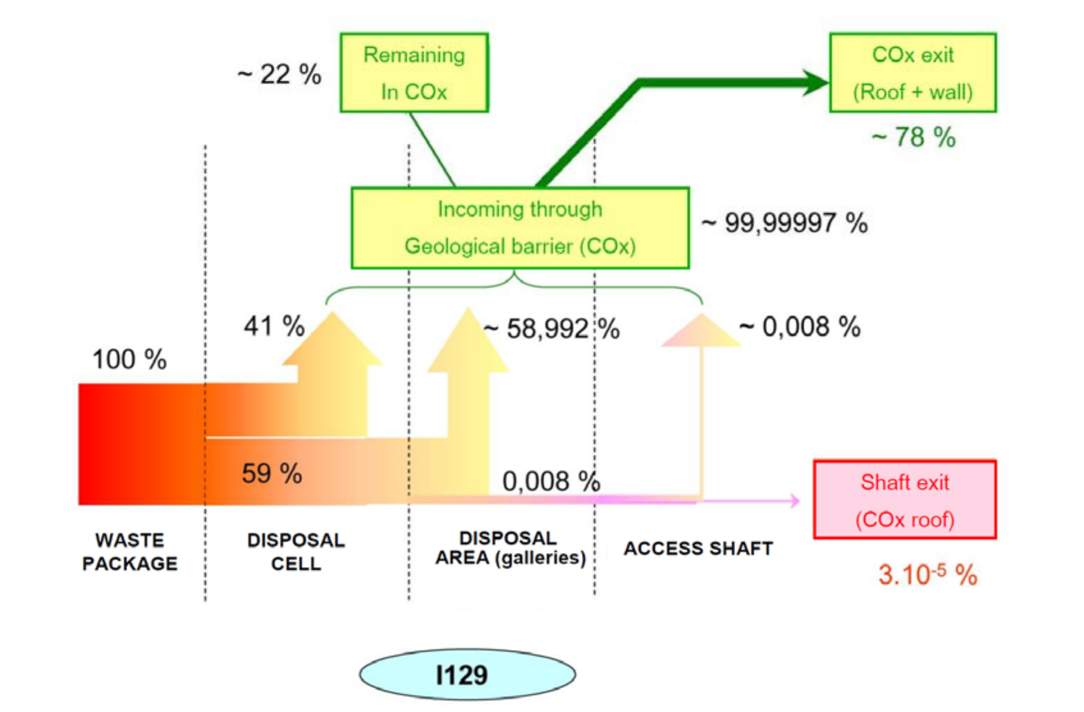
In its 'Dossier 2005' safety case for the disposal of HLW and spent fuel in the Callovo-Oxfordian Clay formation in France, Andra also applied indicators to evaluate the safety functions of the repository and its components. The three main safety functions considered were:

- resisting water circulation;
- limiting the release of radionuclides and immobilising them in the repository; and
- delaying and reducing the migration of radionuclides.

The indicators used to evaluate these safety functions were:

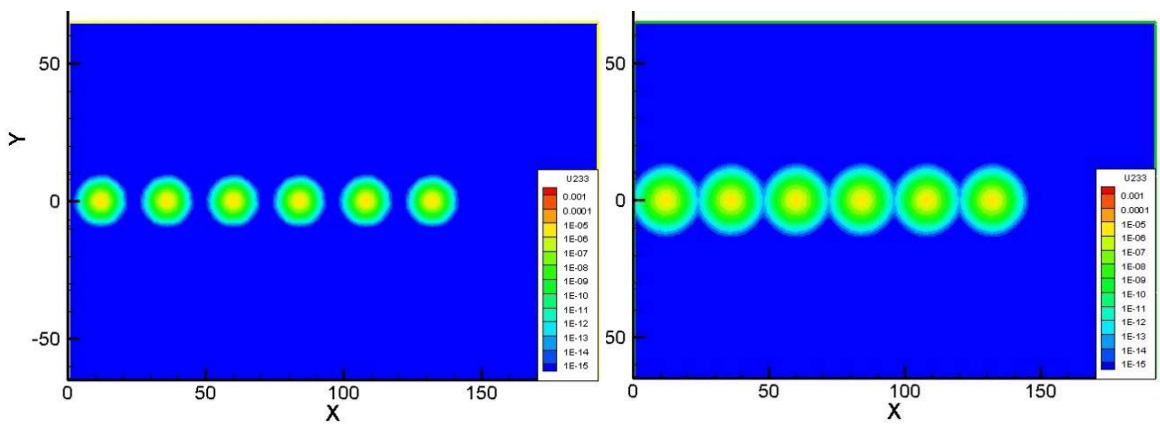
- advective and diffusive flow indicators: Péclet numbers were calculated as well as the contributions of diffusive and advective flux to the total flux;
- the radionuclide mass distribution between the repository structures (e.g. disposal galleries, access ramps, shafts etc.) and the unaltered host clay rock. As an example, the distribution of ^{129}I mass flow through the different repository compartments is illustrated in Figure 9, which shows that only a very small fraction of the ^{129}I migrates through the sealed access shaft;

Figure 9: The distribution of ^{129}I in different repository compartments, calculated for the normal evolution scenario for the French spent fuel repository in Callovo-Oxfordian clay (COX). From Andra (2005).



- the radionuclide activity and/or molar flux released from each repository component (e.g. waste container, disposal cell, host rock) which helps in assessing the ability of each component, and particularly the host rock, to achieve the safety function of 'delaying and reducing the migration of radionuclides', as indicated in Figure 10;
- the distribution of dissolved radionuclide concentrations in the host clay rock and in the surrounding and overlying sedimentary formations.

Figure 10: The concentration (mol/m3) of ^{233}U in the near field of the French spent fuel repository at 200,000 years (left) and 500 000 years (right). From Andra (2005).



The concept of safety function indicators has been developed further by SKB in its recent safety cases for spent fuel disposal in Sweden (SKB, 2006; SKB, 2011), in which safety function indicators were used to identify scenarios and to derive calculation cases for the safety assessment, as described in more detail in Appendix A1.2. The primary safety function of the KBS-3 concept is to completely contain the spent fuel within canisters with a corrosion resistant copper shell over the entire assessment period. Should a canister be damaged, the secondary safety function is to retard any releases from the canisters. It is noted that the containment function is prominent in the KBS-3 concept, reflecting the methodology and structure of the safety assessment for KBS-3, which focuses on the containment provided by the engineered components, in particular on the canister and buffer (SKB, 2011). The containment function is comparatively less emphasised in some other repository concepts which are based on disposal concepts in low permeability argillaceous rocks (e.g. in Switzerland and France).

Containment is also the primary safety function for the German concept for HLW disposal in rock salt but, in this case, containment is provided by both the geological and engineered components of the system (BMU, 2010). In this concept, calculated stresses and pressures within the surrounding host rock (the containment providing rock zone) can be used as indicators for the integrity of the geological barrier, although the applicable criteria (dilatancy criterion, brine pressure criterion) are more complex than the definition of a single reference value.

In the Swedish KBS-3 concept, understanding and evaluating repository safety in a detailed and quantitative manner is achieved through an elaborate description of how the main safety functions of containment and retardation are fulfilled by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of safety functions subordinate to containment and retardation are identified. In this context, a safety function of the KBS-3 concept is defined qualitatively as a role through which a repository component contributes to safety. For example, high isostatic loads could jeopardise the containment function of the canisters. Should the pore water of the buffer freeze, this could lead to a considerably increased isostatic load on the canister. A safety function related to the buffer and subordinate to containment would, therefore, be the buffer remaining in a non-frozen state.

To evaluate safety quantitatively, it is desirable to relate or express the safety functions to measurable or calculable quantities, often expressed in the form of barrier conditions. For example, in the case of the buffer function relating to freezing, the buffer temperature is an obvious quantity to use in order to evaluate the extent to which this function is fulfilled. The buffer temperature is, therefore, a safety function indicator for the buffer function. A safety function indicator needs to be a measurable or calculable quantity through against which the corresponding safety function can be quantitatively evaluated.

To determine whether a safety function is fulfilled or not, it is desirable to have quantitative criteria against which the safety function indicators can be compared. The situation is, however, different from safety evaluations of many other technical or industrial systems in one important sense: the performance of the entire repository system or its component parts do not, in general, change in discrete steps, compared to, for example, a pump or a power system that could be characterised as either functioning or not. The repository system will evolve continuously and, in many respects, there will be no sharp distinction between acceptable performance and a failed system or a sub-system, or regarding detailed barrier features. There are, therefore, many safety function indicators for which no limit for acceptable performance can be given. The groundwater concentrations of chemical species corrosive to the copper canister or that may react with the buffer are examples of this kind of factor related to containment. Usually, these issues are addressed in more complex analyses where a number of parameters together determine whether a safety function is maintained. Most of the factors determining retardation are also of this nature.

Nevertheless, there are some crucial barrier properties on which quantitative limits can be put. Regarding containment, an obvious condition is the requirement that the copper canister should nowhere be penetrated, i.e. there should, over the entire surface of the canister, be a non-zero copper thickness. In addition to this direct measure of containment performance, a number of quantitative supplementary criteria can also be defined. These relate, for example, to the peak temperature in the buffer and to requirements on buffer density and buffer swelling pressure giving favourable buffer properties for maintaining containment. Most of these quantitative limits determine whether certain potentially detrimental processes can be excluded from the assessment. A safety function indicator criterion is, thus, a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is upheld. In the buffer freezing example, the safety function indicator criterion is that a buffer temperature exceeding –4 °C is required to avoid freezing.

It is emphasised that the breaching of a safety function indicator criterion does not mean that the repository is unsafe, but rather that more elaborate analyses and data are needed to evaluate safety in that case (SKB, 2011). The indicator criteria are an aid in determining whether safety is maintained. If the criteria are fulfilled, the safety evaluation is enhanced but fulfilment of criteria alone is not a guarantee that the overall risk criterion can be met. On the other hand, compliance with the risk criterion could well be compatible with failure to meet one or several of the safety function indicator criteria. Such a case would require further analyses to determine the consequences on a sub-system level or a system level.

An example is the criterion that the groundwater cation charge concentration should exceed 4 mM so that buffer erosion can be excluded from the assessment. If this criterion is not met, buffer erosion must be quantitatively evaluated and its consequence in terms of reduced buffer density needs to be propagated to assessments of, for example, buffer swelling pressure and hydraulic conductivity. Any changes to the hydraulic parameters in the buffer could, in turn, influence canister corrosion. A chain of assessments is, therefore, initiated by the failure to meet the first safety function, but the final outcome of a possibly increased corrosion rate does not necessarily have an unacceptable impact on overall repository safety.

The chain of assessments arises because many safety functions are related to other safety functions due to the coupled nature of repository processes. So, for example, safety functions related to the buffer either support safety functions related to the canister, or contribute to retardation in the buffer. Similarly, all safety functions related to the host rock either support a safety function related to the canister directly or indirectly, via a buffer safety function, or contribute to retardation in the rock.

Safety functions are related to, but not the same as, design criteria (SKB, 2011). Whereas design criteria relate to the initial ('as built') state of the repository and, primarily, to its engineered components, safety functions should be fulfilled throughout the assessment period and relate, in addition to the engineered components, to the natural system.

5.5 Scenario identification

A so far unique example for the application of indicators contributing to the identification and selection of scenarios is given by the Swedish SR-site safety assessment (SKB, 2011). In this assessment, a set of safety function indicators were used to identify a set of altered evolution scenarios (in addition to the main scenario) using a structured approach that was intended to provide a comprehensive and critical evaluation of long-term safety of the repository. This case is described in more detail in Appendix A1.2.

The primary safety function of the Swedish KBS-3 concept is to completely contain the spent nuclear fuel within canisters with a corrosion resistant copper shell over the entire assessment period. Should a canister be damaged, the secondary safety function is to retard any releases from the canisters (SKB, 2011). Additionally a number of subordinate safety functions are introduced, which are related to the canister itself, the buffer, the deposition tunnel backfill and the geosphere. The approach used by SKB is directly related to the primary safety function. It concerns the direct failure modes of the canister and how the buffer safety functions are related to these failure modes.

The approach taken in SR-Site is to use the safety functions with their corresponding safety function indicators and indicator criteria to define a set of scenarios that are distinguished by their different status of the safety functions. The scenarios thus consider cases where the possibility and consequences of partially or completely losing one or several of the safety functions are evaluated. Examples are scenarios where canisters fail due to corrosion, to isostatic overpressure or to shear movements in fractures intersecting the deposition hole (SKB, 2011).

The approach taken when selecting scenarios is thus to ask the question 'What characterises a failed repository?' The answer to that question is a list of states where one or several safety functions are not upheld (i.e. the safety function criteria are not fulfilled). One example of a state where this may occur is a situation in which advection is the dominant transport mechanism in the buffer. The analyses of the selected scenarios then focus on identifying and quantifying all conceivable routes by which those failed states may occur. The analyses consider in detail the initial states, and the processes and external conditions that may cause a failed state, and assess the impact against the set of safety function indicators. On that basis it is decided, whether or not it is unrealistic that a safety function indicator criteria is not fulfilled. If unrealistic, the corresponding scenario is considered as a so-called 'residual scenario' and is not included into the risk summation. In this case, the consequence calculations are performed only for illustration purposes. If the assessment shows that it is realistic for a safety function indicator criterion not to be fulfilled, the probability of the scenario is estimated, consequence calculations are performed and the results are included in the risk summation.

In summary, the scenario methodology is an investigation of all routes to canister failure aimed at either ruling them out or quantifying them, considering all conceivable evolutions of the system. The safety functions of the repository components with their indicators and the understanding of the development of the repository system emerging from the analysis of the reference evolution form the basis for exhaustive evaluations of such routes.

5.6 Addressing uncertainty and the assessment of repository safety in different timeframes

Appropriate handling of uncertainty is one of the most important issues for building confidence. There are different forms of uncertainty that need to be addressed in safety assessments and safety cases, and these can be categorised as (Mönig *et al*., 2012):

- *Scenario uncertainties*: Scenario uncertainties arise because it is not known for certain how the repository system will evolve over time.
- *Model uncertainties*: Model uncertainties arise from an incomplete knowledge or lack of understanding of the behaviour of engineered systems, physical processes, site characteristics and their representation using model abstractions and computer codes. It may be possible to model the relevant features, events, and processes (FEPs)

using alternative conceptual models that equally well represent the available data. Model uncertainties may also be introduced by uncertainties in the boundary conditions appropriate for the model calculations.

- *Data and parameter uncertainties*: These uncertainties are associated with the values of the parameters used in safety and performance assessment models. They arise because data may be difficult to measure or are unavailable. Certain parameters required for safety and performance assessments will be for properties which are not only uncertain but are also spatially variable. The characterisation of such variability may lead to additional uncertainty.

In general terms, therefore, uncertainty relates to limitations in our ability to describe qualitatively and quantitatively the long-term evolution of the repository, and to assess its impacts. The levels of uncertainty that apply are not uniform across time and space. As indicated in Figure 11, conceptual, model and parameter uncertainties all generally increase from the engineered barriers out to the humans. Uncertainty also generally increases over assessment time periods, particularly when substantial future climatic change events will inevitably alter the surface and human environments.

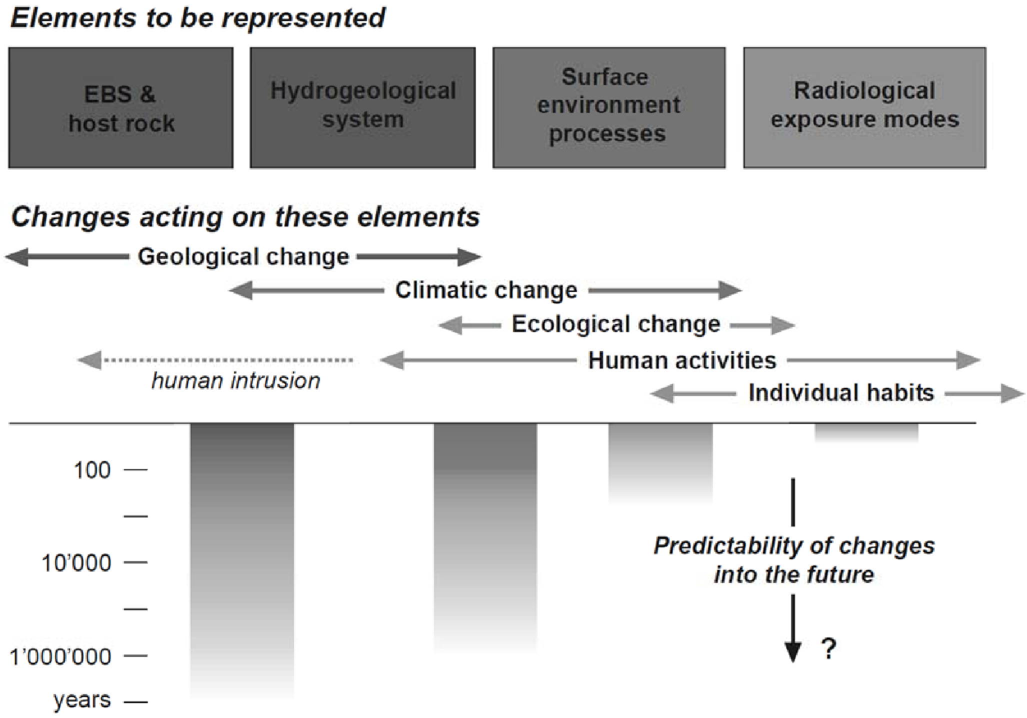
It should be noted, however, that over time the radiological hazard also reduces due to radioactive decay. The reduction in inventory (e.g. total radiotoxicity of the waste over time) may be a useful indicator to demonstrate how the hazard reduces and, in part, offsets the uncertainty associated with the evolution of the repository system. This combination of spatial and temporal uncertainty means that the most uncertain part of the entire repository system is the far-future exposure pathways to humans. As a consequence, future radiological dose and risk calculations based on exposure pathways are fundamentally uncertain. Although the uncertainty associated with dose and risk in the safety case can be managed by considering a number of reference biospheres, complementary indicators provide another way to handle it.

In simple terms, performance indicators can be used to evaluate the containment capacity provided by the engineered barriers and deep rock. As shown in Figure 11, this is the part of the repository system that is subject to the least scenario, model and data uncertainties because evolution of the wasteform and engineered barriers is largely controlled by well understood and predictable physical and chemical processes. Overall, therefore, performance indicators should be the most certain of all possible calculation end-points.

Safety indicators that measure total repository release will be subject to greater uncertainty than performance indicators. This is because the shallow groundwater flowpaths, that are the primary process causing radionuclide release to the surface environment, will vary over time in response to climatic and geomorphological changes. This increases both conceptual and parameter uncertainty. In addition to the physical and chemical processes controlling environmental change, natural biological processes will also apply and can influence the fluxes and concentrations in the surface environment, further increasing uncertainty. This means that fluxes and concentrations within the surface environment may be more uncertain than those at depth below the geosphere-biosphere interface.

Nonetheless, all flux and concentration based safety indicators will be significantly less uncertain than the dose and risk calculations. This is because, to calculate dose, assumptions must be made for future human behaviour and this is as much controlled by unpredictable socio-economic factors as it is physical or chemical ones. Given this analysis, a hierarchy of indicator uncertainty can be established. The actual detail may vary according to the nature of the repository concept and the host geological environment, but a generic hierarchy starting with the least uncertain indicator to the most might be as illustrated in Table 12.

Figure 11: Variation in the predictability of the main repository components, against assessment time. From NEA (1999).



The objective of establishing a hierarchy is not to suggest one type of indicator is better than another. In a safety case, a number of different indicators should be used and it should be explained that the benefits of one can be used to balance the uncertainty in the other. Thus the benefits comes from using a set of complementary indicators rather than any specific 'best' indicator.

In this regard, it should be noted that complementary indicators may help to manage scenario and data uncertainty (compared to dose and risk) but they do not generally reduce model uncertainty. This is because the safety and performance indicators would usually be calculated as interim calculation end-points from the safety assessment models, and so the same modelling uncertainty applied in all cases. The exception would be in cases where a different model was used to calculate the complementary indicators but this may introduce further difficulties when comparing results.

Table 12: Hierarchy of indicators by increasing uncertainty.

Indicator	Category	
Radionuclide concentration in wasteform (inventory)	Performance indicators	Complementary indicators
Radionuclide flux to the engineered barriers		
Radionuclide concentration in the engineered barriers		
Radionuclide flux to deep rock		
Radionuclide concentration in deep groundwater		
Radionuclide flux to shallow rock	Safety indicators	
Radionuclide concentration in shallow groundwater		
Radionuclide flux across the geosphere-biosphere interface		
Radionuclide concentrations in surface compartments		
Dose		Primary indicators
Risk		

As part of the handling of uncertainty in the safety case, it can be useful to present a range of different indicators for different timeframes (NEA, 2009b). For example, in the early time period, when there least uncertainty, in addition to the dose calculations, a set of performance or safety function indicators may be used to assess the containment function provided by the wasteform, canister and other man-made barrier systems. As assessment timeframes and uncertainty increase, greater emphasis may be placed on safety indicators to provide a measure of total system safety. As discussed in Section 6.4, uncertainties will also affect reference values as well as the complementary indicators. Reference values for performance indicators (and safety function indicators) are likely to be established from either expert judgement or by calculation, and so may be subject to all three forms of uncertainty.

Reference values for comparison to safety indicators may be derived from natural systems and so are subject to analytical uncertainties associated with measurement methods but also due to natural variations. For example, if natural radionuclide concentrations in river water are used as a reference values, these would be spatially variable (along and between rivers depending on the geological setting) and also temporally variable, affected by weather, seasons and climate on increasing timescales.

5.7 Communication with non-technical audiences

One of the objectives of preparing a safety case should be to ensure it is accessible and understandable to a wide range of audiences, including non-technical readers. This is, perhaps, most important for safety cases produced to support site selection, when members of the public need to understand the potential consequences of hosting a repository in their local community.

An inherent problem with conventional radiological safety assessments is that they are largely incomprehensible to many readers because they present the potential health, safety and environmental impacts of a repository using measures and words that have no everyday meaning. Units such as Becquerels and Sieverts are not part of people's normal experience, and terms such as 'risk' are not used in the conventional sense of the word.

There is very limited experience internationally of using complementary indicators to help make safety cases more accessible and understandable for non-technical audiences, and so this Status Report makes some suggestions for how they may be applied and tested in the future. By using a range of complementary indicators in a safety case, its appeal can be widened to a larger audience. In particular, using indicators may provide four very important benefits:

- local context,
- comprehensible timescales,
- impact significance, and
- two-way engagement.

Local context comes from presenting the potential impacts of the repository in terms of the local environment. Once a potential site for a repository has been identified, it is possible to develop indicators with local significance. So, although the safety assessment may focus on, for example, dose to a hypothetical future exposed population engaged in subsistence farming, complementary indicators could present these impacts in terms of the present day environment and community. This will enable people to appreciate what the consequences of the repository may be for them and their children, and the things they value. It should be possible, for example, to develop a set of indicators that match and answer the questions that most concern local residents, for example:

Question of concern	Matching indicator / reference value
Will the local river be polluted?	Concentration of waste derived radionuclides in local river water compared to present day tap water quality.
Can I continue to grow fruit and vegetables in my garden?	Concentration of waste derived radionuclides in local soils compared to present day soil quality.
Will my great grandchildren be able to swim at the nearby beach in summer?	Amount of waste derived contamination that will accumulate on the foreshore over the next two hundred years.

As an example of using local context, Nagra (2002) compared calculated radiotoxicity fluxes from the repository to three different natural Swiss waters (the biosphere aquifer, and the waters from the rivers Rhine and Thur) and the indicator radiotoxicity of the wastes to the abundance of naturally occurring radionuclides in both the Opalinus Clay and three different uranium ores of different grade, as shown in Figure 12.

Comprehensible timescales means applying indicators over the assessment timescales that most people are concerned with, which rarely extends beyond the lifetime of the next few generations (their children and grandchildren). This can be important because with most deep repository designs it is extremely unlikely that any releases to the surface will occur within the lifetime of many generations of local residents. Safety assessments therefore generally focus on the far future and on unlikely (conservative) failure scenarios. This approach, whilst technically valid, can give a false and pessimistic sense of the actual expected impacts which can be misleading to non-technical readers.

Indicators that combine the most likely estimates of consequences to the local people and environment, over the timescales they are concerned with (properly explained and presented) should enable readers to comprehend the situation. If no impacts are expected because containment is total, then repository developers should not avoid using indicators that show that.

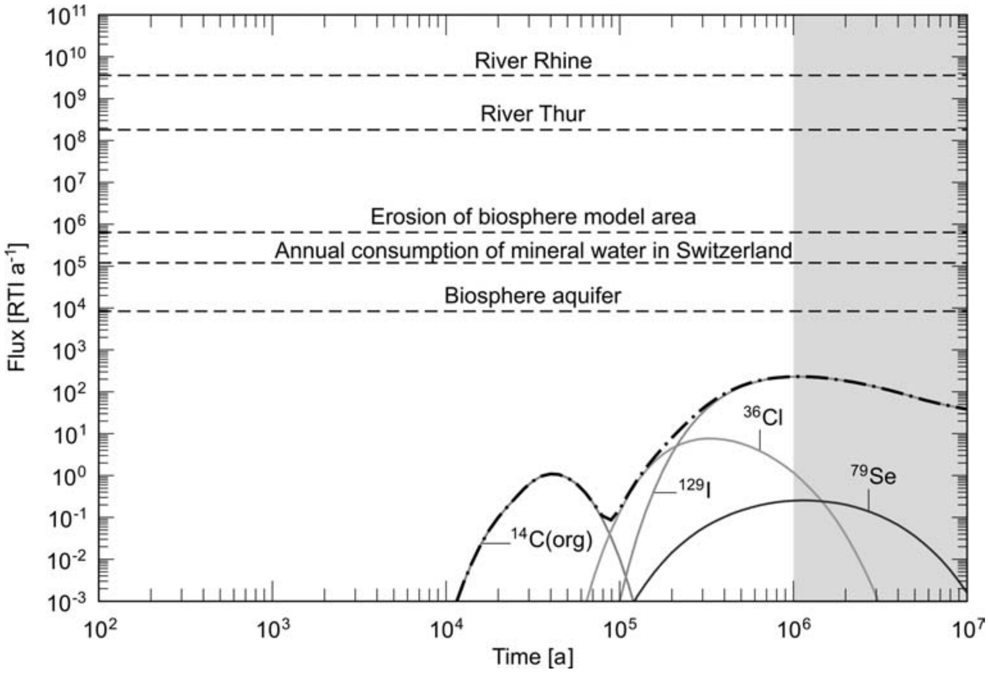
Impact significance means presenting the potential consequences of the repository using units and measures that people understand. Most people do not comprehend a Sievert and so cannot judge for themselves whether a dose of 0.1 mSv/a is indeed high and a cause for concern, or so low as to be of no concern. Most people do, however, know what a kilogram is and so could make a judgement about the ability of the repository to contain the waste if they are told that the amount of material that might return to the surface is only, for example, 0.0001 kg/a.

Suggesting an indicator of mass per year may be controversial for many safety assessors because mass is not intrinsically a measure of safety. However, seen in context, people are frequently told that repositories are needed to contain many thousands of tonnes of waste and, so, calculating how much of this waste can ever get back to the surface is a fundamental measure of how well the repository achieves its intended purpose of containment and isolation.

Two-way engagement comes from working with public and stakeholders to ask them what complementary indicators they would like to see in a safety case, and then making efforts to present them in a clear and unbiased manner. It is possible that two-way engagement could lead to a set of indicators that is significantly different to those that would be suggested by safety assessors (those recommended in the SPIN Project, for example). The important point is not that the indicators asked for by the public should replace the more technically focussed ones, but that they should all be presented collectively, and in a complementary manner.

The broader point here is that repository safety and performance needs to be presented using a wide range of measures and units, so that readers can choose for themselves which is most meaningful (to them) and enables them to understand the likely significance of the repository impacts. It should be recognised that safety means different things to different people, and that the measures of radiological safety are, by themselves, unlikely to engender a sense of 'feeling safe' with the majority of people.

Figure 12: Radiotoxicity flux, for the Reference Case, from the repository (summed over all waste types) at the boundary Opalinus Clay – confining units, compared with a range of radiotoxicity fluxes due to naturally occurring radionuclides. From Nagra (2002).



5.8 Site/formation selection

The application of indicators to site selection or formation selection is obviously related to the transferability of indicators. If used for the selection of a site or formation out of a number of potential candidates, the indicator(s) used need to be transferable. Thus, this section starts with a discussion on the transferability of indicators before illustrating the use of indicators for site selection. In respect to transferability, safety and performance indicators appear to be quite different.

Safety indicators are a measure for the overall safety of the repository system. From this quality of safety indicators it can be reasoned that they have to be applicable in general, provided that the characteristics of the safe state of a repository is specified in the same way for all repositories. This seems to be the case, at least in terms of qualitative transferability, as long as the indicator is related to concentration, such as 'effective dose rate' or a corresponding risk limit is used. The safety statement, that human health is not jeopardised by radionuclides released from the repository under consideration can be derived from the indicator 'dose rate' if the interrelation between dose rate and impact on human health is known.

Quantitative differences might exist between different countries with respect to the defined dose rate or risk limit, because assumptions about the effects of small doses differ to some extent. Quantitative differences also exist with respect to the expected duration of validity of the indicator in different countries. But, beside this quantitative difference, there is agreement in principle about the effect which ionising radiation might have on human health (e.g. ICRP, 2007; UNSCEAR, 2001, 2006, 2010). Therefore, the safety indicator 'dose rate' is applicable in general, no matter which type of repository in which host rock type is under consideration, and which type of radioactive waste it contains.

The only determining factors are the amount and point in space and time of the release of radionuclides into the biosphere.

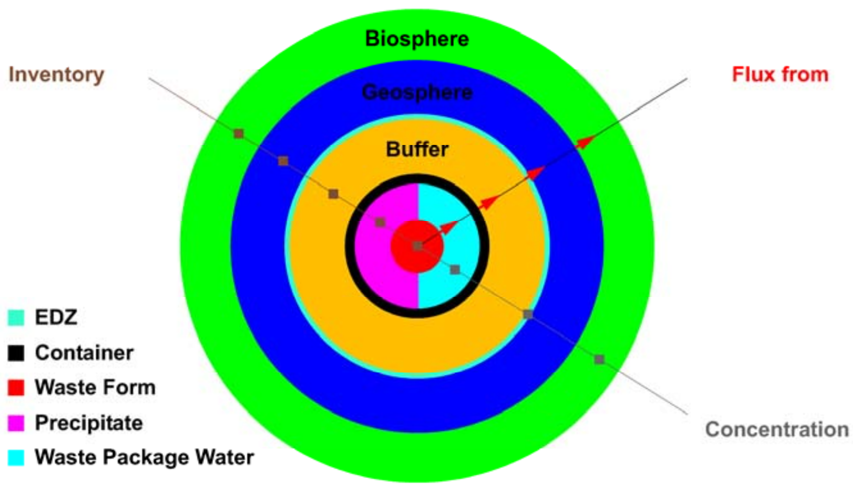
In other words, the concentration related safety indicator 'effective dose rate' (or a corresponding risk) is a generally applicable and transferrable indicator, because the interrelation between a certain dose rate and human health is always the same, independent of repository concept, host rock type and waste type. The same is true for other complementary indicators which are calculated like the dose rate from the activity concentration in biosphere water using specific conversion factors, such as the ingestion dose coefficients for calculating radiotoxicity.

The situation is slightly different for safety indicators based on flux, such as 'radiotoxicity flux from the geosphere'. This is because natural radiotoxicity fluxes (as absolute flux through a given cross section, Sievert per time) can differ by several orders of magnitude in different geological environments, meaning that the safety statement derived from this safety indicator is not in all cases the same, but depends on the (local) reference value that is used for comparison.

In contrast to safety indicators, performance indicators depend much more on the respective repository concept and design, including the host-rock formation. One important reason is the different safety and repository concepts, and the resulting different structure of models used for near-field calculations. For crystalline rocks, the radionuclide release from one container is usually assumed to be independent from all others and calculated representatively for only one or a limited number of containers failed at a given time. This suggests a compartment structure as shown in Figure 13.

The container representing one or a group of containers with radioactive waste is surrounded by a bentonite buffer, which itself is surrounded by the host rock. Finally, the biosphere compartment forms the outer rim of the compartment structure. A similar structure may also be used for a repository in clay formations but a different structure applies for repositories in rock salt. In this case, different emplacement areas which are not independent of each other are typically considered in the assessment because contaminated brine might be transported by convergence-driven advective flow through the drifts from one disposal area to the other, and mixing processes may take place. This is taken into account by using different model compartments for each of the disposal areas and by other model compartments representing the drifts and shafts of repository (Wolf *et al.*, 2008).

Figure 13: Compartment structure for a repository in granite. From Becker *et al.* (2003).



Furthermore, there are performance indicators that are applicable to only one specific formation or design concept. One example is the indicator 'closure time for plugs and seals in rock salt' (NRG, 2000), which is comparable to the safety function indicators discussed previously. The closure processes for plugs and seals, in particular the consequences for modelling, is specific for rock salt formations. Seals and plugs are made of rock salt and will reach the permeability of undisturbed rock salt by compaction after a certain period of time. At this point they are regarded in the models to be no longer permeable, i.e. no more fluid flow through these barriers is possible after closure of the plugs and seals. Another example is the state of stress, which can serve as an indicator for the integrity of the geological barrier in a salt dome. As long as the applied load on the salt rock is below the dilatancy boundary, any deformation of the salt due to creeping processes will not impair the barriers tightness.

Therefore, it is not directly evident that performance indicators can be used to compare the behaviour of different repository concepts, particularly in different rock types. Nevertheless, recently an attempt has been undertaken within the German VerSi project to apply indicators to support siting of a HLW repository by evaluating the potential containment capacity of alternative host rocks (Resele *et al.*, 2011). In this project, a set of three indicators based on the radiotoxicity fluxes from the containment providing rock zone were introduced to measure the relative performance of repositories in different host rocks. For each indicator a criterion of insignificance was adopted. Indicator values smaller than this criterion are considered to be equal to a zero-release from the repository. This criterion was necessary to facilitate the comparison because, in the case of a repository in salt host rock, scenarios with no releases are possible. The VerSi project is described in greater detail, including the definition of the indicators, in Appendix A1.1.

5.9 System design and optimisation

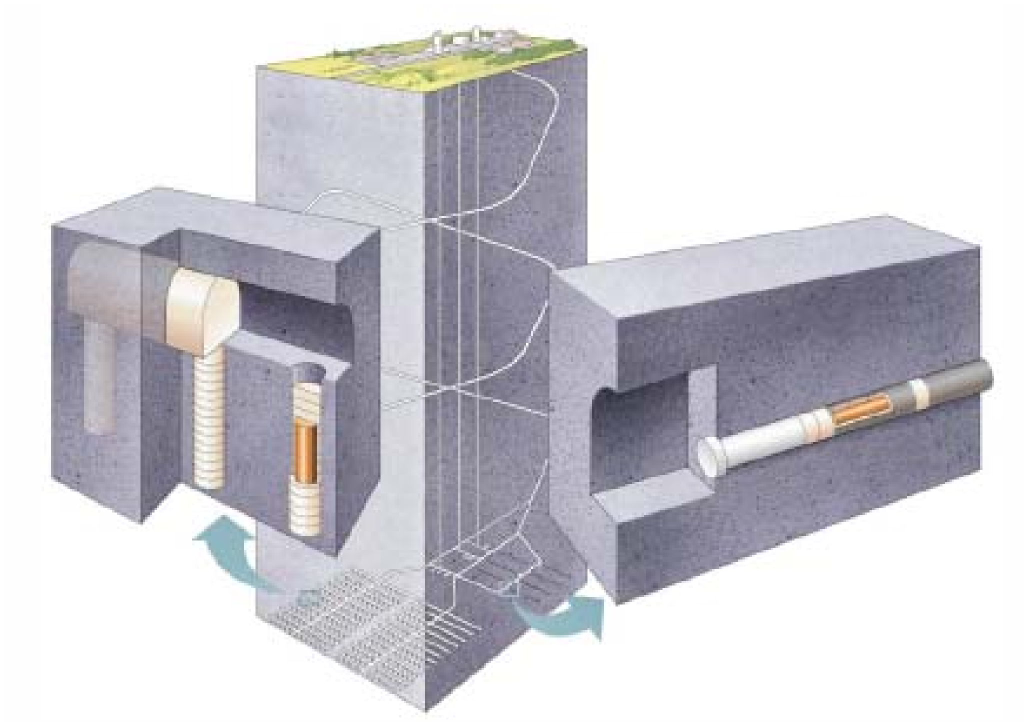
The application of complementary indicators to repository system design and optimisation is a relatively new development, although it has been common place to compare the assessed containment of alternative design in performance assessments.

The advantage of using complementary indicators is that they provide a structured approach to the comparison of design alternatives that is both transparent and auditable. By using a number of different but relevant safety and performance indicators, the various attributes of interest can be readily compared and contrasted. For example, they will allow the balance between containment capacity of the engineered barriers and the rock to be compared for different repository designs. In a similar manner, once a preferred design has been chosen and a site characterised, performance indicators may be used to optimise the design against known subsurface conditions, and to ensure the overall cost and effort for constructing the repository are not excessive.

To date, however, complementary indicators have rarely been applied explicitly in a structured manner in such comparisons. One example where it has been done with success is the KBS-3 concept for the disposal of spent fuel which has been the subject of collaboration between SKB (Sweden) and Posiva (Finland) who have compared two design variants. In the KBS-3V variant, copper canisters are emplaced individually in vertical disposal holes located in the floor of a disposal tunnel whilst, in the KBS-3H variant, multiple containers are emplaced horizontally along the axis of long disposal tunnels, as shown in Figure 14.

The comparison of the design variants has involved practical work in the Äspö Hard Rock Laboratory and parallel safety assessment modelling (Posiva, 2008). The safety assessment of KBS-3H made use of safety functions and safety function indicators using the same approach applied to assessment of KBS-3V within the SR-Can safety assessment (SKB, 2006). A systematic 'difference analysis' was then made between the KBS-3H and KBS-3V assessment results, and conclusions were drawn regarding how each design variant performed against the safety functions. That difference analysis showed that the most significant differences in the performance of the KBS-3H and KBS-3V designs relate mainly to the engineered barrier system and to the impact of local variations in the rate of groundwater inflow on buffer saturation along the drifts. The safety functions of the geosphere did generally not differ significantly between the two designs.

Figure 14: Left: The KBS-3 method with vertical emplacement of the canisters (KBS-3V) which is the reference design. Right: The KBS-3 method with horizontal emplacement of the canisters in up to 300 m-long deposition drifts (KBS-3H). From Posiva (2008).



The comparative analysis of the KBS-3H design is not yet completed but the approach of using safety function indicators in a structured manner to enable the comparison of design alternatives has been shown to be promising, and worthy of further investigation.

5.10 Repository monitoring

In general, monitoring can be defined as continual checking, supervising, critically observing or determining the status of a system to identify any change from the performance level required or expected. In the case of a repository, monitoring will inevitably take place during the operational phase and may continue into the post-closure phase. The concept of geological disposal is, however, based on a 'passive safety' strategy and post-closure monitoring is not necessary to provide for safety. Nonetheless, post-closure monitoring may enhance public and stakeholder confidence, and so is very likely to be performed at most facilities. Various monitoring objectives have been identified for both the operational and post-closure phases, including (IAEA, 2001):

- Supporting management decisions in a staged programme of repository development by:
  - monitoring conditions of emplaced waste packages
  - monitoring repository structures and the host rock

  - monitoring backfill and seals
- Strengthening understanding of system behaviour
- Assisting societal decision making
- Accumulating an environmental database
- Supporting nuclear safeguards
- Making decisions based on monitoring information

All of these may contribute to decisions governing the stepwise disposal process and may also contribute to enhance stakeholder confidence in the process and the safety assessment. As a consequence, each of these objectives should be addressed by repository monitoring programmes (MoDeRn, 2011).

5.10.1 *The linkage between complementary indicators and repository monitoring*

If there were no technical limitations, all complementary indicators could be monitored. The safety assessments provide the expected development in time for each indicator value. As such, monitoring by measuring the indicator values would either confirm the expected behaviour or identify changes from the expected performance level. In that sense, all indicators could be used for 'confirmation monitoring' to verify and confirm the basis for the predicted behaviour of the repository system. Significantly, this application of indicators is characterised by the use of measured (observed) quantities rather than calculated ones, which is the case in most other applications of indicators.

There are, however, practical limitations to what can be monitored. It is difficult to monitor groundwater and radionuclide fluxes directly in the sub-surface and, consequently, monitoring may be restricted to measurements of radionuclide concentrations in the accessible parts of the repository system and the biosphere, without causing disturbance to the barrier system. Even though it makes good sense to monitor concentrations in these compartments, poor containment performance would generally only be noticed after very long periods of time (i.e. decades to centuries) because of the slow migration processes that would transport radionuclides from the near-field to the monitored areas

In contrast, several of the status of barrier indicators, such as SKB's safety function indictors, offer opportunities for more immediate confirmation through monitoring but still not all of these can be readily measured. Considering SKB's safety function indictors, measuring temperature and (bentonite) swelling pressure are within technological reach (and may potentially be done remotely in the post-closure phase using geophysical techniques), but measuring canister (copper) thickness and integrity, and hydraulic conductivity of the buffer would be far more difficult to achieve in the post-closure period.

It is clear that most complementary indicators have not been defined for monitoring purposes, but rather for safety assessment and explanation, and for establishing design requirement specifications. It is worthwhile, however, to consider the linkage between complementary indicators and monitoring, and identify what indicators amenable to measurement might be used to increase confidence in the repository safety assessment.

5.10.2 *Performance confirmation monitoring*

Performance confirmation is a specific form of monitoring that is undertaken in the period between waste emplacement and closure of the repository, when access to waste packages and direct measurements of the status of the near-field materials and components is possible. These direct measurements are then compared to model predictions (related to the safety assessment models), allowing the actual early stage evolution of the repository to be confirmed. Radionuclide containment should be absolute during this period, but other parameters such as temperature, stresses, water ingress etc. could be measured.

In the USA, performance confirmation is part of the regulatory requirements for the operating WIPP repository, following recommendations that the best activity to enhance stakeholder confidence in the safe and long-term performance of the repository is to monitor critical performance parameters during the long pre-closure phase of repository operations. As such, numerous physico-chemical processes have been identified that are substantial as well as conducive to confirmation measurement. Due to the nature of the salt host rock at WIPP, performance confirmation monitoring pays particular attention to brittle deformation in the engineered damaged zone (EDZ) and plastic deformational processes in the remainder of the host rock. This is because the safety strategy for the WIPP repository is based on slow plastic deformation to close all void spaces around the waste, so ensuring containment.

In certain sedimentary host rocks, it may also be especially important to confirm the limits and processes within the EDZ because it pertains to an initial increase in hydraulic permeability and the subsequent re-establishment of low permeability conditions due to self-sealing mechanisms. Process models for sedimentary rock usually consider diffusion-limited transfer, chemically reducing environments and sorption, all of which offer possibilities for confirmation by way of a long-term testing and monitoring programmes.

Another parameter particularly relevant to long term safety is the very low potential for water influx from the host rock into the repository excavations. While this would only be evident in the millennia after closure (due to the reestablishment of hydraulic equilibrium in the groundwater system), evidence for this slow evolution may very well be obtained by monitoring the potential water influx from the host rock into the repository during the operational phase.

Near-field monitoring methods might also be devised to measure possible chemical interactions between the host rock and groundwater, and reactive iron or concrete components of the engineered barrier materials. This could provide information on the slow processes of alteration and degradation of the near-field components that contribute to isolation of the waste.

6. REFERENCE VALUES AND INDICATOR CRITERIA

6.1 Defining reference values and indicator criteria

When applying measurable or calculable quantities, such as indicators, to the evaluation of safety relevant aspects of repository systems, it is often useful to compare these to 'yardsticks' that can be used to judge actual levels of safety and performance, e.g. the effectiveness of barriers or the acceptability of calculated safety levels. Such 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 (IAEA, 2003).

Consistent with the definitions of safety indicators, performance indicators and safety function indicators used in this report (see Section 3) a distinction is made between three types of yardsticks: reference values, indicator criteria and safety function indicator criteria.

1. *Reference values* must be used in combination with a safety indicator, and they are comparative values used to establish the acceptable level of impact for their corresponding indicators. To evaluate the calculated results for safety indicators, the results of a safety assessment must be compared with established reference values that indicate an adequate and acceptable level of safety. If a safety indicator is below the corresponding reference value, it can be stated that the repository is 'safe' with regard to the particular safety aspect being considered. Without a reference value, safety cannot be judged and, therefore, a reference value is a requirement when using safety indicators. Most complementary safety indicators and their reference values generally have no formal regulatory character and so may be defined by the safety assessor, although there are a few examples when they are specified by regulators, such as the case for the Finnish spent fuel repository, as described in Section 4.1.2. Here, the regulator has defined radionuclide specific constraints for activity releases for comparison with flux based indicators.

2. *Indicator criteria* are used in combination with performance indicators, although there is no requirement to have a criterion for each performance indicator. Performance indicators comprise a great variety of different types of indicators. For some performance indicators, relative comparisons may be of value, for example the same performance indicator may be calculated for alternative design options, to allow their comparative performance to be evaluated and compared. Such comparisons can lead to enhanced system understanding without defining any yardsticks and are often used in performance assessment during the phase of concept development and model setup. Less often, performance indicators may be used to present the results of calculations for specific scenarios for established designs and systems, such as the fluxes or concentrations outside of the engineered barriers. For this purpose, comparisons with yardsticks are more illustrative. Some performance indicators are defined by a ratio, e.g. the ratio of transport time of a radionuclide to its half-life or the ratio of the rate of advection

of a radionuclide to its rate of diffusion or Péclet number, (e.g. as is done in the French programme and described in Section 5.4). For this particular form of performance indicator, the yardstick is an implicit part of the definition.

3. *Safety function indicator criteria* are used in combination with safety function indicators. These criteria define the quantitative limits (maximum or minimum conditions) that are the boundary conditions under which the matching safety function may be maintained, and will generally be derived from independent studies. Although there is some similarity between performance indicators and safety function indicators (in so far as they both relate to the evaluation of system components or sub-systems) there is a fundamental difference with regards criteria because a safety function indicator should always be compared with a corresponding indicator criterion, whereas a performance indicator need not always have a matching criterion for comparison.

The distinction between reference values and other indicator criteria is used in this report to structure the discussion on yardsticks and is not meant to stipulate formal definitions and approaches for how to use indicators and corresponding yardsticks in a safety case. The use of indicators and corresponding yardsticks is highly dependent on the context of each national programme and the applicable national regulations. It is considered generally useful, however, to make a distinction in terminology between yardsticks that relate to total system safety (e.g. reference values) and those that relate to aspects of system performance (e.g. indicator criteria).

Independent from the classification of yardsticks, the derivation of such yardsticks is a crucial aspect to consider when applying complementary indicators in a safety case. Internationally recognised yardsticks are not available for all complementary indicators, and this is one reason why their use has not gained universal support (IAEA, 2005).

6.2 Sources of reference values and indicator criteria

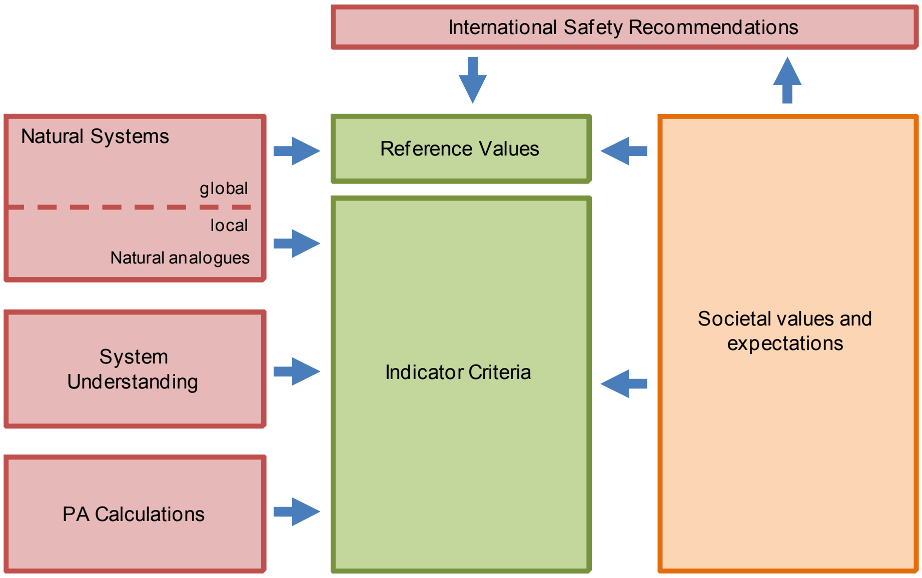
Reference values and indicator criteria may be derived from a number of sources, as indicated in Figure 15. National regulations typically provide the formal limits and constraints that are compared to the primary safety indicators of dose or risk.

Apart from the regulatory requirements, the following sources for reference values and indicator criteria for comparison with complementary indicators can be identified (IAEA, 2003):

- Safety recommendations from international organisations that may relate to radiological safety (e.g. guidance from the ICRP) or broader health and environmental safety (e.g. drinking water standards defined by the WHO).
- The principle that the repository should not significantly perturb the radiological or chemical conditions naturally present in the environment. Corresponding yardsticks can be derived from observations (measurements) of radionuclide concentrations and fluxes in nature averaged over both global and local scales.
- Consideration of the physical processes by which the safety functions of the disposal system are provided. Such yardsticks are directly derived from system understanding, which may be developed from combinations of modelling and laboratory studies.
- The results of calculations conducted in performance assessment. Typical values for specific quantities that may be used as yardsticks can be derived by such calculations (e.g. a critical minimum container lifetime).
- Societal values or expectations. The subjective perception of different risks in human society can influence the derivation of yardsticks from other sources (e.g. by using safety margins to meet the safety culture in different countries) but also stakeholder

expectations may derive minimum performance requirements as part of negotiations for a local community hosting a repository.

Figure 15: Sources of references values and indicator criteria.



6.2.1 *Reference values and indicator criteria derived from natural systems*

An independent, objective and reliable source of safety relevant reference values and indicator criteria is the observation of natural systems. Such systems are either investigated to assess the overall safety of a repository, or to generally compare some specific sub-system or radiological aspect of the repository with a natural analogue. Since the latter approach does not provide a strict safety statement, the yardsticks it yields are not suitable as reference values for safety indicators. The two approaches are described in the following.

6.2.1.1 *Reference values for safety indicators*

A reference value for a safety indicator should indicate a level that is generally accepted to be safe. A repository system can be considered safe if possible radionuclide releases remain low in comparison with the natural radionuclide content of the environment, measured normally in terms of concentration or flux. This is, however, a somewhat problematic principle because the radionuclide fluxes and concentrations in natural systems vary widely. On the one hand, there is no guarantee that the undisturbed natural environment is actually radiologically safe. In certain geological formations, there can be high natural concentrations of uranium or other radionuclides that may pose a potential hazard to humans and other biota. That said, there is no epidemiological evidence to suggest people living in the areas with the highest natural background radiation experience any increased risk of cancers or other chronic disease compared to the global average.

Nonetheless, it should be demonstrated by some adequate assessment that the natural system used for deriving reference values can, without doubt, be regarded as a radiologically safe environment. A good argument for this would be that humans have been living in close contact with this natural system and using its drinking water for many centuries without any evidence of getting ill from it. On the other hand, the natural radionuclide content can be extremely low in some geological environments and lead to unduly low reference values. Both extreme ends of the natural range in natural radionuclide content should be avoided when deriving reference values to avoid biasing the assessment. Reference values for safety indicators, based on natural systems, can be global or local. This has nothing to do with national or regional regulations, neither does it refer to the method of determination. The global or local character of a reference value refers to its validity (and transferability), and results from the different spatial characters of the natural processes considered.

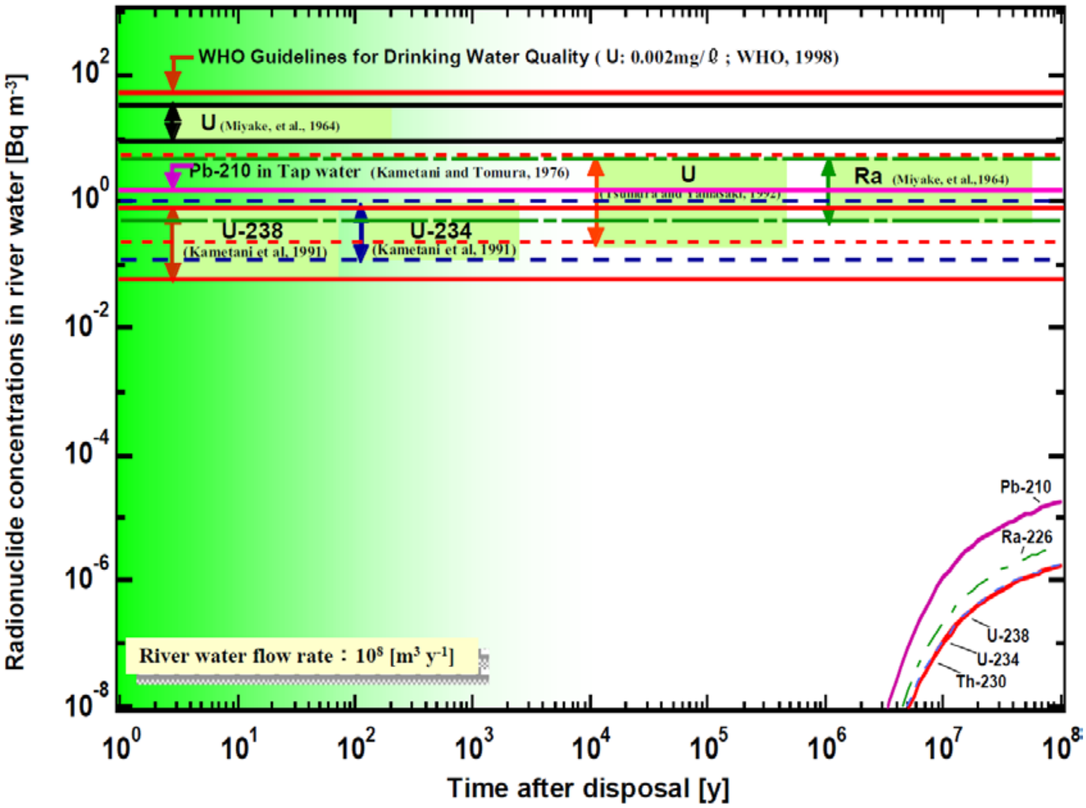
Global reference values are valid in equal measure everywhere in the world, and at all times, for as long as the conditions they have been derived for do not change. Such changes could happen, for example, due to climate change processes that would alter global average indicator values or, on a longer timeframe, biological evolution of mankind, resulting in a reduced or increased radiosensitivity. In this context, 'global' does not mean that the numerical value is unique and will never change, but that the validity of the quantity for assessing safety is independent of space and time. Of course, it is possible that different researchers may come to different conclusions concerning the numerical value. A good example for a global reference value is the acceptable radiotoxicity concentration in drinking water. By analysing different drinking waters that have been consumed by humans for decades or centuries without any signs of detrimental effects, it is possible to define a level of radiotoxicity that is obviously harmless for the human physiology and can be globally used as a reference value. This does not mean, however, that all such investigations will yield the same numerical value.

Local or site-specific reference values have a different character. Such values are determined for a specific repository site (or surrounding area) and only make sense if applied to that particular location. The general idea of local reference values is that the local natural environment of the repository, which is assumed to be radiologically safe, should not be significantly disturbed by the repository. Since the geological conditions and the specific transport paths from the repository near-field to the biosphere differ essentially from site to site, the acceptable values of radionuclide releases from the repository can be very different and, if determined for one site, are not readily transferable to another. Typical quantities that can be used as local reference values for safety indicators are natural radionuclide fluxes and concentrations in the deep groundwater in the host geosphere, or the radionuclide fluxes in nearby rivers.

To understand better the ranges and variations in the fluxes and concentrations of naturally occurring radionuclides and other chemical species, the IAEA ran a Coordinated Research Project that sought to develop international consensus on the assessment of the long term safety of radioactive waste disposal using complementary safety indicators derived from observation of natural systems. Nine countries participated in the project: Argentina, Brazil, China, Cuba, Czech Republic, Finland, Japan, Sweden and the United Kingdom (IAEA, 2005). As a consequence of the variability and heterogeneity of the datasets collected in the participating countries (environmental concentrations and fluxes), it was decided that it was most appropriate to report the geochemical data separately for each country. Furthermore, it was suggested that the most appropriate spatial scales for the comparison between the disposal and natural systems used to derive reference values for safety indicators in a safety case was the site or local area scales, and to focus more on regional datasets that address the geochemical variability on spatial scales similar to those in which a disposal system would be located.

One example of the application of reference values derived from nature is given in the 'H12' safety case for disposal of spent fuel in Japan (JNC, 2000). In this case, releases from the repository were compared to radionuclide concentrations in a number of different waters, including river waters and tap (drinking) water in Japan, in addition to the WHO drinking water standard. From this comparison, it is evident that the calculated concentrations of radionuclides originating from the repository for the reference case scenario are several orders of magnitude lower than those of naturally occurring radionuclides and the WHO guideline, as shown in Figure 16.

Figure 16: The comparison between the calculated repository releases from the Japanese spent fuel repository, and a range of Japanese river waters and the WHO drinking water standard. From JNC (2000).



6.2.1.2 Indicator criteria from natural analogues

A natural system is called a natural analogue if it is, with some respect, comparable to the repository system under consideration. A quite recent definition was given by the NAnet project *"Analogue studies are investigations of natural, anthropogenic, archaeological or industrial systems which have some definable similarity with a radioactive waste repository and its surrounding environment"* (Miller *et al.*, 2006).

Natural analogues can put the radiological impact of a repository system into perspective by comparing it with something that occurs in nature. A yardstick value derived from a natural analogue does not automatically define a 'safe' level; therefore, it does not make sense to consider it as a limit. In fact, such values are often used to illustrate the order of magnitude of some radiological measure of the repository.

An example of a natural analogue serving as source for an indicator yardstick is the natural radiotoxicity content of specific geological formations. The Cigar Lake uranium orebody in Canada is often used to demonstrate that containment of radioactive waste within the geosphere is possible. Although the natural radiotoxicity content of the uranium deposit is not at a level that can be considered 'safe', it can be helpful to compare the time-evolution of the radiotoxic inventory of a repository to this value, to show that, at least after some period of decay, the radiotoxicity concentration in the ground reaches a value that also occurs in nature without causing environmental damage.

6.2.2 Indicator criteria derived from performance assessment calculations

As explained earlier, reference values for safety indicators should define a level that can generally be considered safe with respect to some given aspect of the repository. It is not very probable that a suitable reference value can be derived from calculations assessing the performance of a repository system, because the verification of such calculations (as well as a safety statement derived by these calculations) is generally not possible. Furthermore, deriving a reference value from the same, or similar, model calculations used for the safety assessment would not provide for independence or transparency.

Although reference values for comparison with safety indicators cannot be derived from calculation, criteria for comparison with performance indicators can be. If certain properties of individual barriers are to be assessed, it is possible to calculate their performance under idealised conditions and use the calculated values as indicator criteria. For example, calculation could indicate that a repository system needs to provide complete and permanent containment of the radioactive waste for a certain minimum time to allow for sufficient radioactive decay to occur. If the container lifetime is assessed to be definitely longer than this minimum time, it provides a strong argument for the good performance of the overall repository system.

6.2.3 Indicator criteria derived from safety functions

As explained earlier, safety function indicators differ from performance indicators because, in part, there is a quantitative requirement to compare them to corresponding criteria. A safety function indicator criterion is a quantitative limit such that, if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained (SKB, 2006). The successful application of safety functions rests, therefore, on the ability to define appropriate safety function indicator criteria. In most cases, these are usually defined by modelling studies, rather than through laboratory measurement or observations of natural systems.

As an example of the derivation of safety function indicator criteria, in the Germany programme for the disposal of HLW the safety concept is based on the safety function 'containment'. This safety function is characterised by the requirement for the waste to be adequately contained over the long term within the engineered barriers and the surrounding block of rock that hosts the repository (referred to in this report as the 'containment providing rock zone'). For the assessment of this containment providing rock zone, three indicators are defined in Germany regulations (BMU, 2010). These have the characteristics of safety function indicators, although that term is not explicitly used in the German regulations:

- *Dilatancy indicator*: The anticipated stresses should not exceed the dilatancy strength of the rock formations in the containment providing rock zone outside of the disturbed rock zone.
- *Fluid pressure indicator*: The anticipated fluid pressures must not exceed the fluid pressure capacity of the rock formations in the containment providing rock zone in a manner that could lead to the increased ingress of groundwater into the containment providing rock zone.
- *Temperature indicator*: The barrier effect of the containment providing rock zone must not be inadmissibly influenced by temperature development.

The first indicator is based on comprehensive laboratory analyses of the petrophysical and geotechnical properties of different rock types, plus mining experience and observations, that show that stress states below the dilatancy limit do not cause any long-term structural damage to the rock mass. Stress states above the dilatancy limit can, however, cause permanent alteration of the rock microstructure, which in turn can lead to the gradual formation of a network of microfissures if such conditions persist, increasing the hydraulic permeability of the rock. The corresponding indicator criterion is, therefore, set at the calculated dilatancy limit for the host rock type.

The second indicator is based on the fact that the physical integrity of the geological barrier provided by the host rock will be maintained for as long as the main compressive stress exceeds the hydrostatic pressure at the depth of the repository. The corresponding indicator criterion is derived by a simple calculation of the hydrostatic pressure.

The third indicator is intended to ensure that the host rock cannot be damaged (e.g. by differential thermal expansion) caused by excessive near-field temperatures due to heat generation within the waste. The corresponding indicator criterion is set at a maximum admissible temperature of 200°C on the basis of thermal modelling of salt rock systems.

6.2.4 Reference values and indicator criteria from other safety recommendations

In addition to the international recommendations for radiological safety that underpin most national regulations, other organisations provide various recommendations related to protection of humans and the environment that may be used to define reference values and indicator criteria. These are most prominently illustrated by international safety recommendations and guidelines for drinking water quality, such as those issued by the World Health Organisation (WHO, 2011). The aim of the WHO when setting guidelines for drinking water is to *"describe reasonable minimum requirements of safe practice to protect the health of consumers and/or derive numerical 'guideline values' for constituents of water or indicators of water quality. In order to define mandatory limits, it is preferable to consider the guidelines in the context of local or national environmental, social, economic and cultural conditions."*

For radiological aspects the guidelines for drinking water give guidance levels for radionuclides in drinking water, which can be used as global reference values for acceptable radionuclide concentrations in drinking water. In general, international safety recommendations and guidelines, (such as those issued by IAEA, ICRP, and WHO) provide an important basis for deriving reference values for complementary indicators.

6.2.5 Reference values addressing societal values and expectations

International safety recommendations, such as the recommendations of the ICRP and WHO, have to be considered in the context of the societal values and expectations. One important concept in this regard is the concept of 'acceptable risk' which has been described in the following terms (WHO, 2011) as *"The judgement of safety – or what is an acceptable level of risk in particular circumstances – is a matter in which society as a whole has a role to play"*.

The concept of defining an acceptable risk evolved from the fact that absolute safety can never be achieved in any everyday activity or industrial practice, including radioactive waste disposal. The exposure of people and other biota to even very low radiological or chemotoxic substances involves some risk. The concept of acceptable risk has been discussed intensively in the literature (e.g. Fischhoff *et al*., 1981), and has been applied in guidelines and regulation in several countries. In the UK, for example, the Health and Safety Executive (HSE) defines acceptable risks as a *"level of risk which, provided there is a benefit to be gained, and proper precautions are taken, does not worry us or cause us to alter our ordinary behaviour in any way"*. It is expressed in terms of the probability of an individual dying in one year as 10^{-6}. This risk constraint was derived after considering risks in other contexts, e.g. that of dying in a road traffic accident (HSE, 2001).

In many other international guidance documents and national regulations, an individual risk of 10^{-6} per year of suffering a serious health effect is often applied as a 'target level' for an acceptable risk. An acceptable risk of 10^{-6} per year can, therefore, be seen as representing the safety performance expected from state-of-the-art science and technological practices, and can provide a reference value for indicators based on risks.

Nevertheless risks (and their benefits) are quite differently distributed across societies, and the factors and processes that determine whether a risk is acceptable will change with time. These factors also affect the public perception of risk, and may cause discrepancies in subjectivity judgment and statistically based measures of risks.

6.3 Quantifying reference values and indicator criteria for comparisons

In the previous section, the possible sources of reference values and indicator criteria were described. Identifying a source is often not sufficient, however, to be able to apply a yardstick to an indicator because care needs to be taken to ensure the source and indicator are directly comparable. This is especially important for indicators compared to yardsticks derived from natural systems. Before applying data as reference values or indicator criteria, i.e. to compare them to an indicator, some fundamental questions have to be answered (IAEA, 2005):

- What elements to consider?
- What spatial scales to consider?
- How to address heterogeneities?

The measurement of natural concentrations or fluxes in a specific environment normally consists of a set of data, obtained at different points and different times, within some smaller or wider band of variation. There are two principally different approaches to deriving reference values from such data sets. The first possibility is to use some fraction of the actual measured value, taken as the mean of the data set. The idea behind this concept is that it will be acceptable if the release from the repository does not significantly increase the level of radionuclide concentration or flux compared to the natural background, which has been proved to be safe. It has to be defined, of course, what 'significantly increase' means in this context. Although it depends on subjective perceptions, an increase of 10 % of the mean natural value is often considered an acceptable limit.

The second approach does not use the mean value of the data set but considers the variation or range in the data. This concept is based on the idea that it cannot be harmful to add to the natural background an amount of radionuclide concentration or flux that could just as well have been added by the nature itself (i.e. is within the natural range). The problem is, however, that the variation of the natural background is not obviously safety relevant. Following this approach, a system with a high but relatively constant background will lead to a low reference value, while a system with a highly variable background can yield a reference value that is higher than the mean. As a consequence, this approach could lead to unacceptable total concentrations or fluxes if a high repository release (close to the reference value) is added to a high natural background value at the upper end of the range of natural variation.

It is important, therefore, that whatever source and approach is used to derive a reference value or indicator criteria is justified and transparently explained, so that they may accepted by the regulators and other stakeholders who have an interest in the safety case.

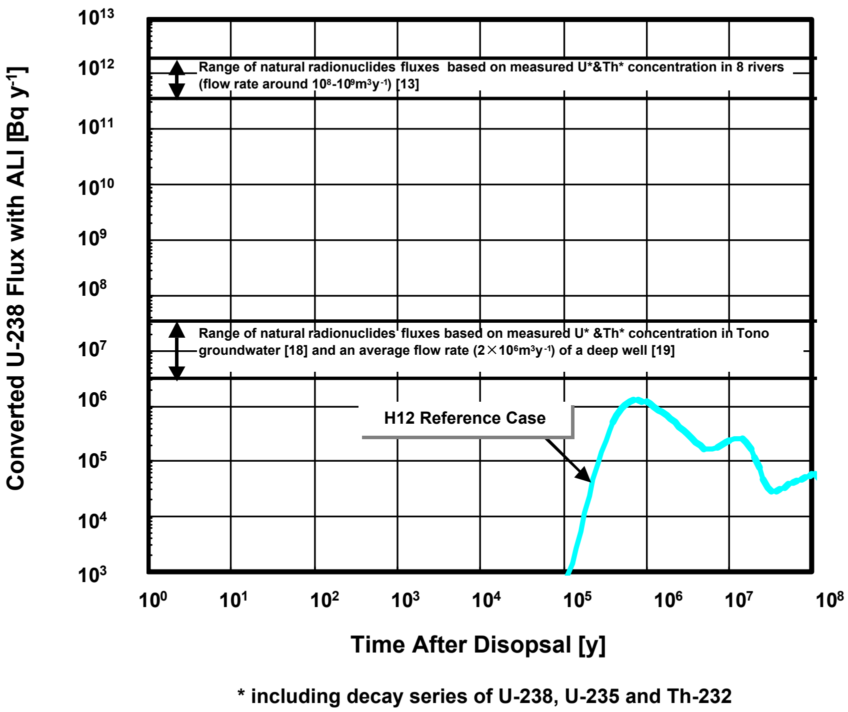
6.4 Dealing with averages and uncertainties in reference values and indicator criteria

There are accepted approaches to dealing with the various forms of uncertainties in safety and performance assessments (see Section 5.6). This concerns scenario and model uncertainties as well as parameter or data uncertainties. The reference values and indicator criteria used in assessments, however, are most often taken as fixed values. This is an appropriate approach to take when considering safety indicators because it is necessary to determine whether safety is met by comparison with a specified 'limit' defined by the reference value. Comparing the outputs of a safety assessment to a diffuse band of values can result in an ambiguous statement about repository safety.

The determination process for a reference value for a safety indicator should, therefore, result in a unique value. The basis for this process, however, is normally a set of distributed data from natural systems or other sources. Following strict conservatism, it would be appropriate to choose the lower boundary of the uncertainty limit (provided that a high indicator value stands for high environmental impact). This may not always be an appropriate approach, however, because some very low values may occur within the data, which are too conservative to be used as reference values. The other extreme is to use the highest value that can still be proved to be safe. This approach leads to a practical reference value but can provoke objections of missing conservatism. In fact, there is no standardised procedure for handling data uncertainty when determining reference values. Some further research on this issue is desirable.

When considering performance indicators or when making more general comments about system understanding and consequences, however, it can be appropriate to compare calculated results to a range of indicator criteria. For example, the calculated concentrations due to repository releases to the geosphere may be compared to the range in naturally occurring concentrations in similar rock types. By this it can be shown that the increase in risk caused by the repository is lower than the variation in risk associated with the range in the abundance of naturally occurring radionuclides. As an example of this type of presentation, in Japan the calculated equivalent ^{238}U fluxes from the repository to the geosphere have been compared to the range of naturally occurring radionuclide fluxes in a variety of deep groundwaters and rivers in Japan. The results of the comparison show that the repository release fluxes are at least two orders of magnitude less than the natural groundwater fluxes and up to six orders of magnitude less than occur in rivers (Figure 17).

Figure 17: Comparison of the calculated equivalent ^{238}U fluxes from the repository to the geosphere (in the H12 performance assessment) against the ranges of natural uranium fluxes in groundwater and river waters in Japan. From Miyahara *et al.* (2001)



6.5 Compilation of reference values and indicator criteria

The responses to the Indicators Questionnaire revealed over 50 separate indicators with matching reference values or indicator criteria, and these are listed in Table 13 and grouped by the reported category of indicator. A number of the reported reference values are those recommended in the SPIN and PAMINA Projects but others have been derived from site specific or regional geochemical data (e.g. measured radioactivity levels in natural environments).

Table 13: Indicators with reference values reported in the Indicators Questionnaire. SI = safety indicator, PI = performance indicator, RTI = radiotoxicity index, N/A = not applicable.

Indicator	Type	Reference Value	Comment	Source
Radiotoxicity concentration in groundwater	SI	20 $\mu Sv/m^3$	Value from SPIN Project.	SCK•CEN
Radionuclide concentration in groundwater	SI	Generic standard applied to WIPP	$^{226}Ra + ^{228}Ra < 5$ pCi/L [< 0.19 Bq/L]	USA
Radionuclide concentration in groundwater	SI	Gross alpha < 15 pCi/L [< 0.56 Bq/L]	Comparison with numerical radiological protection criteria for drinking water used for current practices.	USA
Radionuclide concentration in groundwater	SI/PI	Range of natural radionuclide concentrations in groundwaters.	Comparisons made against a number of deep, reducing groundwaters and shallow, oxidising hot springs found in Japan.	Japan
Radiotoxicity concentration in biosphere water	SI	20 $\mu Sv/m^3$	Comparison with numerical radiological protection criteria used for current practices.	NRG
Radiotoxicity concentration in biosphere water	SI	2×10^{-6} Sv/m^3 1.1×10^{-5} Sv/m^3	The first value is a comparison with average levels of natural radioactivity in German drinking waters. The second value was derived from the Morsleben site.	GRS
Radiotoxicity concentration in the biosphere water	SI	2×10^{-5} Sv/m^3	Value from SPIN Project.	Enresa
Radiotoxicity concentration in surface waters	NC	2×10^{-5} Sv/m^3	Comparison with natural radioactivity. Regional scale average from Canadian Shield Lakes.	NWMO
Relative activity concentration in biosphere water	SI	1	Calculated values scaled with exemption levels in Dutch legislation for groundwater.	NRG
Concentration of radiotoxic or chemically toxic elements in the biosphere over time	SI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
Flux out of host formation	SI	60 Sv/a	Value from SPIN Project.	SCK•CEN
Radiotoxicity flux from geosphere	SI	60 Sv/a	Value from SPIN Project.	NRG
Radiotoxicity flux from the geosphere	SI	60 Sv/a	Preliminary value taken from SPIN project. In ENgranite the activity (not radioactivity) leaving the geosphere was compared with the natural activity in 1 m^3 of granitic soil (10^7 Bq).	Enresa
Radiotoxicity flux from the geosphere	SI	0.12 Sv/a	Comparison with existing levels of radiation local to the Morsleben site.	GRS
Radiotoxicity flux from the geosphere	SI	0.1 Sv/a	Comparison with existing levels of radiation local to the Gorleben site.	GRS
Radiotoxicity flux to surface	NC	600 Sv/a	Comparison with natural radioactivity. Reference value derived from average deep groundwater discharge rate or erosion rate from a 100 km^2 area of Canadian Shield.	NWMO

Indicator	Type	Reference Value	Comment	Source
Radiotoxicity flux from the geosphere to the biosphere over time	SI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
RTI flux to biosphere	SI/PI	RTI flux in aquifer, river water, erosion of biosphere area and consumption of mineral water	Comparison with existing levels of natural radiation, regional average for Opalinus Clay.	Nagra
Equivalent fluxes of ^{238}U from the geosphere	PI	Range of natural radionuclide fluxes in river waters.	Geosphere fluxes calculated for an assumed water conducting fault in the geosphere.	Japan
Power density in groundwater	SI	25 $MeV/s/m^3$	Value from PAMINA Project, based on the natural value in the aquifer at the Gorleben site including a safety margin.	GRS
Power density in groundwater	SI	80 $MeV/s/m^3$	Value from PAMINA Project, based on the natural value in the aquifer at the Gorleben site.	NRG
Power density in biosphere water	SI	80 $MeV/s/m^3$	Value from PAMINA Project, based on the natural value in the aquifer at the Gorleben site.	Enresa
Index of Radiological Insignificance (RGI)	SI	1	Comparison with global average levels of natural radiation.	GRS
Effective dose rate	SI	0.3 mSv/a	Comparison with numerical radiological protection criteria used for current practices.	NRG
State of stress (dilatancy criterion) in containment providing rock zone	SFI	Dilatancy boundary	Reasoning about performance.	BGR
State of stress (fluid pressure criterion) in containment providing rock zone	SFI	Minor principle stress	Reasoning about performance.	BGR
Minimum copper thickness	SFI	> 0	Directly related to containment.	SKB
Isostatic load on canister	SFI	> 45 MPa	Directly related to containment.	SKB
Buffer hydraulic conductivity	SFI	$< 10^{-12}$ m/s	Ensuring diffusion barrier properties.	SKB
Buffer swelling pressure	SFI	> 1 MPa	Ensuring self healing.	SKB
Ionic strength $\sum q[M^{q+}]$	SFI	> 4 mM	Avoid buffer erosion.	SKB
pH	SFI	< 11	Avoid buffer mineral transformation.	SKB
Total waste radioactivity	NC	Rock above/around repository: ~ 400 TBq footprint ~ 20,000 TBq total site.	Comparison with natural radioactivity. Regional values used initially, and site data used in the final assessment.	NWMO
Containment factor defined as the activity released from the GDF divided by activity disposed of, over time	PI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
Radiotoxicity inventory over time in components of the geological disposal system	PI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
Distribution of activity concentration	PI	N/A	Reasoning about performance. Radionuclide transfer pathways at specific dates. Illustrates phenomena such as precipitation and sorption.	Andra
RTI of waste on ingestion	SI/PI	RTI of the host rock and of natural uranium ore	Comparison with existing levels of natural radiation, regional average for Opalinus Clay.	Nagra
RTI concentration at top of host rock	SI/PI	RTI concentration naturally present in host rock	Comparison with existing levels of natural radiation, regional average for Opalinus Clay.	Nagra

Indicator	Type	Reference Value	Comment	Source
Advection / diffusion	PI	N/A	Reasoning about performance. Pe < 2.	Andra
Radiotoxicity flux over time from components of the geological disposal system	PI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
Cumulative radiotoxicity flux up to given times from components of the geological disposal system	PI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
Flux across defined accessible environment boundary	SI	Cumulative releases per year for specific radionuclides	Specified limit at this boundary is protective of biosphere.	USA
Radionuclide mass transport rock v. shafts	PI	N/A	Reasoning about performance. Radionuclide mass transport in host rock >> in shafts.	Andra
Diffusion process in rock and seals	PI	N/A	Reasoning about performance. Transfer time long and spreading out of the radionuclide mass.	Andra
Radionuclide molar flux (maximum)	PI	N/A	Reasoning about performance. Attenuation of radionuclide mass in a component.	Andra
Radionuclide molar flow (mass over assessment period)	PI	N/A	Reasoning about performance. Attenuation of radionuclide mass in a component.	Andra
Radionuclide molar flow (time of maximum flow)	PI	N/A	Reasoning about performance. Transfer time long and evaluation of the maximum dose at the outlet.	Andra
Diffusive transport time through host rock: half life	SI/PI	1	Reasoning about performance. Indicates where decay during transport starts to become significant.	Nagra
Transport time through components of the geological disposal facility	PI	N/A	Distribution of naturally occurring chemical species. To be defined when a site is identified.	RWMD
Steady state transport distance	SI/PI	Thickness of buffer and host rock.	Reasoning about performance.	Nagra
Engineered barrier containment time requirement	PI		Specific to Yucca Mountain.	USA
Post-containment engineered barrier release rate limit	PI	$^{226}Ra + ^{228}Ra < 5$ pCi/L [< 0.19 Bq/L]	Gross alpha < 15 pCi/L [< 0.56 Bq/L]	USA

7. SUMMARY AND RECOMMENDATIONS

In this section we first provide a summary of the main observations drawn from the current status of the use of indicators in the safety case and, in particular, the responses to the Indicators Questionnaire. We then provide a number of recommendations that we hope will be useful to organisations developing their assessment methodologies and who wish to apply indicators in their safety cases.

7.1 Summary and main observations

7.1.1 Acceptance of indicators

It is evident from the responses to the Indicators Questionnaire, that complementary indicators are now accepted by the majority of regulators and implementers as an important component of a safety case. It is highly likely that all future safety cases will integrate one or more complementary indicators in their evaluation of repository safety and performance. How this is done will, undoubtedly, vary on a case-by-case basis but it seems certain that standard dose and risk calculations are no longer the sole focus of assessments.

This is a markedly different position from a decade ago, when the potential for complementary indicators was still under investigation. This shift in approach is consistent with the development of safety cases using multiple lines of reasoning which require the mechanics of repository evolution to be understood at the sub-system and component or process level.

7.1.2 Development and application of indicators

There has been considerable development in the thinking that underpins the application of complementary indicators in safety cases over the last decade. The early approach was based on comparing calculated repository releases with the measured abundances of naturally occurring radionuclides in the environment as a means of making a comparative evaluation of safety that was not subject to the inherent uncertainties associated with calculations of far-future dose and risk.

This basic approach is still valid and the most widely reported indicator remains ‘radionuclide concentration in groundwater’. Nonetheless, the scope of complementary indicators has been expanded considerably, in part driven by the work of the EC’s SPIN and PAMINA Projects, to now also include additional indicators to evaluate safety, and for the quantitative evaluation of the containment performance afforded by different barriers and repository sub-systems.

7.1.3 The different types of indicators

A large number of individual indicators have been suggested and trialled in individual safety cases but there are relatively few that appear to be generic and conceptually different to each other, and these can each be placed into one of three main groups: ‘content and concentration’ related, ‘flux’ related and ‘status of barriers’ related. Some of the most commonly reported indicators in these groups are:

- *‘Content and concentration’* related indicators:

  - Radioactivity/toxicity concentration in the wasteform
  - Radioactivity/toxicity concentration in the engineered barrier system components
  - Radioactivity/toxicity concentration in the geosphere (particularly in groundwater)
  - Radioactivity/toxicity concentration in the biosphere (particularly in surface waters)
  - Power density in groundwater
- *'Flux'* related indicators:
  - Radioactivity/toxicity flux from the engineered barriers to the geosphere
  - Radioactivity/toxicity flux from the geosphere to the biosphere
  - Integrated radioactivity/toxicity flux from the geosphere to the biosphere over time
  - Radionuclide molar flow (mass over the assessment period)
- *'Status of barriers'* related indicators (examples):
  - Groundwater age
  - Container lifetime
  - Transport times through the engineered barrier system components and the geosphere
  - State of stress in the near-field rock (containment zone)
  - Swelling pressure (buffer and backfill)
  - Ionic strength (geosphere groundwater)

The concentration and flux based indicators are sometimes reported in terms of radioactivity and sometimes in terms of radiotoxicity (and sometimes both). It is likely that, in some cases, these terms have been used loosely and interchangeably, but in other cases, a distinction is clearly intended. In certain cases, radioactivity is used in the context of specific key radionuclides and radiotoxicity in the context of a weighted sum over all radionuclides. The different terminology used may reflect the maturity of the different assessment programmes and the fact that some organisations have not yet developed their approach to applying complementary indicators in their assessments.

7.1.4 Classification of indicators

Whilst considerable progress has been made in the development and application of complementary indicators at a technical level, it is clear that there is no universally accepted agreement on the definition and categorisation of different indicators. This is due, in part, to differences in the regulatory regimes and safety assessment methodologies adopted in different countries.

Several organisations have chosen to make a distinction between safety indicators and performance indicators, following the recommendations in IAEA reports and the outcomes of the EC's SPIN and PAMINA projects. A number of other organisations are beginning to develop and apply the concept of safety functions indicators. The latter approach is most commonly adopted by the more mature programmes that are moving towards implementation and are performing site-specific assessments, and undertaking design optimisation. Some organisation, however, have deliberately chosen not to use any defined classification scheme and prefer to use more general terminology that does not suggest any hierarchy amongst the complementary indicators they use.

This lack of consistency should not be viewed as a negative point. One of the strengths of complementary indicators is that they can be applied flexibly in safety cases to provide a number of benefits, and to align with the assessment context and intended audience.

7.1.5 Reference values and indicator criteria

The issue of defining appropriate reference values and indicator criteria remains an area of considerable uncertainty. Following the PAMINA definitions for safety and performance indicators, it is clear that a reference value is an essential component for safety indicators but a matching indicator criterion is only a recommendation for performance indicators. In the developing concept of safety function indicators, these too generally require a corresponding indicator criterion to be applied.

Where reference values are available for comparison with safety indicators, there appears to be a general trend towards using site-specific ones because these are considered to provide the most relevant local context. Several organisations anticipate deriving site-specific reference values from characterisation studies, once sites have been chosen. Nonetheless, for certain indicators, such as radiotoxicity concentration in groundwater, many organisations favour the use of global standards such as maximum permissible concentrations in drinking water because this allows direct intercomparison between assessments, and because compliance with this standard is considered to be safe.

There are relatively few defined indicator criteria for comparison with performance indicators, and most that are used have been derived from modelling work, although there appears to be some scope for deriving some from natural analogues in certain cases. Often, however, performance indicators are expressed as relative fractions and, thus, do not require matching indicator criteria. Performance indicators are not readily transferrable because of the differences in repository designs and site conditions and, consequently, indicator criteria, if used, generally need to be determined on a case-by-case basis.

The situation is more complicated for organisations that do not adopt the PAMINA definitions of safety and performance indicators because most other alternative definitions are not explicit about whether or not a reference value or criteria is an absolute requirement.

7.1.6 Indicators in regulation

It is encouraging to see regulators begin to include complementary indicators within the scope of their expectations of a safety case. At the present time, new regulations have been produced in final or draft form in several countries (e.g. Finland and Germany) that include a requirement to use some form of complementary indicator. There are clear differences in approach between these regulations that is driven, in part, by differences in the repository safety and design concepts in each country. For example, the Finnish regulations are expressed in terms of maximum allowable concentrations of repository releases in groundwater (a form of safety indicator), whereas the German regulations are expressed in terms of the functional requirements for the containment providing rock zone (a form of performance or safety function indicator).

In many more countries, complementary indicators are featured in regulatory guidance documents and are sometimes addressed within the wider context of 'multiple lines of reasoning' and confidence building. By their nature, these guidance documents are non-statutory but, nonetheless, the language used in them often makes it evident that the regulator has a strong expectation that the repository developer *will* use complementary indicators to support their safety case, even if there is no formal requirement in law to do so.

7.1.7 Indicators to support other activities in a repository development programme

Most of the uses of complementary indicators to date have focussed on their application within safety assessment and safety cases, but there are a number of novel uses that relate more to other activities within a repository development programme.

In Germany, indicators are being tested for their use in site selection, to compare the potential containment capacity of different rock types and geological environments. A similar structured approach to using indicators to help evaluate alternative design concepts, and for design optimisation, is also being followed jointly in Finland and Sweden.

Consideration is now also being given to the application of indicators to post-emplacement monitoring. The suggestion is that indicators could be used explicitly to help define the expected performance envelopes and likely threshold levels against which monitoring results may be compared. This application is characterised by the use of measured (observed) quantities rather than calculated ones, which is the case in most other applications of indicators. This is similar to the performance confirmation monitoring approach that is applied in the USA.

7.1.8 Indicators for communication

Safety indicators may be used to illustrate the magnitude of the impacts of repository releases to the surface environment, and place them in a local (site) context. Similarly, performance indicators can help to explain and illustrate how the various components of the repository system contribute to the containment and isolation of radionuclides. It is often assumed that such comparisons between repository and natural systems using complementary indicators will be readily understood and appreciated by non-technical audiences. There appears to be scope for using indicators to help provide context for non-technical readers but, to date, there has been limited experience in using them for this purpose or testing their efficacy.

7.2 Recommendations

Below we set out a number of recommendations that are intended to be useful to organisations developing their assessment methodologies and who wish to apply indicators in their safety cases. We do not, however, recommend a ‘best’ set of indicators to use or provide a ‘preferred’ way that indicators should be calculated or presented. This is because the safety case developer is encouraged to give careful thought to choosing and applying indicators so that they are consistent with their own assessment purpose and their intended audience.

1. Complementary indicators should feature in all safety cases but their use should be aligned to the purpose of the assessment and consistent with:

   a. *the regulatory context:* the use of indicators may be constrained by the regulatory context and, in some cases, the calculation of specific indicators may be a formal requirement. Nonetheless, the repository developer will usually have some flexibility to choose additional indicators to those specified in formal regulations or informal guidance documents, to support the overall evaluation and presentation of repository safety and performance.

   b. *the assessment context:* the use of indicators will vary depending on the purpose of the assessment. If, for example, the assessment is primarily intended to help quantitative system understanding, then performance indicators that evaluate the functioning of the engineered barriers may be the most appropriate ones to use. If, on the other hand, the assessment is intended to support formal decision making, then safety indicators that illustrate the overall impact of the repository on the surface environment may be more appropriate.

c. *the assessment methodology:* the use of indicators must be consistent with the assessment methodology. In assessments that attribute specific safety functions to the repository design, then indicators should be chosen that best reflect them. Similarly, different indicators are likely to be used in assessments of concepts that put high reliance on the engineered barriers to provide containment (e.g. those in crystalline rock) than assessments of concepts that place greater emphasis on the geological barriers (e.g. those in clay and salt rock).

d. *the stage in the repository development programme:* the use of indicators is likely to change as a repository programme matures. In the early, generic stages of a programme it is probable that only a few indicators may be required to enable the behaviour of alternative disposal concepts to be compared. As the programme matures, and moves towards implementation, there may be a need to use a larger number of indicators to provide a more comprehensive presentation of the containment provided by the engineered barriers and to assess a broad range of environmental impacts due to the repository on a site-specific basis.

e. *the intended audience(s) for the safety case*: the use of indicators should reflect the interests, concerns and level of knowledge of the intended audience. In some cases, such as assessments primarily intended to develop system understanding, then the audience is likely to be technically mature and quantitative indicators would be appropriate. On the other hand, assessments to support key decisions (especially related to siting) are likely to be read by a broader range of people and, consequently, indicators with a more illustrative or qualitative basis may be more appealing to non-technical readers. In all cases, however, it is important that indicators are presented honestly and their meaning is not over-stated.

2. Whilst some organisations find it useful to classify indicators as safety, performance and safety function indicators, it is not essential that this is done in a safety case. As a starting point, however, we recommend the definitions provided in the EC's PAMINA Project:

   > *A <u>safety indicator</u> is a quantity, calculable by means of suitable models, that provides a measure for the total system performance with respect to a specific safety aspect, in comparison with a reference value quantifying a global or local level that can be proven, or is at least commonly considered, to be safe. A <u>performance indicator</u> is a quantity, calculable by means of appropriate models, that provides a measure for the performance of a system component, several components or the whole system.*

   Regardless of whether a formal classification scheme is adopted or not, what is important is that indicators are applied in a manner consistent with the assessment context and methodology, and that all indicators are clearly defined and described. In particular, any requirement for a matching reference value should be explicitly stated if definitions other than those from PAMINA are used.

3. A simple and alternative approach to categorising indicators that does not imply any hierarchy may be used in safety cases when no other scheme is required or applied. This approach is based simply on the character of the indicators considered and what they are intended to measure or illustrate, and is based on the three simple groups of:

   - 'content and concentration' related indicators,
   - 'flux' related indicators, and

- ‘status of barriers’ related indicators.

4. Safety indicators should generally only be used in a safety case when it is legitimate to provide a measure of the total system safety impact of the repository and when appropriate reference values for comparison are available. Safety indicators can be developed to evaluate both radiotoxic and chemotoxic hazards associated with repository releases, and this will provide additional context to the safety case. There are only a few generic forms of safety indicators that are widely used and these are:

   - fluxes (e.g. across the geosphere-biosphere interface),
   - concentrations (e.g. in far-field groundwater or surface waters), and
   - inventory (e.g. total radiotoxicity in the surface environment, and its evolution over time).

   The way these generic forms of safety indicator may be expressed in an actual safety case should take account of the assessment context, and the appropriate concept and site-specific conditions. For example, for a repository within a well defined water catchment, the most appropriate flux-based indicator could be the radiotoxicity flux associated with groundwater discharging to local surface waters (Sv/a) but in a shield area with very large groundwater flow systems, such a calculation may not have any local meaning or significance.

5. Safety indicators are most usefully presented in a timescales context. In far-future assessment time periods (especially after significant climate change may have occurred) the calculation of dose and risk will be most uncertain, and it is then that the presentation of complementary safety indicators will have the greatest potential benefit because they do not rely on assumptions for future human behaviour. There is considerable value from explicitly demonstrating how the advantages of one indicator may offset the disadvantages of another, so that the suite of indicators robustly addresses uncertainty.

6. Reference values for comparison with safety indicators should have a generally accepted safety significance and, ideally, local context. Good examples of reference values are:

   - maximum permissible concentrations defined in drinking water standards such as those provided by the World Health Organisation;
   - measured concentrations in local rivers and groundwaters; and
   - measured fluxes in the accessible environment (e.g. due to groundwater discharge or surface erosion).

   When using locally derived reference values, care should be taken to evaluate spatial and temporal variations, and to express this appropriately. Understanding and confidence in the use of safety indicators may be increased by comparing the calculated indicators to multiple reference values, such as the measured concentrations in more than one river when there are notable spatial differences.

7. Most safety indicators are transferrable between repository concepts and host geological environments because they provide an integrated measure of total safety and, as such, may be used to compare the relative safety performance of different repository systems. This aspect may usefully be applied in site selection or design optimisation. Great care must be taken in doing this, however, to ensure that any underpinning assumptions and modelling approaches are also comparable. Given that these factors vary considerably between assessments, it is generally not considered helpful directly to compare the safety indicators calculated in safety cases produced by different organisations without a thorough understanding of the differences.

8. Performance indicators provide a way to evaluate how individual barriers (and sub-systems) behave and contribute to the overall safety performance of a repository design. For example, calculated radionuclide fluxes through barriers over time can be used to determine whether long-term containment of the waste is provided predominantly by the physical engineered barriers or by hydrogeochemical conditions in the host rock. The importance of performance indicators is that they provide a means for demonstrating a comprehensive understanding of the overall repository system, that cannot be gained from the calculation of dose or risk alone.
9. Most performance indicators are specific to the repository design and geological environment, and so are not readily transferrable between different concepts and assessments. As such, it is important that performance indicators are chosen carefully to reflect the specific design and functioning of the repository. For example, greater emphasis may be placed on performance indicators for the canister for spent fuel than would be the case for waste packages for cemented ILW, because of the different emphasis between physical and chemical containment functions in the two designs. The purpose of each performance indicator should be clear and justified. The use of just a few well considered performance indicators in a safety case is much preferable to a longer list of indicators whose roles are not well defined.
10. If used, indicator criteria for comparison with performance indicators are most likely to be derived from modelling studies than from natural systems. This is in contrast to the derivation of reference values for safety indicators. There are, however, a few examples where natural and archaeological analogue studies may yield appropriate indicator criteria, such as corrosion rates for metals, but care is need to ensure the analogue is appropriate. Nonetheless, there is the potential for further developments in this area.
11. Indicators may be relevant in safety cases that explicitly apply safety functions to components and processes in the repository system. Their use is most valuable in mature safety cases when a repository design and host geological environment have been well defined, and for concepts in which a long lasting (physical) containment period is assumed, where the use of safety function indicators helps to demonstrate the ability of the system to provide the safety functions needed. For generic safety cases performed at an early stage in the repository development programme, it is likely that the use of a small number of safety and performance indicators would be more appropriate to use.
12. Some indicators may be expressed using multiple parameters. For example, fluxes may be expressed in terms of either mass (e.g. kg/a), radioactivity (e.g. Bq/a) or radiotoxicity (e.g. Sv/a). This sequence has progressively more direct safety relevance but is also progressively less comprehensible to non-specialists. A balance therefore needs to be stuck when choosing indicators to ensure they are appropriate for the assessment context and intended audience. Clearly, if expressing indicators using mass which has no direct safety relevance, the meaning of the indicator should not be over-interpreted (e.g. it may be a useful illustration of containment provided by the barriers but not of intrinsic hazard associated with any releases).
13. There is very limited experience internationally of using complementary indicators to help make safety cases more accessible and understandable for non-technical audiences. By using a range of complementary indicators in a safety case, its appeal may potentially be widened to a larger audience. In particular, using complementary indicators may provide benefits in terms of placing the calculated repository impacts into a more comprehensible context (e.g. in terms of locality, timescale and significance).

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APPENDICES

A1. Case Studies

APPENDIX A1.1: GERMANY

Indicators for comparison of the performance of different repository sites (Project VerSi)

In the German project VerSi, an attempt has been made to apply indicators to support siting of a HLW repository by evaluating the potential isolation capacity of alternative host rock types (Resele *et al.*, 2011). For this purpose a set of three indicators to measure the relative performance of repositories in different host rocks, in relation to each other, has been introduced:

- I1, the maximum annual radiotoxicity flux out of the containment providing rock zone (in mSv/a);
- I2, the maximum annual radiotoxicity flux density (averaged over an area of 104 m2) on the boundary of the containment providing rock zone (in mSv/m2/a); and
- I3, the radiotoxicity flux out of the containment providing rock zone integrated over time (in Sv).

Indicator values (or indicator value differences) below an indicator specific level are rated the same as zero. This indicator specific level is denominated as the (indicator specific) zero-level.

The indicator values are calculated with state-of-the-art simulation models in a similar fashion as for long-term safety analyses for licensing purposes, but conservative assumptions and simplifications are avoided so far as possible and the consequences of inevitable conservatisms must be quantified. The main results of the model calculations and the basis for the comparison of the repository systems are the median, the 95-percentile and the mean of the three indicators, together with their respective confidence intervals. Additionally, the robustness is defined as the ratio of the 95-percentile and the median. This definition implies that the closer the robustness value is to unity, the more robust is the repository system. The comparison method is based on five major steps:

1. *Definition of indicators and criteria*: The primary quantifying parameters are three indicators *based* on radiotoxicity fluxes from the containment providing rock zone, weighted by dose conversion factors. For all three indicators, levels of insignificance are defined. Releases below the level of insignificance are treated as zero.
2. *Identification* of scenarios and their statistical weights: A set of scenarios is defined independently for each repository system. A stepwise approach has been developed involving a group of experts assigning a statistical weight to each of the scenarios. Very unlikely scenarios (corresponding to a weight of less than 1%) are not considered further.
3. *Calculation* of long-term safety assessments: Probabilistic safety assessments are performed independently for each repository system. The values of at least 20 of the most relevant input parameters are varied statistically by choosing one of five discrete values. The indicator values resulting from each simulation are weighted by the product of the different parameter weights and the weight of the respective scenario.

4. Analysis *of the probabilistic simulation results: Three statistical characteristics are calculated* for *each* indicator: weighted mean, median and 95-percentile, along with their statistical uncertainty.

5. Comparison *of repository systems:* The comparison is based on the statistical *characteristics* of the indicators, their distribution functions, and an additional assessment of the robustness. Results with overlapping uncertainty intervals do not differ in a statistically significant way and are considered equivalent.

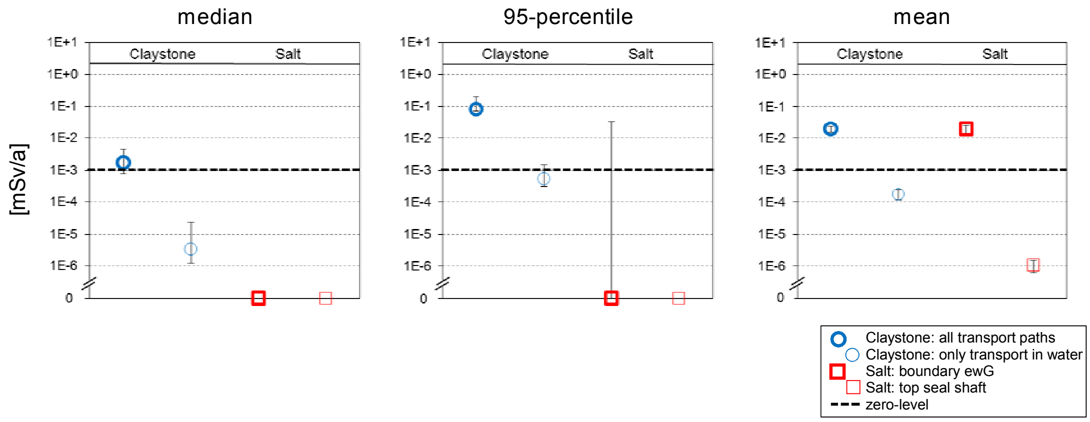
The method has been applied for two repository systems, in salt and clay, as an example of the approach. Selected results are shown in Figure A1, for indicator I1. The zero-level (for insignificance) of indicator I1 has been set to 10^{-3} mSv/a. The indicated confidence intervals correspond to ± 1σ intervals. For the repository in salt, the indicator values are calculated according to the indicator's strict definition on the boundary of the containment providing rock zone (which has been defined at the outer end of the drift seal between the emplacement area and the infrastructure area of the repository) and, additionally, at the top of the shaft seal. For the repository in clay, the indicator values are determined taking into account the calculated gas-phase release of $^{14}CH_4$ and, additionally, for the liquid-phase transport of radionuclides alone. Among others the following conclusions are drawn:

The medians and the 95-percentiles of the indicators for the salt repository and for the clay repository (only liquid-phase transport for the latter) are all in the range of, or below, the respective zero-levels. If the gas-phase transport is ignored, the two repository systems are equivalent with respect to these statistical key figures.

The mean values of the indicators I1 and I2 for the salt repository (at the boundary of the containment providing rock zone) and of the clay repository (including the gas-phase transport) are above the respective zero-levels and comparable, while all other mean values are below the respective zero-levels.

The medians and the 95-percentiles of the indicators I1 and I2 for the clay repository, taking into account the gas-phase transport, are above the respective zero-levels and larger than the corresponding key figures of the salt repository (calculated at any location).

Figure A1: Comparison of the statistical key figures of indicator I1 including all scenarios



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APPENDIX A1.2: SWEDEN

Use of indicators derived from safety functions in the Swedish safety case

In recent years there has been a trend in the development of safety cases to use the main protective functions that are taken into account to illustrate compliance with the principles of safety and radiological protection. Such functions are called safety functions, and are used to structure and assess the performance of different repository sub-systems.

Using the concept of safety functions, the safety case has to explain how the characteristics and properties of each component of the disposal system (waste form, engineered barriers placed around the waste and the geological environment) are intended to provide for safety. To quantitatively evaluate the role of a component for a specific safety function, that safety functions has to be expressed as a measurable or calculable quantity (an indicator).

When presenting the safety case, emphasis is placed on the key safety functions, such as containment of the waste or retardation of radionuclide releases, and on those arguments that are considered the most convincing at any given time in the evolution of the repository and its environment. In the following text, SKB's use of safety functions in its recent safety assessments is summarised.

Safety functions in SR-Can/SR-Site

SKB introduced the concept of safety functions in its SR-Can safety case (SKB, 2006) and, subsequently, gave the following definitions with the scope of the SR-Site safety case (SKB, 2011):

- A safety function is a role through which a repository component contributes to safety.
- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

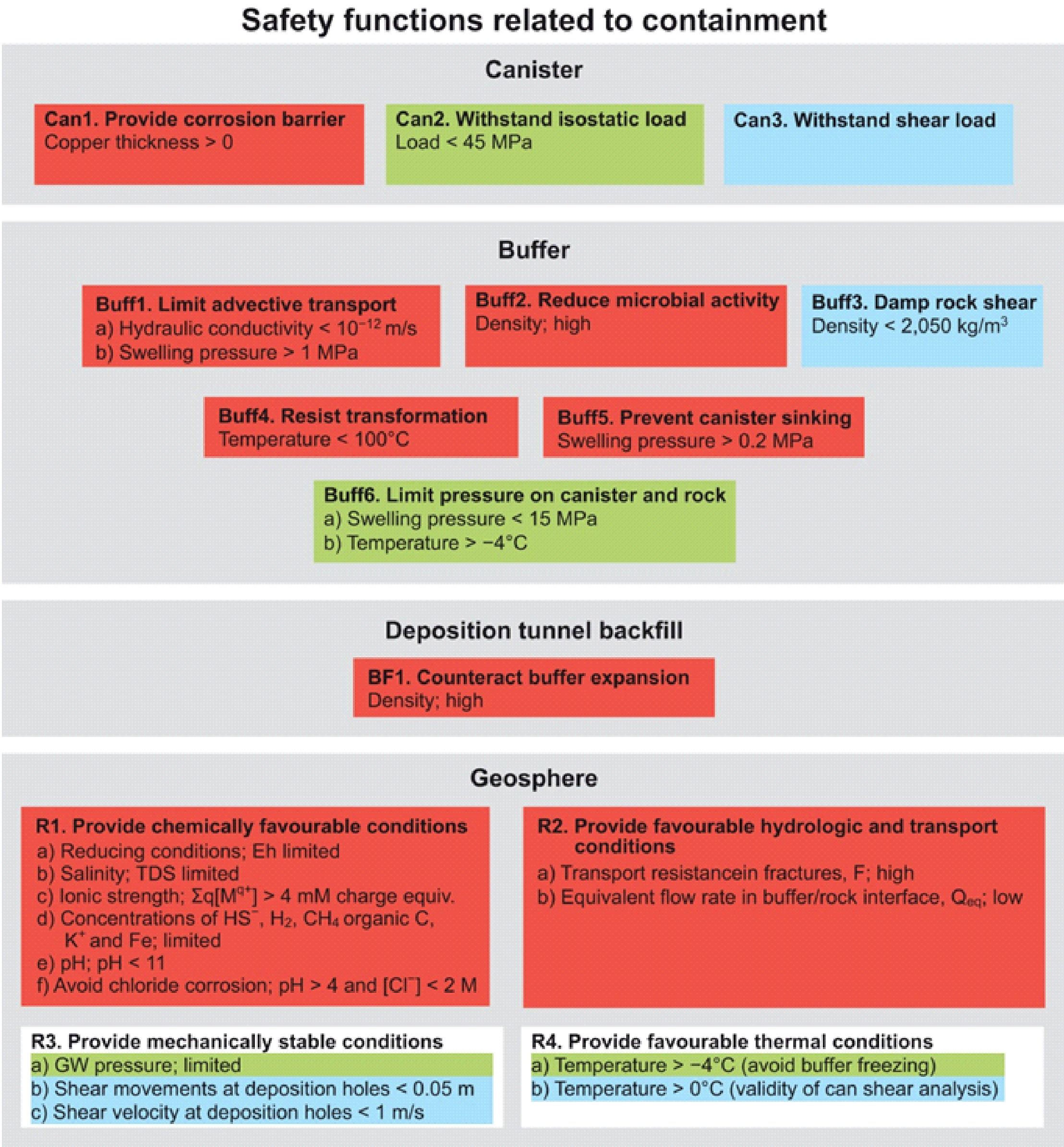
In both SR-Can and SR-Site, the primary safety function of the KBS-3 type repository is to completely contain the spent nuclear fuel within copper canisters over the entire assessment period, which is one million years. Should a canister be damaged, the secondary safety function is to retard any releases from the canisters. The two safety functions of 'containment' and 'retardation' are thus of primary importance throughout the assessments (SKB, 2011).

A more detailed evaluation of how the safety functions 'containment' and 'retardation' are fulfilled by the components of the repository system is carried out by SKB by identifying subordinate safety functions to containment and retardation, and relating these functions to measurable or calculable quantities, known as the safety function indicators (Figures A2 and A3).

Safety function indicators

The scientific understanding of the long-term evolution of the repository is the basis for the derivation of subordinate safety functions and barrier requirements. All processes that are identified as relevant for long-term safety have been considered with the aim of determining if a safety function relating to the process could be defined, ideally accompanied by an indicator and a criterion (see below). All identified processes within the system boundary relevant to the long-term evolution of the system are described in three process reports for (i) the fuel and canister, (ii) the buffer, backfill and repository seals, and (iii) the geosphere.

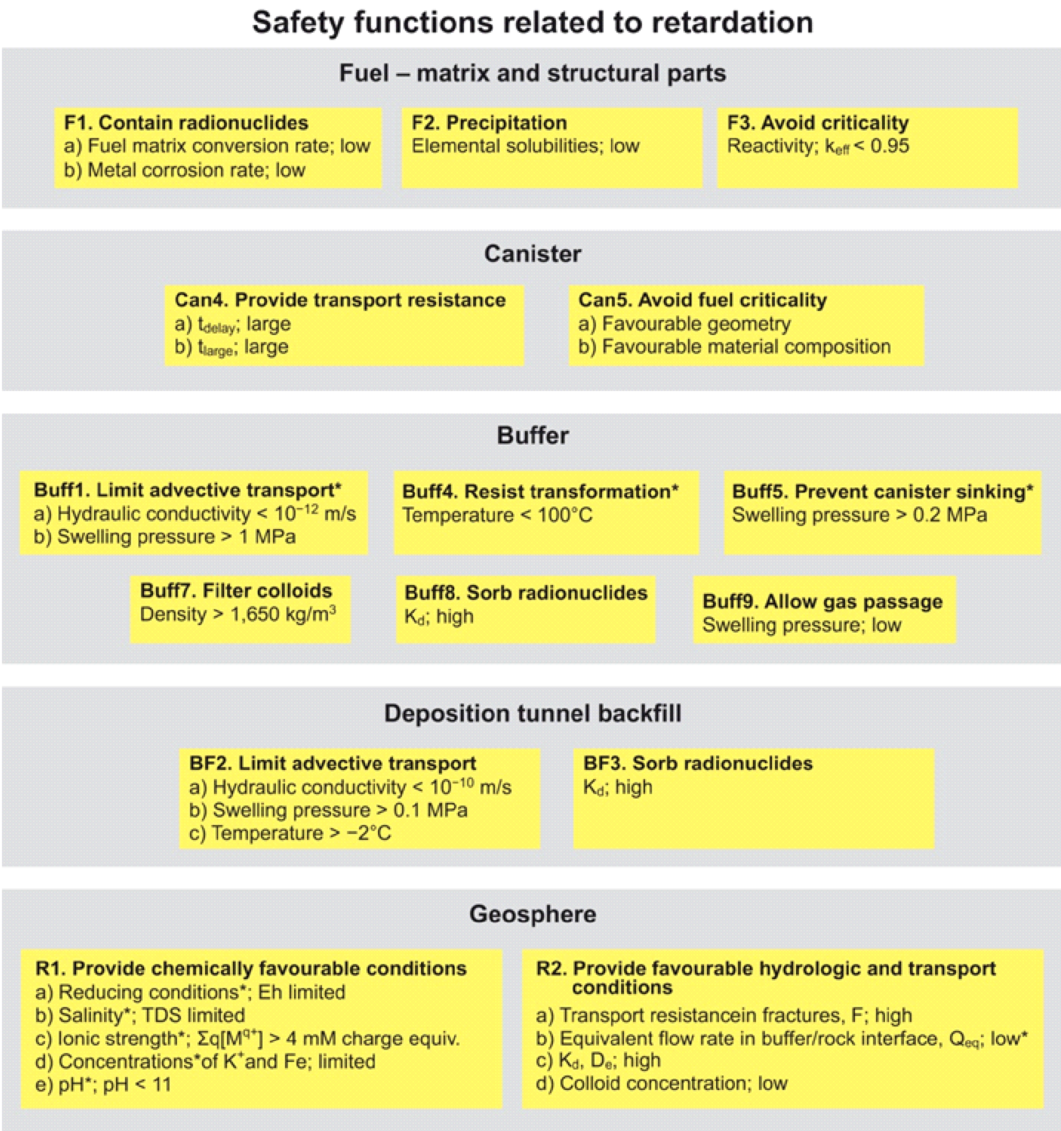
Figure A2: Safety functions (bold), safety function indicators and safety function indicator criteria related to containment. The colour coding shows how the functions contribute to the canister safety functions Can1 (red), Can2 (green) or Can3 (blue). From SKB (2011).



Based on the process identification, 14 safety functions related to the primary safety function 'containment' (Figure A2) and 15 safety function for the secondary safety function 'retardation' (Figure A3) were derived. As an example, one derived safety function for the bentonite buffer is to limit advective transport (Figure A2) so as to ensure that diffusion is the dominating mechanism for both inward transport of canister corroding agents in the groundwater and potential outward transport of radionuclides. If a particular barrier has a safety function related to limiting advective transport, then the hydraulic conductivity of the barrier may be a suitable quantity to use to evaluate the extent to which the safety function is fulfilled. In such a case, the hydraulic conductivity is said to be the safety function indicator for the safety function 'limit advective transport', which contributes to the primary safety function 'containment'.

A safety function indicator is, thus, a measurable or calculable quantity through which a safety function is quantitatively evaluated.

Figure A3: Safety functions (bold), safety function indicators and safety function indicator criteria related to retardation. Safety functions marked with an asterisk (*) apply also to containment, see Figure A2. From SKB (2011).



Safety function indicator criteria

To determine whether a safety function is maintained or not, safety function indicator criteria are defined against which the safety function indicators are evaluated over the time period covered by the safety assessment. A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained (SKB, 2006).

As stated in SKB (2011) the situation for the derivation of safety function indicator criteria is different from safety evaluations of many other technical and industrial systems in one important sense: the performance of the repository system or its parts does not, in general, change in discrete steps, compared with, say, a pump or a power system that could be characterised as either functioning or not. The repository system will evolve continuously and in many respects there will be no sharp distinction between acceptable performance and a failed system or a sub-system or regarding detailed barrier features. There are, thus, many safety function indicators for which no limit for acceptable performance can be given. The groundwater concentrations of canister corroding agents or agents detrimental to the buffer are examples of this kind of factor related to containment. When quantitative criteria cannot be given, terms like ‘high’, ‘low’ and ‘limited’ are used to indicate favourable values of the safety function indicators. Usually, they enter in more complex analyses where a number of parameters together determine behaviour, e.g. the corrosion rate of the canister. Most of the factors determining retardation are also of this nature (Figure A3).

However, there are several crucial barrier properties on which quantitative limits can be put. Regarding containment, an obvious condition is the requirement that the copper canister should nowhere be penetrated, i.e. there should, over the entire surface of the canister, be a non-zero copper thickness. In addition to this direct measure of containment performance, a number of quantitative supplementary criteria can also be defined. These relate, for example, to the peak temperature in the buffer and to requirements on buffer density and buffer swelling pressure giving favourable buffer properties for maintaining containment. Most of these determine whether certain potentially detrimental processes can be excluded from the assessment. For the example of the safety function for the bentonite buffer ‘limiting advective transport’ discussed above, the safety function indicator criterion is that a hydraulic conductivity lower than 10^{-12} m/s is required to fulfil the safety function.

It is emphasised by SKB that the breaching of a safety function indicator criterion does not mean that the repository is unsafe, but rather that more elaborate analyses and data are needed in order to evaluate safety. The criteria are an aid in determining whether safety is maintained. If the criteria are fulfilled, the safety evaluation is facilitated, but fulfilment of criteria alone is not a guarantee that the overall risk criterion (the primary safety indicator according to Swedish regulations) is fulfilled. On the other hand, compliance with the risk criterion could well be compatible with a violation of one or several of the safety function indicator criteria. A violation would be an implication of caution; further analyses could be required in order to determine the consequences on a sub-system level or a system level.

Table A1 gives a summary of criteria and notes on margins to appropriate functioning for the safety function indicator criteria for containment and retardation.

Table A1: Safety function criteria applied for SR-Site. From SKB (2011).

Indicator	Criterion	Notes on margin
Safety function: containment		
Minimum copper coverage	0	No margin, for trivial reasons.
Isostatic load on container	45 MPa	Criterion from design premises. Shown in design analysis that canister sustains load with a margin that could possibly be considerable (up to roughly 100 MPa) for global collapse.
Shear load on canister Fracture shear distance Maximum buffer density Shear velocity Minimum temperature	 5 cm 2,050 kg/m^3 1 m/s 0 °C	Set of criteria from design premises. Shown in design analysis that canister sustains shear under those conditions, but 5 cm shear is without a margin to calculated failure for the most unfavourable rock fracture locations and angles with the maximum buffer density.
Buffer maximum hydraulic conductivity (to ensure diffusion barrier properties)	10^{-12} m/s	The margin is related to the hydraulic gradient and the diffusivity of species in question. The margin is considerable.
Buffer minimum swelling pressure (to ensure self healing)	1 MPa	As the swelling pressure drops, the possibility for pathway formation in the buffer increases. There is an effect of the hydraulic gradient and possibly of salinity. Laboratory samples show piping at ~60 kPa, i.e. the margin to observed malfunction is considerable.
Buffer maximum temperature (to avoid mineral transformation)	100 °C	The extent of mineral transformations in the buffer is related to both the temperature and to the duration of the thermal pulse. Since the duration of the thermal pulse is short (on a geological timescale) the margin is considerable.
Buffer maximum swelling pressure (to limit isostatic pressure on canister)	15 MPa	Contributes to isostatic load on canister. See above for a discussion of margins on limits for isostatic load.
Buffer minimum temperature (to avoid freezing)	-4 °C	The freezing point of compacted bentonite depends strongly on density. For the lowest accepted buffer density the freezing point is c. –4 °C and for nominal buffer density, the freezing point is lower than –6 °C. For a given temperature drop below the freezing point, only a portion of the water in the bentonite turns into ice, i.e. any possible pressure build-up occurs gradually with decreasing temperature and will be less than 13.5 MPa/°C, which defines the phase boundary between ice and liquid bulk water. Furthermore, the lowering of the freezing point of water in the buffer will have additional contributions from the hydrostatic pressure at repository depth as well as from any dissolved salts in the ground water.
Buffer minimum swelling pressure (to avoid canister sinking)	0.2 MPa	Modelling has been done for swelling pressures down to 80 kPa, a value for which the consequences of canister sinking could be considered to be acceptable since for this swelling pressure, the buffer thickness below the canister would still be higher than that around the canister wall.
Groundwater minimum ionic strength (to avoid buffer erosion)	$\sum q[M^{q+}] \geq 4$ mM	The experimental margin on this value is a factor of two. However, there could be other factors that could limit erosion.
Groundwater maximum pH (to avoid detrimental effects on buffer)	≤ 11	The value is a practical limit. The duration of the conditions with increased pH and mass balances of involved reactions need to be evaluated when consequences are analysed.
Groundwater pH and chloride concentration (to avoid chloride assisted corrosion of copper)	pH > 4 and $[Cl^-]^{GW} < 2$ M	No margin to onset of chloride assisted corrosion, but considerable margin to conditions ever expected in groundwater at repository depth at Forsmark.

Indicator	Criterion	Notes on margin
Safety function: Retardation		
Fuel reactivity	$k_{eff} < 0.95$	Established according to principles generally applied for handling of nuclear fuel.
Backfill hydraulic conductivity	$< 10^{-10}$ m/s	The criterion is defined to ensure limited overall transport (not to guarantee diffusion). The margin is largely dependent on the characteristics of the rock.
Backfill swelling pressure	$P_{sw} > 0.1$ MPa	Piping has been observed at ~60 kPa, however at gradients much higher than those projected to occur in the repository.
Backfill temperature	> –2 °C	The minimum density in a cross-section the backfill will be 1,458 kg/m^3. This would give a swelling pressure of ~2.5 MPa and a critical temperature of −2 °C.

Use of safety function indicators

The safety functions with their indicators and associated criteria are used, in SKB's recent safety assessments, to structure the long-term evaluation of safety and play a key role in the selection and analyses of scenarios. They assist in the safety case essentially in three ways:

4. They provide an early identification of critical issues to be studied in the safety *assessment*.
5. In *the* analysis of a comprehensive main scenario describing a plausible evolution of the repository system, the safety function indicators provide a structure for evaluating safety. The repository evolution is analysed in a number of timeframes and for each timeframe, safety is systematically evaluated through an account of the status of the safety function indicators during and at the end of that timeframe.
6. The safety functions and safety function indicators are used in the derivation of *additional* scenarios for the evaluation of uncertainties not taken into account in the main scenario.

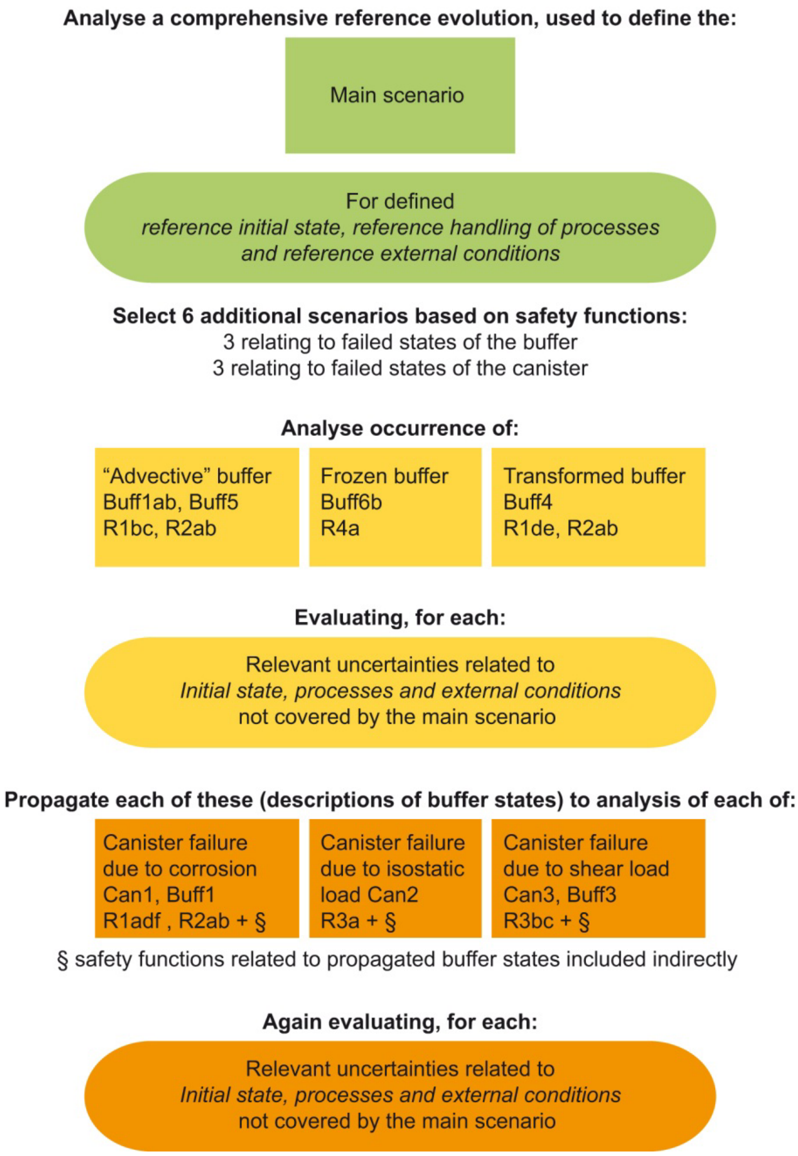
The latter aspect is a so far unique example for the application of indicators. The safety function indicators are used to obtain by a structured selection approach a set of scenarios (in addition to the main scenario) that can be argued to be comprehensive for the critical evaluation of long-term safety of the repository. The approach taken in SR-Site is to use the safety functions with their indicators and indicator criteria as expressed in Figure A4 to define a set of scenarios that are distinguished by their different status of the safety functions. The scenarios thus consider cases where the possibility and consequences of partially or completely losing one or several of the safety functions are evaluated. Examples are scenarios where canisters fail due to corrosion, to isostatic overpressure or to shear movements in fractures intersecting the deposition hole (SKB, 2011).

The approach taken when selecting scenarios is thus to ask the question: What characterises a failed repository? The answer to that question is a list of states where one or several safety functions are not upheld (the safety function criteria are not fulfilled), e.g. a situation where advection is the dominant transport mechanism in the buffer. The analyses of the selected scenarios then focus on identifying and quantifying all conceivable routes to these failed states. The goal, for each scenario, is to either dismiss it, since no credible such route can be identified, or to assess its likelihood and consequences so that it can be included in the risk summation for the repository.

Part of the procedure is schematically shown in Figure A4. The main scenario is based on the reference evolution of the repository system for a realistic initial state and for a credible evolution of external conditions over the assessment period. The safety functions directly connected to the primary safety functions are the three subordinate safety functions for canister failure. From these three canister safety functions, three scenarios are derived, namely canister failure due to corrosion, due to isostatic load or due to shear load, respectively. Since the failure of the container could be strongly affected by the properties and processes in the buffer, a comprehensive evaluation of the container failure must thus encompass an evaluation of the safety functions of the buffer.

From the buffer safety functions six related states of the buffer can be derived, namely the intact buffer, the buffer with advective conditions, the transformed buffer, the frozen buffer, the dense buffer and a buffer containing active microbes. From these six buffer states characterising a failed buffer three additional scenarios are derived, because the two scenarios dense buffer and a buffer housing microbes are related to the buffer density and the swelling pressure, and are already analysed in the appropriate canister scenarios.

Figure A4: The main components of the scenario selection and analysis procedure where safety functions of the canister and buffer are used to derive additional scenarios (yellow and orange squares). The safety function indicators of relevance in each scenario are given with the same term as in Figure A2. From SKB (2011)



For each scenario, uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration are scrutinised. The analysis of the reference evolution is used as starting point.

For illustration, consider a scenario with canister failures due to isostatic collapse, relating to safety function Can2. In this canister failure scenario, all possible routes to this failed state are critically evaluated, including assessments of the most unfavourable external conditions, in this case pressure from a glacier overburden of maximum thicknesses, and initial conditions, in this case e.g. a maximum initial buffer density yielding a maximum buffer swelling pressure acting on the canister. The aim is to determine whether the scenario should be assigned a finite probability or whether it could be ruled out as a risk contributor and only analysed as a pure ‘what if’ scenario.

More details about the approach can be found in SKB (2011). In summary, the scenario methodology is an investigation of all routes to the three identified canister failure modes aiming at ruling them out or at quantifying them, considering all conceivable evolutions of the system. The safety functions of the repository components with their indicators and the understanding of the development of the repository system emerging from the analysis of the reference evolution form the basis for exhaustive evaluations of such routes.

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SKB (2011) Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark. Main Report of the SR-Site Project, SKB Report TR-11-01, Svensk Kärnbränslehantering AB, Stockholm, Sweden.

APPENDIX A2: THE INDICATORS QUESTIONNAIRE

The Indicators Questionnaire was sent to implementing organisations and regulatory agencies in Member States in February 2010, and twenty one responses were received from the following organisations:

Organisation	Abbreviation	Country	Role
Studiecentrum voor Kernenergie	SCK•CEN	Belgium	Research Organisation
Federaal Agentschap voor Nucleaire Controle	FANC	Belgium	Regulator
Nuclear Waste Management Organisations	NWMO	Canada	Implementer
Radioactive Waste Repository Authority	RAWRA	Czech Republic	Implementer
Nuclear Research Institute	NRI	Czech Republic	Research Organisation
Posiva Oy	Posiva	Finland	Implementer
Agence nationale pour la gestion des déchets radioactifs	Andra	France	Implementer
Bundesanstalt für Geowissenschaften und Rohstoffe	BGR	Germany	Research Organisation
Gesellschaft für Anlagen- und Reaktorsicherheit (Braunschweig)	GRS-B	Germany	Research Organisation
Gesellschaft für Anlagen- und Reaktorsicherheit (Koln)	GRS-K	Germany	Research Organisation
Japan Atomic Energy Agency	JAEA	Japan	Research Organisation
Nuclear Research and Consultancy Group	NRG	Netherlands	Research Organisation
Empresa Nacional de Residuos Radioactivos SA	ENRESA	Spain	Implementer
Strålsäkerhetsmyndigheten	SSM	Sweden	Regulator
Svensk Kärnbränslehantering AB	SKB	Sweden	Implementer
Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle	Nagra	Switzerland	Implementer
Environment Agency (for England and Wales)	EA	UK	Regulator
Radioactive Waste Management Directorate (part of the Nuclear Decommissioning Authority)	RWMD	UK	Implementer
Department of Energy*	DOE	USA	Implementer
Environmental Protection Agency*	EPA	USA	Regulator
Nuclear Regulatory Commission*	NRC	USA	Regulator

*Note, the DOE, EPA and NRC collectively submitted a single response for the USA.

The questions asked in the Indicators Questionnaire are shown below, and a summary of the responses received is given in Appendix A.3.

I) Regulatory context and Guidance

I.1) What is the regulatory basis for using complementary indicators (i.e. complementary to primary safety indicators such as dose or risk) in your country? (Please provide references.)

- Does the regulator prescribe or suggest either
  - the specific indicator, or
  - type of indicator to use, or
  - the reference value(s) for comparison?
- Has the regulator issued any guidance to explain the regulatory expectations?

II) Status of Repository Development Programme.

Please explain briefly

II.1) What is the status of the repository development programme(s) in your country?

II.2) How does your use of complementary indicators support the safety case/safety assessment?

II.3) How do you anticipate that use may change as the repository development programme moves to forward stages (e.g. siting and implementation)?

II.4) If you have not used complementary indicators so far, do you intend to use them in the future?

III) Use of Complementary Indicators

Note that all the information given under issue III should be filled in table format. Please answer the following questions on the uses of complementary indicators for your most recently completed (or currently developed) safety case / safety assessment

III.1) Indicators, definitions, terminology, categorisation

For implementers or research organisations supporting them:

- Which complementary indicators have you applied in a recently completed safety case / safety assessment or are you applying to any safety case / safety assessment that is currently under development?
- If used, how did you define or categorise them? For example, did you make a distinction between safety indicators and performance indicators and/or did you derive indicators systematically from safety functions.
- Did you
  - use the definitions provided by the NEA, IAEA, or in EU reports such as the SPIN report (see e.g. draft of the MeSA issue paper), or
  - develop your own classification system, or
  - use one provided by your regulator?
- Please provide the definitions you used.

For regulators / authorities or their TSOs:

- Which complementary indicators do you require or which complementary indicators have been applied in any completed safety case / safety assessment in your country that you have reviewed?

- How were they defined or classified? Was a distinction made between safety indicators and performance indicators?
- Were the definitions
  - provided by the NEA, IAEA, or in EU reports such as the SPIN report used, or
  - was a classification system provided by you or another authority?

III.2) Purpose of the indicators

- For each indicator, please explain its purpose in the safety case/Safety Assessment. For example,
  - as additional illustrations of safety or
  - to confirm the performance of a particular system component or
  - to support decision making or
  - to optimise the repository layout
  - or any other purpose.
- Please note which indicator(s) was/were required by the regulator and which was/were developed independently by the implementer.

III.3) Time frames for indicators

- Were all indicators for all timeframes derived or calculated or were certain indicators only evaluated in certain timeframes?
- If evaluating multiple indicators in each timeframe, was their importance 'weighted' in the safety case?
- Please explain your reasoning.

III.4) Calculation / measurement of indicators

- Please explain any calculations, measurements, assumptions or definitions that were necessary to determine the indicators.
- If based on radionuclide concentration, flux or radiotoxicity, was the indicator calculated for all nuclides or a certain set?
- Please explain the reasoning behind your approach.

III.5) Reference values

- Please define what reference values were used (if any) to compare with each indicator and whether a reference value is included in the definition of the indicator or not.
- Please explain any calculations, measurements or assumptions that were necessary to derive the reference values.
- If natural abundances of radioactive or chemical species were used please list them and describe what you considered in terms of:
  - natural materials (rock, groundwater etc.),
  - geographical regions,
  - volume/time averaging calculations
- Please explain the reasoning.

III.6) Please comment on the transferability of the indicator. Do you think it is

- universally applicable, or
- site / formation specific, or
- concept specific, or
- its use is restricted by any other issue?

IV) Your Experience

Please comment briefly on your experience of using complementary indicators. For example:

- What did your complementary indicators provide that is not provided by dose or risk?
- Was it straightforward or did you have to overcome unexpected difficulties?
- How did they help you build and demonstrate confidence in the overall safety of the repository?
- Did specific indicators work especially well (or otherwise) for communicating safety case findings to specific audiences?

V) Areas of Uncertainty or Future Development

V.1) What do you believe are the greatest areas of uncertainty or difficulty with regard to complementary indicators? Please explain your reasoning!

V.2) Do you consider that greater consistency and guidance at an international level would be useful? For example, to derive common terminology (e.g. safety indicator, performance indicator, …) or a standard set of indicators and 'reference values' that might aid international comparisons? Please explain your reasoning.

VI) Indicators Table

Please fill in all information about complementary indicators asked for under issue III in a condensed form in a tabular format. [Note this information is collated and all entries included in Table 2 of this Status Report].

APPENDIX A.3: SUMMARY OF RESPONSES TO THE INDICATORS QUESTIONNAIRE

This section provides a short summary of the responses received to each question.

> I) Regulatory context and Guidance
>
> I.1) What is the regulatory basis for using complementary indicators (i.e. complementary to primary safety indicators such as dose or risk) in your country? (Please provide references.)
>
> Does the regulator prescribe or suggest either
>
> - the specific indicator, or
> - type of indicator to use, or
> - the reference value(s) for comparison?
>
> Has the regulator issued any guidance to explain the regulatory expectations?

All organisations provided answers to this question but with differing levels of detail. The more detailed answers included references to and quotes from regulatory documents, while the less detailed answers provided short overview comments.

It is evident that the regulatory basis for the use of complementary indicators varies from country to country. The common theme is that all regulatory systems recognise the potential value of indicators additional to dose and risk but they take considerably different stances when it comes to prescribing (formally) or recommending (informally) their use in safety assessments and safety cases.

In only one country (the USA) are complementary indicators currently a requirement specified in primary legislation (law). In this case, maximum permissible concentrations of certain repository derived contaminants in groundwater (^{226}Ra, ^{228}Ra, total α and β/γ) are defined for the Yucca Mountain project in 10 CFR Part 63. Similarly, maximum permissible concentrations and radionuclide-specific release limits are defined for the operating WIPP repository in 40 CFR Part 197 and 40 CFR Part 191.

In a few countries, the regulatory basis for the use of complementary indicators is addressed in secondary legislation (regulations). In Finland, regulations for spent fuel disposal (YVL 8.4) include a constraint on the amount of activity that may be released from the waste to the accessible environment. This indicator is expressed in the form of nuclide-specific radioactivity fluxes, for example the constraint for the long-lived, alpha emitting radionuclides of Ra, Th, Pa, Pu, Am and Cm is 0.03 GBq/a. Different numerical constraints apply to other important radionuclides in the waste. This flux based indicator is intended to ensure that:

- at their maximum, the radiation impacts arising from disposal can be comparable to those arising from natural radioactive substances; and
- on a large scale, the radiation impacts remain insignificantly low.

The Finnish regulations specify that that these fluxes apply to normal evolution scenarios, several thousands of years after closure, and that the fluxes can be averaged over 1,000 years at the most.

Regulations that specify the use of complementary indicators are being developed in a number of other countries. In Germany, for example, new regulations set criteria for the mechanical integrity and containment capacity of the 'containment providing rock zone' within the repository host rock that are, amongst other things, specified in terms of stress, fluid pressure and temperature. These criteria may be considered as examples of performance indicators, although this terminology is not explicitly used in the regulations.

Similarly, in Belgium, the use of complementary indicators is a requirement set out in a regulatory guide for the development of a LLW repository and it is planned to make these requirements also applicable to deep repositories. The regulatory guide includes a list of specified indicators:

- extent of the potentially contaminated zone;
- radioactivity and radiotoxicity concentrations in the liquid and solid phases;
- flux of radioactivity and radiotoxicity released out of the disposal system; and
- total radioactivity and radiotoxicity released out of the disposal system.

Reference values for these indicators are not currently provided, although reference values for radiotoxicity and radioactivity concentrations in groundwaters may be provided in later revisions of the regulations.

In most other countries (e.g. Canada, Finland, France, Sweden, Spain, Switzerland, UK), complementary indicators are addressed in the guidance documents that accompany the regulations, and usually within the wider context of 'multiple lines of reasoning' and confidence building, particularly for far-future assessment time periods. By their nature, these regulatory guidance documents are non-prescriptive but, nonetheless, the language used in them often makes it evident that the regulator has a strong expectation that the repository developer will use complementary indicators to support their safety case.

The guides usually do not specify what indicators the regulators expect to see in a safety case, or how they should be calculated, but a number of guides (e.g. Canada, Sweden and UK) do provide clear suggestions to the developer such as groundwater age and travel times, and radionuclide fluxes and concentrations in different compartments. None of these regulatory guidance documents provide quantitative reference values for comparison with the suggested indicators.

In France, in addition to setting an overall dose limit, the regulatory guide requires an evaluation of the performance of those components of the repository that have a defined safety function, individually and collectively. The guide suggests that complementary indicators may be used to do this but does not specify which ones should be used or how they should be applied.

Such non-prescriptive regulatory guidance that recommends but does not mandate the use of complementary indicators, and does not specify particular indicators to use or reference values, is the most widely adopted regulatory basis reported in the questionnaire responses.

It should be noted that the majority of the answers provided were clearly written in the context of regulation for radiological protection. In many countries, other environmental regulations will also apply and these may have relevance to complementary indicators. For example, repositories in Europe will be subject to the 2000

Water Framework Directive and the 2006 Groundwater Directive which are intended to protect groundwater from pollution from any industrial activity. National regulations that transpose these Directives are likely to set maximum permissible limits on the amount of chemical and radioactive substances in groundwater, and these may be considered as examples of complementary indicators and corresponding reference values.

II) Status of Repository Development Programme.
Please explain briefly

III) What is the status of the repository development programme(s) in your country?

All but one organisation provided an answer to this question. It is clear that the answers reflect considerable differences in the stages reached in the various national disposal programmes, with some countries having operating repositories whilst, at the other end of the spectrum, several countries are in developmental stages and are not anticipating having an operating repository for several decades.

Deep geological repository are operating in two countries: the TRU waste WIPP repository (USA) and the short-lived L/ILW repository at Morsleben (Germany), although the latter facility has now stopped accepting waste and is scheduled for closure pending regulatory approval. A further repository at Konrad (Germany) has been partially constructed and is awaiting permission to operate.

Preferred sites for spent fuel repositories have been identified at Olkiluoto (Finland) and Forsmark (Sweden), and a site for a deep L/ILW repository has also been identified in Kincardine (Canada). Detailed site characterisation work is underway at all three locations and construction licence applications are expected to be submitted in the next two to three years for each of these repositories. In the USA, the future of the Yucca Mountain project is uncertain.

Active site selection programmes are underway in a number of countries (e.g. Canada and UK). In France, the broad regional area and host rock (clay) has been chosen and the final site within that region is now being defined. In a few other countries, the preferred host rocks or rock types have also been chosen (e.g. the Boom Clay in Belgium and the Opalinus Clay in Switzerland), whilst other countries remain focussing on generic R&D and have yet to begin siting programmes.

In very general terms, the most advanced repository development programmes are also the ones that have the greatest experience in using complementary indicators. For example, much of the recent development work on the identification and application of indicators has been promoted by Germany, Sweden and Finland to support their respective programmes for recent or planned submissions of safety cases to regulators. In contrast, less emphasis has typically been placed on the development of complementary indicators in countries where regulatory submissions are not anticipated in the next several years.

This observation may also reflect a broad view that the value of complementary indicators increases significantly when a preferred site has been identified and the emphasis changes from undertaking generic safety assessments to evaluating specific impacts to a particular community and environment, and when meaningful, local reference values for comparison with safety indicators can be established (see Question III.5).

II.2) How does your use of complementary indicators support the safety case/safety assessment?

All but one organisation provided an answer to this question. One immediate and important observation is that all of the organisations who answered confirmed that they already had, or are planning to use, complementary indicators to some extent in their safety assessment programmes. This reflects the growing international awareness and perceived importance of indicators other than dose and risk.

The level of experience in developing and applying complementary indicators to safety assessment clearly varies between organisations and, to a large extent, relates to the progress in national repository development programmes, and this is reflected in the level of detail in the answers provided. Several organisations described their experience of integrating complementary indicators into a full safety assessment:

- NWMO in OPG L&ILW DGR post-closure safety assessment (2009);
- Posiva in safety assessment for Olkiluoto spent fuel repository (ongoing);
- SKB in the SR-Can spent fuel assessment (2006);
- GRS-B in the ERAM assessment for Morsleben (2007);
- ENRESA in the ENgranite (2000) and ENclay assessments (2003);
- Andra in Dossier 2005 Argile and in Dossier 2005 Granite (2005);
- Nagra in Project Opalinus Clay for HLW (2002);
- USDOE in the WIPP relicencing application (2009); and
- UDOE in the Yucca Mountain project licence application (2008).

In addition, several other safety assessments have been completed by organisations that did not respond to this questionnaire. In some of these safety assessments, just a few complementary indicators were used whilst in others greater emphasis was put upon them for system understanding and for hazard assessment, as described below.

Some other organisations that do not yet have a site to assess have gained experience in developing and testing methodologies within international efforts such as the EC-funded SPIN and PAMINA projects.

A varied range of reasons was provided in the responses for the use of complementary indicators in safety assessments and safety cases. A number of the answers were quite general and qualitative in style, and referred to a few generic objectives such as ‘building confidence’, ‘increasing system understanding’ or ‘illustrating hazard’ but they didn’t elaborate on how these objectives would be realised.

Several of the answers did, however, go into more detail when discussing the general aim of increasing system understanding and provided examples of how complementary indicators could be used to provide a measure of disaggregated system performance, including:

- to increase robustness in the safety assessment;
- to evaluate the containment/integrity/retention capability of engineered barriers;
- to evaluate the containment/integrity/retention capability of the natural barriers and biosphere;
- to verify that the safety functions of the repository components will be met, both individually and collectively;
- to describe the time dependent hazard/radiotoxicity of the waste;
- to describe the time dependent distribution of radionuclides/radiotoxicity in different compartments over time;

- to evaluate the safety of the repository system in the very long term after it has been affected by significant climate change events; and
- to evaluate radionuclide transport times across compartments and to the accessible environment.
- Similarly, several of the answers provided more detail when discussing the general aim of illustrating hazard and provided examples of how complementary indicators could be used to compare repository impacts with those from natural systems, including:
- by comparison of total radioactivity/radiotoxicity released to the surface with natural background;
- by comparison of radionuclide/radiotoxicity fluxes and concentrations in different compartments with the distributions of natural decay series radionuclides in the same compartments; and
- by comparison with radionuclide/radiotoxicity concentrations measured in drinking water and with maximum permissible levels in drinking water.

With regards to hazard, SKB noted explicitly that comparisons with natural systems can be used to provide additional arguments that the releases from the repository have only a limited effect on the environment, i.e. that the repository releases would result in only an insignificant increase in the total radiation environment at and around the repository site.

Both SKB and Andra describe using complementary indicators to evaluate the performance of specific repository components and systems against their defined safety functions, and both organisations have developed their own indicators for this purpose.

Most of the answers provided reflected one or more of the concepts listed above. The answers used a diversity of language to express these concepts (as suggested by the alternatives in the lists) but the intended meanings were broadly the same. This difference in language is partly a reflection of the lack of internationally agreed terminology.

A number of the answers gave examples of the uses of complementary indicators that were not mentioned by the other organisations, although this probably reflects the summary nature of some responses rather than actual unique thinking on the part of the organisations.

The response from the USA was the only one that explicitly mentioned the use of complementary indicators for regulatory compliance which reflects the fact that the USA specifies the use of these indicators in its primary legislation.

SKB was the only organisation to mention that safety function indicators play a prominent role in the selection of scenarios to be evaluated in the safety assessment. The answer did not elaborate further on how this is achieved but it marks an important development in the application of complementary indicators within the assessment process, rather than simply an evaluation of the results of the assessment calculations.

GRS-B was the only organisation explicitly to discuss using complementary indicators for making safety statements that are independent of those derived from dose and risk calculations, stating that:

> *"Although the calculated safety indicators were based on the same model evaluation, the safety statements are indeed independent of each other because they are compared with independent reference data like the natural radionuclide concentration in drinking water or the natural fluxes in the environment of the repository."*

The lack of discussion by the other organisations regarding the perceived independence of complementary indicators is surprising given the importance of this concept, and the application of multiple and independent lines of reasoning in a safety case.

GRS-B was also the only organisation explicitly to raise the idea of geographic scale, and mentioned that in terms of reference values some have a global while others have a local character, which needs to be considered when using complementary indicators. In answers to other questions, however, some organisations echoed this view and commented on the importance of site-specific reference values for comparison with indicators.

Although several responses mentioned the potential indicator time dependent change in the hazard posed by the waste only NWMO and Nagra expanded on this theme and explained the use of the indicator to provide a timeframe for the assessment context and a justification for a cut-off to the assessment time period.

Note that the responses from the regulators (e.g. SSM, FANC, EA) largely referred to the use of indicators by the implementing organisations in their own countries. Although regulators do sometimes undertake their own safety assessments, no such regulator-led assessments were reported in the questionnaire responses. This underpins the answers described later for Q III.1 which were addressing separately the views of implementers and regulators.

II.3) How do you anticipate that use may change as the repository development programme moves to forward stages (e.g. siting and implementation)?

All but one organisation provided an answer to this question. Unfortunately, few of the answers actually addressed the main thrust of the question which relates to the potential change in the use of complementary indicators that might be expected as a repository development programme moves from, say, generic assessments to a site-specific assessment. Instead, most answers discussed general development and improvements to their methodology for calculating and applying complementary indicators in safety assessment, but didn't address the issue of their application to a phased repository development programme.

Only NRG (Netherlands) identified in their written answer to this question that in moving towards the siting and implementation phases, there could be more emphasis placed on the use of indicators for design optimisation. Interestingly, however, a number of other organisations (FANC, ENRESA, Andra, RAWRA, BGR, GRS-K) did make reference to the potential use of complementary indicators for design optimisation in answers to other questions, even if they did not pick up on the theme in this question. In a related area, GRS-B described the methodology developed within the VerSi research project to define a set of indicators that may be used in the future with a site selection process for HLW disposal to make a choice between different repository sites. These indicators relate to the barrier system function within and including the 'containment providing rock zone'.

RWMD, ENRESA and SCK•CEN all made reference in their written answers to the fact that when moving from generic to site-specific assessments, they would be able to use real site data rather than generic or average data to inform their choice and use of indicators. The answers also show that other organisations plan to develop site specific indicators and reference values once sites are chosen.

A number of organisations suggested that they would make progressive or iterative improvements to the way they integrate complementary indicators in the safety assessments, as they further develop their approaches (e.g. ENRESA, RWMD and Andra).

Several of the organisations indicated that they do not expect there to be any significant changes in their future use of complementary indicators (e.g. NWMO, Posiva, Nagra, SSM, SKB). Not all of these 'no change' answers provided a justification for this response but it might be assumed that the programmes that have made the greatest use of indicators in previous assessments must be broadly satisfied with their use to date.

The USA response (USNRC) makes an interesting link between complementary indicators and performance confirmation monitoring in the post-emplacement stage. Once waste has been emplaced, predicted performance can be compared with actual measured performance for certain indicators (e.g. canister corrosion rates) provided measurements are possible. If deviations are identified then further analyses and investigations would be required.

II.4)	If you have not used complementary indicators so far, do you intend to use them in the future?

Only half of the organisations provided an answer to this question. All of the answers provided confirmed that the organisations already have used or are developing their thinking on the use of complementary indicators to some extent, and will continue to use them in the future.

Building on answers to the previous question, a few organisations (NRI, GRS-B) indicated that they may increase the number of indicators used. Some answers (RAWRA, NRG) raised the possibility that regulations may change in the future to prescribe the use of specific complementary indicators.

III)	Use of Complementary Indicators
III.1)	Indicators, definitions, terminology, categorisation
	For implementers or research organisations supporting them:
	Which complementary indicators have you applied in a recently completed safety case / safety assessment or are you applying to any safety case / safety assessment that is currently under development?

For this and some of the subsequent questions, several of the organisations provided no written answer but did complete the table of indicator. The discussion below covers both the written answers and entries provided in the table.

There were 120 individual indicators reported from all of the various questionnaire responses, and these are individually tabulated in Table 2 of the Status Report. This lists the non-dose and risk indicators reported by each organisation in terms of its name/description and classification (transferability, category, group and purpose). The entries in the table are taken directly from the information supplied by each organisation in their questionnaire responses and so the classification of each indicator is that provided by them.

It is obvious from the answers that many of the reported indicators are broadly similar to each other, although the exact names and descriptions used vary between the organisations. In some cases, the names and descriptions provided are rather generic (e.g. activity in compartments) whilst in other cases they appear to be specifically tailored to particular repository designs and host geological environments (e.g. the use of state of stress indicators in Germany which are specific to salt host rocks). To some extent, this difference between generic and specific forms of the indicators reflects differences in the status of national disposal programmes and the amount of experience organisations have in developing and applying complementary indicators.

Another related issue is that most indicators are reported in either of two versions based on activity and toxicity, for example radioactivity concentration compared to radiotoxicity concentration. It may be argued that these are conceptually equivalent indicators because they both provide a measure of the amount of contamination in a particular compartment of the repository system but, strictly, they are different because the radioactivity version is a gross measure of radioactive decay whilst the radiotoxicity version takes account of the potential impact on human health of the specific radionuclides decaying, assuming ingestion. In some of the answers provided by the organisations, it is likely that the terms radioactivity and radiotoxicity have been used loosely and interchangeably.

This may reflect the fact that some organisations have not yet fully developed their approach to using complementary indicators and so have not decided whether radioactivity or radiotoxicity based indicators would be most relevant to their own safety assessment context. In other cases, a distinction is clearly intended and, in a few responses, both indicators are separately listed. This differing use of the term radiotoxicity and radioactivity in the written answers probably reflects the amount of experience organisations have in developing and applying complementary indicators. Interestingly, ENRESA noted that they adopt radioactivity as a measure when referring to individual radionuclides and radiotoxicity when discussing the whole inventory. It would be useful when making intercomparisons if other organisations adopted a similar approach and explained their reasoning for the choice of indicators.

Unlike most other organisations, Andra have adopted the concept of mass as well as radioactivity or radiotoxicity to define some of their indicators, for example radionuclide molar flux (maximum) and radionuclide molar flux (mass over assessment period) can be expressed in units of mol/a.

The wide range of names and descriptions, coupled with the variable use of the terms activity and toxicity, tends to mask the real number of conceptually different indicators used by the organisations.

Looking at the indicators at a generic level it is evident that there are actually relatively few fundamentally different indicators, and that they fall into three main groups: 'content and concentration' related, 'flux' related and 'status of barrier' related. The most widely reported indicator that has been applied in safety assessment to date is radioactivity/toxicity concentration in the geosphere (groundwater) which was referenced by the majority of the organisations. The next most commonly used indicator was radioactivity/toxicity flux from the geosphere to the biosphere.

Not every organisation has applied every one of these generic style indicators in a safety assessment. A few organisations have integrated one or more of these indicators in full safety assessments (e.g. NWMO, RAWRA, Posiva, GRS-K, GRS-B, SKB, Nagra, USDOE) and other organisations have tested these indicators within international projects such as the EC SPIN and PAMINA projects (e.g. GRS-B, NRG, ENRESA). Other organisations noted that they are still developing their methodology for using complementary indicators in a safety assessment (e.g. RWMD), and so the list of indicators represents the ones they potentially may use in future assessments.

For implementers or research organisations supporting them:

- *If used, how did you define or categorise them? For example, did you make a distinction between safety indicators and performance indicators and/or did you derive indicators systematically from safety functions.*
- *Did you*
  - *use the definitions provided by the NEA, IAEA, or in EU reports such as the SPIN report (see e.g. draft of the MeSA issue paper), or*
  - *develop your own classification system, or*
  - *use one provided by your regulator?*
- *Please provide the definitions you used.*

Only around half of the organisations provided written answers to this question. Some organisations answered each sub-part (bullet) separately whilst others provided an overarching answer that addressed all parts. In general the written answers provided were relatively short and did not provide specific detail. The answers provided further information on the complementary indicators used by each organisation, and how they were categorised.

None of the organisations had developed their own classification scheme, or had them provided by the regulators.

RAWRA used definitions from IAEA TECDOC 1372 which states that 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.

Several of the organisations (GRS-B, NRG, ENRESA, Andra, SCK•CEN) stated that they had adopted the recommendations from the EC SPIN and PAMINA projects. It should be noted that the definitions from these two projects are similar but not identical, and so some of the questionnaire answers may lack precision with regard to the actual definition used by certain organisations. The most quoted definition is from PAMINA:

A safety indicator is a quantity, calculable by means of suitable models, that provides a measure for the total system performance with respect to a specific safety aspect, in comparison with a reference value quantifying a global or local level that can be proven, or is at least commonly considered, to be safe. A performance indicator is a quantity, calculable by means of appropriate models, that provides a measure for the performance of a system component, several components or the whole system.

Posiva commented that they use the definitions from the SPIN project but classify them on the basis of what they indicate (e.g. dose or activity fluxes) and upon the time period to which they apply. This is presumably because the Finnish regulations have a specific requirement for a particular flux-based indicator (a constraint on the amount of activity that may be released from the waste to the accessible environment after the period of significant climate change) but there is no prescription on the use of other indicators.

Neither NWMO, BGR nor Nagra said they apply any formal categorisation system or definitions. NWMO noted that the indicators are largely self-defining (e.g. flux across barriers), whilst Nagra noted that they had used the terms ‘complementary safety indicators’, ‘complementary safety and performance indicators’ and ‘other safety indicators’ in the Project Opalinus Clay safety assessment, but in an informal manner and these terms were used interchangeably. This is indicated in Table 2 of the Status Report in which all entries from Nagra are categorised as SI/PI.

Similarly in the USA, which applies prescriptive regulation, no distinction is made between performance indicators or safety indicators, and both types of complementary indicators are considered to have an underlying safety (risk) criterion. The indicators that are required to be calculated are specifically defined in the prescriptive USA regulations.

In Sweden, SKB and SSM also make no distinction between safety and performance but a system of safety function indicators has been developed by SKB and these are described in detail in the Main Report to the SR-Can safety assessment. This report provides the following definitions:

A safety function is a role through which a repository component contributes to safety.

A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.

A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

SKB note that safety functions are an aid to evaluating safety but the fulfilment of all safety function indicator criteria is neither necessary nor sufficient to argue safety. The different safety function indicator criteria are furthermore determined with varying margins to acceptable performance.

Andra also adopts the concept of using indicators to evaluate the safety functions of the repository and its components. Unlike SKB, however, Andra have categorised these indicators as performance indicators (and adopted the PAMINA definition of this indicator) rather than safety function indicators, although their application by both organisations in safety assessment appears to be broadly the same.

SCK•CEN noted that they have not, so far, derived indicators or requirements from safety functions but they have developed performance indicators that quantify the contribution of the active safety functions to the isolation and containment provided by the repository system. The only two other organisations to make reference to safety function indicators were RAWRA and BGR who both stated that they did not derived safety indicators systematically from the safety functions.

Other organisations (e.g. RWMD) are still developing their methodologies, and so the classification system and definitions that will be applied later in safety assessments remain open questions.

On the basis of these written answers, it is clear there is no commonly agreed approach to the classification or definition of complementary indicators, although several organisations have adopted the recommendations of the EC's SPIN and PAMINA projects and, in the absence of other specific regulatory guidance, these provide valuable support to repository developers.

The entries in Table 2 broadly confirm what was stated in the written answers. Other than NWMO who does not apply any categorisation scheme, and Nagra who use the terms safety indicator and performance indicator interchangeably, all other organisations did uniquely categorise each of the indicators they listed in the table as either safety indicators, performance indicators or safety function indicators.

All of the indicators categorised as safety indicators broadly relate to the abundance (e.g. concentration) and migration (e.g. flux) of repository derived radionuclides in the geosphere or biosphere. Examples include:

- source term / water activity on the interface repository/host rock,
- radiotoxicity concentration in biosphere water,
- power density in groundwater,
- radiotoxicity flux from the geosphere,
- concentration of radiotoxic or chemically toxic elements in the biosphere over time.

In contrast, many of the indicators categorised as performance indicators relate to the evolution and radionuclide release from the wasteform and engineered barrier system. Examples include:

- container lifetime,
- stress and fluid pressure with the containment providing rock zone,
- radiotoxicity concentration in compartments (of the engineered barriers),
- transport time through compartments,

- radiotoxicity flux over time from components of the geological disposal system.
- Some indicators categorised as performance indicators by some organisations do, however, relate to the geosphere and biosphere, such as:
- radiotoxicity in compartments (waste container, concrete buffer, gallery, clay, biosphere),
- radiotoxicity flux from compartments (flux from: waste container, disposal cell, host formation),
- radionuclide concentrations in the host rock and in the surrounding and overlying formations.
- Only BGR and SKB categorised some indicators as safety function indicators, these were:
  - state of stress (dilatancy criterion) in the containment providing rock zone [BGR]
  - state of stress (fluid pressure criterion) in the containment providing rock zone [BGR]
  - minimum copper thickness, of the canister [SKB]
  - ionic strength of groundwater [SKB]

SKB also noted that they may use a much wider range of safety function indicators other than the two examples listed above. Reference to SKB's SR-Can Main Report provides other examples [not included in their questionnaire response] of safety function indicators considered for each of the main components of the repository system.

Although Andra did not use the term safety function indicator in their questionnaire response, they did explicitly use indicators in their Dossier 2005 assessments to evaluate the following three main safety functions of the repository system:

- Resisting water circulation;
- Limiting the release of radionuclides and immobilising them in the repository; and
- Delaying and reducing the migration of radionuclides.

The indicators used to evaluate these safety functions were:

- advective and diffusive flow indicators;
- the radionuclide mass distribution between the excavated repository structures (e.g. disposal galleries, access ramps, shafts etc.) and the unaltered host clay rock;
- radionuclide activity and/or molar flux exiting each repository component (e.g. waste container, disposal cell, host rock); and
- distribution of dissolved radionuclide concentrations in the host clay rock and in the surrounding and overlying sedimentary formations.

Although this list of indicators is different in detail to those described by SKB in the SR-Can report, the approach adopted by both SKB and Andra to use indicators to evaluate repository safety functions is broadly the same. The fact that SKB define these indicators as safety function indicators and Andra describe them as performance indicators further highlights the potentially confusing difference in terminology adopted by various organisations.

It can be concluded from the practical way that many organisations (other than FANC, NWMO and Nagra) classified their own indicators that there is broad agreement amongst them that a safety indicator relates in some way to the total containment capacity afforded by the repository system, while a performance indicator relates to sub-system behaviour, where the sub-system could be any part or parts of the waste package, engineered barriers, geosphere or biosphere. This is consistent with the PAMINA definitions.

There was some difference in the way certain indicators were categorised, most notably regarding the concentration and fluxes in the biosphere. As can be seen from the bulleted lists above, some organisations have defined radiotoxicity concentration in biosphere water to be a safety indicator while other organisations have defined it as a performance indicator. Similarly, the two indicators defined as safety function indicators by BGR are defined as performance indicators by GRS-K.

The reason why apparently the same (or very similarly described) indicators are categorised differently is likely to be due to the context in which these indicators have been applied in safety assessments. For example, in one assessment an indicator may be used to make a definitive safety statement for the whole system and will be compared to a specific reference value (thus used as a safety indicator) whilst in another assessment the same indicator may be used to make a simple comparison between the containment capacity provided by alternative engineering barrier designs (thus used as a performance indicator in this context). Whilst such differences can be explained, they do not make for simple comparisons between assessments and can potentially give rise to confusion.

For regulators/authorities or their TSOs:

Which complementary indicators do you require or which complementary indicators have been applied in any completed safety case/safety assessment in your country that you have reviewed?

Fewer regulators completed the questionnaire than implementers and, consequently, only three written answers were received for this question. SSM, FANC and EA all commented that they do not set any formal requirements for operators to use specific complementary indicators but they do recommend their use in their guidance documents, and provide examples of the types of indicators that could be used, such as:

- the extent of the zone potentially impacted by the release of radionuclides;
- radiotoxicity concentrations in liquid and solid phases; and
- radiotoxicity flux out of the system.

Both FANC and EA noted that they had not yet received a safety assessment from a developer for a deep repository to review, and so cannot comment on how the developers apply the guidance. The EA did note, however, that some use of radionuclide fluxes and concentrations had been made in a developing safety case for the operating surface LLW repository in the UK, mainly to compare different options and to make comparisons with background.

In the case of the prescriptive regulatory regime operating in the USA, the EPA specifies the use of complementary indicators in 40 CFR Part 197 (for Yucca Mountain) and 40 CFR Part 191 (for general application to higher activity waste management and currently applied to WIPP). No distinction is made between safety and performance indicators in the regulations. The prescribed indicators are:

- groundwater protection standards, concentrations in groundwater (Parts 191 and 197); and
- cumulative radionuclide-specific release limits scaled to the repository inventory (Part 191).

These indicators formed part of the original application for certification of WIPP in 1998 and its re-certification applications in 2004 and 2009.

It was noted that the groundwater protection standards were based on USEPA drinking water standards, making a direct connection between radiological and environmental protection in the application of complementary indicators.

> For regulators/authorities or their TSOs:
>
> How were they defined or classified? Was a distinction made between safety indicators and performance indicators?
>
> Were the definitions
>
> - provided by the NEA, IAEA, or in EU reports such as the SPIN report used, or
> - was a classification system provided by you or another authority?

Only three written answers were received for this question. FANC commented that they do not make a distinction between safety and performance indicators, but it is expected that complementary indicators used by a developer in a safety assessment would be classified according to their purpose; i.e. assessment of radiological impact and assessment of disposal system performance. The indicators listed by FANC in Table 2 are thus not categorised as either safety or performance indicators.

GRS-K noted that current German regulations make no distinction between safety and performance indicators, and the term ‘indicator’ is not used at all. Nonetheless, new draft regulations currently set criteria for the mechanical integrity and containment capacity of the repository host rock within the ‘containment providing rock zone’ that are similar in concept to safety and performance indicators, and are categorised as such by GRS-K.

SSM noted that SKB have developed a system of safety function indicators, and do not use or recognise a separate distinction between safety and performance indicators. SSM commented that all of SKB’s safety function indicators are all, in some sense, performance measures and would be less relevant as safety indicators.

The EA does not use the terms safety indicators or performance indicators, preferring the more general descriptor environmental safety indicators in the UK regulatory guide. The EA notes that for near-surface disposal, these should be regarded primarily as performance indicators in accordance with the SPIN project definition.

> III.2) Purpose of the indicators
>
> For each indicator, please explain its purpose in the safety case/Safety Assessment. For example,
>
> – as additional illustrations of safety or
> – to confirm the performance of a particular system component or
> – to support decision making or
> – to optimise the repository layout
> – or any other purpose.
>
> Please note which indicator(s) was/were required by the regulator and which was/were developed independently by the implementer.

Most organisations provided a written answer to this question. The answers provided further information on the intended purpose of the indicators used by each organisation.

Both the written answers and entries in Table 2 of the Status Report suggest that most organisations have an intended purpose for the use of each indicator, which is typically to make either a safety statement for the entire repository system or a performance statement for a repository component. In addition, some organisation also recognise a range of additional purposes to which the same indicators can be applied, such as for design optimisation or improving communication. On the whole, the questionnaire responses would suggest that these additional applications appear to be less well developed and tested, and so the various uses to which indicators have been put (to date) can be considered as primary and secondary in nature, as indicated below.

Note that the distinction between primary and secondary purposes is made by the author and these terms were not actually used in any of the questionnaire responses.

Primary and secondary purposes for indicators

Category	Primary Purpose	Secondary Purposes
Safety indicator (SI)	Safety statements for the whole system (SSS)	Performance statement, whole system (PSS) -Design optimisation (D) -Communication (C) System understanding (S)
Performance indicator (PI)	Performance statements for a system component (PSC)	Performance statement, whole system (PSS) Design optimisation (D) Communication (C) System understanding (S) Site selection
Safety function indicator (SFI)	Performance statements for a system component (PSC)	Assessment activity (A) Design optimisation (D) Communication (C) System understanding (S)

Neither FANC nor NWMO classify their indicators as either safety, performance or safety function indicators but the reported purposes of their indicators are consistent with those in the table above but, in addition, FANC uses some indicators for performance comparison of design variants (PCV) and NWMO for model validation (V) and as an assessment activity (A), which are purposes not reported by other organisations.

In the written answers, a number of organisations expanded on the various purposes identified above and the most commonly described uses are as indicators of:

- containment which is variously expressed as system integrity, confinement performance, etc.
- radionuclide distributions and migration between components of the repository system; and
- safety hazard posed by the waste and releases to the accessible environment.

Each of these uses could be within the context of a safety assessment (e.g. multiple lines of reasoning within an integrated safety case) or for specific communication purposes.

Andra provided a detailed description of their use of performance indicators to evaluate the safety functions of the repository. In this case, performance statements for a system component (PSC) and performance statements for the whole system (PSS) can be aligned with specific safety functions and the indicators used to evaluate them. For example, the indicator distribution of dissolved radionuclide concentrations in the host clay rock and in the surrounding sedimentary formations is used explicitly to assess both the safety functions 'limiting the release of radionuclides and immobilising them in the repository' and 'delaying and reducing the migration of radionuclides'. By undertaking a quantitative assessment of time-dependent radionuclide distributions in the repository, performance statements were made regarding the barrier functions of individual components of the repository. Considering the Callovo-Oxfordian clay host rock, Andra are able to state it can lead to 'almost total confinement of actinides within a zone only a few meters wide in the near-field clay adjacent to the disposal cells'.

Interestingly, the answers to this question demonstrate a growing use of complementary indicators in a design and engineering context, such as for evaluating the performance of design variants, design optimisation and site selection. This is a relatively new area of interest that was not generally discussed in early reports promoting complementary indicators. Note that more organisations report the use of indicators for design optimisation than explicitly did so when answering Question II.3.

In the majority of cases, the indicators used and their purposes were chosen by the developer. In only a few cases are certain uses of complementary indicators specified by the regulator, notably in the USA and Finland (and in draft guidance being developed in Germany and Belgium) as discussed under Question I.1.

III.3)	Time frames for indicators Were all indicators for all timeframes derived or calculated or were certain indicators only evaluated in certain timeframes? If evaluating multiple indicators in each timeframe, was their importance 'weighted' in the safety case? Please explain your reasoning.

All but three organisations provided a written answer to this question. The entries to Table 2 of the Status Report provided some additional information on timescales.

Several of the answers noted that the calculation of dose and risk becomes progressively more uncertain in far future assessment times, and complementary indicators may provide a way to mitigate against this uncertainty in the assessment. For example, this concept is explicitly recognised in the Swedish regulatory guide produced by SSM that states the following in regard to long assessment time periods beyond 100 000 years:

"The assessment of the protective capability of the repository should instead be based on reasoning on the calculated risk together with *several supplementary indicators of the protective capability of the repository such as barrier functions, radionuclide fluxes and concentrations in the environment."*

Although no particular application of complementary indicators is specified in these regulations, this general requirement has led SKB to develop and apply a suite of safety function indicators.

Several organisations suggested that the relevance of some complementary indicators may vary in different time periods in response to the evolution of the repository system. The EA noted that different features and processes may be effective for isolating waste at different times and, by implication, different indicators may be used to evaluate this. Using similar logic, NRG commented that some indicators have specific relevance to particular time periods, such as those that relate to canister performance in the 'early' phase and those that relate to geosphere performance in the 'late' phase.

Despite reflecting on the potential for complementary indicators to have higher value in different assessment time periods, all of the organisations that have calculated complementary indicators in a safety assessment, indicated that they did so for all assessment time periods, and did not apply any weighting.

ENRESA did comment that there can be a preference for particular indicators in different timeframes even if no formal or mathematical weighting is applied, and referred to the conclusions of the SPIN project:

"…, the three proposed safety indicators and their preferred application timeframes are:

- *Effective dose rate: most relevant to early timeframes.*
- *Radiotoxicity concentration in biosphere water: preference for medium timeframes,*

– *Radiotoxicity flux from the geosphere: preference for late timeframes.*

Each of the three indicators can and should be applied to all timeframes, but there are preferences."

Similarly, GRS-B raised the importance of complementary indicators being independent of dose and risk calculations, and so suggested that their relevance is greater for far-future time periods (due to uncertainty in biosphere processes and in evaluating exposures to humans). In their ERAM assessment for Morsleben, this approach was followed and greater emphasis was placed on radiotoxicity flux to the biosphere for assessment periods in excess of 100 000 years. It should be noted that some commentators question that degree of independence of complementary indicators because they are often calculated using the same models as the safety assessment calculations, although this argument was not drawn in any of the questionnaire responses.

NWMO noted that, in general, complementary indicators such as fluxes and concentrations follow the same general time-dependent behaviour as dose, and so the main effect is in choosing relevant reference values.

In the USA, the prescriptive nature of the regulations mandates the use of particular indicators over certain time periods. So, for example at the Yucca Mountain project, doses are required to be calculated in the assessment out to 1 million years but environmental groundwater standards apply only to 10,000 years. No weighting is applied and all standards have equal measure in determining compliance.

Given that one of the early drivers for the development of complementary indicators was to mitigate against the uncertainties inherent in the calculation of dose and risk in far-future assessment time periods, it is perhaps surprising that none of the organisations gave substantially greater emphasis or weighting to their use in the longer time periods.

A couple of the answers reflected on a cut-off for the assessment time period but Nagra was the only organisation that explicitly mentioned the use of complementary indicators as a justification for a cut-off by demonstrating the very low radiotoxicity of the waste in the far-future (calculated out to 10^8 years), irrespective of its distribution in the repository or environment. FANC suggested that indicators should be quantified for as long as there is sufficient confidence in the disposal system to fulfil its safety function, and at least until the peak impact has occurred.

In another time related issue, the Finnish regulatory guide which sets nuclide-specific numerical limits for radioactivity fluxes to the surface environment, also specifies that those fluxes should be averaged over 1 000 years at the most. The time-averaging of the dynamic processes that control radionuclide distributions and fluxes is an important issue that is not explicitly addressed in any other questionnaire response. Averaging over disproportionately short or long periods may bias the calculated indicators (or reference values if derived from natural systems) and make intercomparisons between assessments difficult if different averaging periods have been used.

III.4)	Calculation / measurement of indicators Please explain any calculations, measurements, assumptions or definitions that were necessary to determine the indicators. If based on radionuclide concentration, flux or radiotoxicity, was the indicator calculated for all nuclides or a certain set? Please explain the reasoning behind your approach.

All but three organisations provided a written answer to this question. The answers varied in the level of detail provided, with a few organisation providing explicit accounts of how they calculate indicators but most answers provided short, qualitative descriptions only.

A general comment is that most organisations found it relatively simple to calculate the various complementary indicators. In the case of many of the indicators, these are calculated as intermediate outputs directly from the existing assessment codes or from supporting side calculations. With regard to the most common indicators of the form concentration in compartments or flux between compartments a few particular issues were raised in some of the answers:

- the geometry and boundaries of the compartments of the disposal system and the environment have to be more clearly defined than may normally be required in the dose and risk calculations;
- concentration-based indicators require assumptions to be made for volumes and dilution factors within compartments (e.g. amount of groundwater present in a volume of far-field rock);
- area flux-based indicators of the form Bq/km2 require assumptions to be made for the surface areas of compartment boundaries over which transfer occurs (e.g. the area of ground surface where releases occur); and
- radiotoxicity-based indicators require assumptions to be made for the amount of radionuclide ingested (e.g. total amount or that present in a specified volume of water).

None of these assumptions and associated uncertainties is grossly different in nature to those that are made in the course of normal dose and risk calculations. It is possible, however, that different assumptions may be made within different safety assessments, making intercomparisons problematic or misleading. For example, different assumptions for the area of ground over which releases may occur may lead to substantially different calculated radiotoxicity fluxes if expressed as Sv/km^2.

In the case of most of the concept-specific indicators (e.g. time to plug closure considered by NRG for a salt host rock), they cannot be calculated as intermediate outputs of the normal assessment codes and new approaches have been required to evaluate them. For example, when BGR calculate the state of stress in the containment providing rock zone they developed a finite element model of the repository with the heat generating waste in it, the surrounding salt barrier and the overlying rock to calculate the effect of interacting mechanical, thermal and hydraulic processes.

In the majority of cases, concentration, flux and radiotoxicity-based indicators were calculated for all radionuclides or at least the same set of radionuclides considered in the corresponding safety assessment for the calculation of dose and risk. Several organisations note that the indicators can be calculated for individual nuclides or restricted sets, and GRS-B note that this can help to illustrate the effect of processes such as solubility and sorption. Similarly, NRG note that although they calculate for all nuclides, they present the results for those nuclides considered to be most relevant for safety. ENRESA commented that it is sensible to present results for alpha and beta/gamma emitters separately because of their generally different transport and retardation behaviours.

Andra noted that they selected indicators specifically to address the intended safety assessment context and the purpose of specific calculations. For example, when evaluating the ability of the host clay rock to meet the safety function ‘delaying and reducing the migration of radionuclides’ with regard to the non-sorbing radionuclide ^{129}I, a total of 4 separate indicators were used: hydraulic flux, radionuclide mass distribution in the repository, molar flux, and time of maximum molar flux. The intention is to focus the indicator on the assessment objective rather than calculate all possible intermediate values indiscriminately.

In most cases, the developer has chosen the method to calculate the indicators, except in the case of the USA where the regulations prescribe the calculations that are required. It was noted that the SPIN and PAMINA projects provided a forum to test calculation methods, and several, but not all, organisations have followed the approaches from these projects.

> III.5) Reference values
>
> Please define what reference values were used (if any) to compare with each indicator and whether a reference value is included in the definition of the indicator or not.
>
> Please explain any calculations, measurements or assumptions that were necessary to derive the reference values.
>
> If natural abundances of radioactive or chemical species were used please list them and describe what you considered in terms of:
>
> - natural materials (rock, groundwater etc.),
> - geographical regions,
> - volume/time averaging calculations
>
> Please explain the reasoning.

Most organisations provided a written answer to this question. The answers provided further information on the reference values used. A few of the organisations provided details in their written answers of how reference values were calculated but most organisations simply stated the source of their reference values but did not explain their derivation.

Of the 120 complementary indicators listed in Table 2 of the Status Report only around one third had a matching reference value described either qualitatively or quantitatively. The fact that the large majority of indicators considered by the different organisations do not have an established corresponding reference value would suggest that this issue remains the most problematic area in the development and application of complementary indicators with safety assessment.

Where no reference value is provided, the written answers did not usually explain why this is the case, although there is frequent reference to the difficultly of obtaining appropriate data from natural systems. It is also clear that reference values are generally available for most indicators defined as safety indicators but are much less commonly available for those defined as performance indicators. This is consistent with the PAMINA definition of a safety indicator. The important point of this definition is that a reference value is considered to be of such high importance it is included in the definition of a safety indicator.

The PAMINA definition of a performance indicator does not, in contrast, require a reference value, and one would not be needed in many situations, such as when the behaviour of two alternative designs is being compared. A reference value could, however, be used to provide additional context depending on the purpose of the assessment and the intended audience.

As a general observation, it is clear that those organisations that have adopted the SPIN and PAMINA definitions of safety and performance indicators have mostly defined reference values for their safety indicators but have not done so for the majority of performance indicators. Many of these organisations have also quoted the same reference values that were considered in the SPIN project for the safety indicators radionuclide concentrations in groundwater (20 $\mu Sv/m^3$) and radionuclide flux to the geosphere (60 Sv/a).

Similarly, BGR and SKB which both use safety function indicators have defined these in a way that requires a matching safety function indicator criteria for comparison, and so has defined appropriate reference values for their own indicators. A similar approach is adopted by Andra who, although they do not use the term 'safety function indicator', do use performance indicators explicitly to evaluate safety functions of the repository. Andra have defined quantitative reference values in only one case (for the indicator advection/diffusion where the reference value is Pe < 2) but for all other indicators they have adopted qualitative or comparative indicators, such as the indicator radionuclide mass transport in rock v. shafts for which the indicator is 'radionuclide mass transport in host rock >> in shafts' which is consistent with the safety function 'resisting water circulation'.

The situation is less clear for organisations that do not adopt the SPIN and PAMINA definitions or do not make any distinction between types of indicators (e.g. NWMO and Nagra). In this case, it is not obvious whether or not their intended use of indicators in assessments would require a reference value or not, although both NWMO and Nagra have derived reference values from natural systems to compare with many (but not all) of the indicators they use but this appears to have been done largely to provide context to repository performance rather than as a formal evaluation.

With the exception of the USA and Finland, the written answers indicate that no regulator currently specifies both the complementary indicator to be evaluated and the reference values with which it should be compared. In the USA, the prescriptive regulatory regime includes maximum permissible limits on the concentrations of certain nuclides and total radioactivity in groundwater which are adopted as reference values for the corresponding indicators. In Finland, the regulations set nuclide-specific limits on the far-future activity fluxes (release rates) to the surface environment.

Drinking water standards are used as a reference for the indicators radiotoxicity in biosphere water and radionuclide concentration in groundwater by GRS-B and in the USA, respectively. One advantage of using drinking water standards as a reference values is that there are existing, established international values available, such as those published by the World Health Organisation. This aids intercomparisons between assessments in a way that is not possible in the case of other complementary indicators that are compared to site-specific reference values.

In Belgium, FANC is also considering providing reference values in their regulatory guide for the radiotoxicity and radioactivity concentrations in groundwaters which might be derived from maximum permissible values in drinking water. FANC also note that generic values are preferred to site specific values.

Many organisations indicated that they have derived global or regional reference values to apply in generic safety assessments and, in contrast to FANC's position, there appears to be a trend to move towards (or an intention to move towards) the use of more local and site specific reference values when preferred sites for a repository are chosen. For example, GRS use site-specific reference values for the assessment of the existing repository at Morsleben and Nagra use rock-specific reference values from the Opalinus Clay, which is their preferred host rock although a site has not yet been chosen. Both NWMO and RWMD are currently using regional or generic reference values and intend to adopt more local reference values when sites are chosen.

In some cases, complementary indicators may be compared to a number of different reference values, and not one single value, to provide greater context and illustrate the variability in natural systems. Nagra, for example, compares the indicator radiotoxicity fluxes from the repository to three different natural waters – the biosphere aquifer, and the waters from the rivers Rhine and Thur – and the indicator radiotoxicity of the wastes to the abundance of naturally occurring radionuclides in both the Opalinus Clay and three different uranium ores of different grade.

A similar approach was followed by JAEA, who compared the calculated concentrations and fluxes of repository derived radionuclides released to the biosphere (from the H12 performance assessment), with the measured abundances of naturally occurring radionuclides in a range of Japanese groundwaters and river waters, as well as the WHO drinking water standards. To demonstrate the variation in natural abundances, comparisons were made with reducing groundwaters from deep crystalline and sedimentary rock formations, as well as from shallow, oxidising hot-springs.

With a similar idea, ENRESA compared the indicator radiotoxicity fluxes from the geosphere with the preliminary values from the SPIN project but also noted that this indicator could be compared with other radiotoxicity fluxes that do not raise concern, and examples were given of such fluxes including fluxes associated with natural erosion of granitic soil and the spread of natural fertilisers. ENRESA noted that one objective of using the indicator radiotoxicity fluxes from the geosphere is to demonstrate that the releases from the repository cause only an insignificant increase to the total background radiation.

There is a potential uncertainty in defining reference values associated with the indicators of radioactivity/radiotoxicity concentrations and fluxes due to assumptions for secular equilibrium in the natural series decay chains if total activity is calculated from the abundance of parent nuclides (e.g. ^{238}U, ^{235}U, ^{232}Th). If equilibrium is assumed in the derivation of a reference value then this may result in a high (non-conservative) reference value because the volatile behaviour of Rn is likely to mean that the decay chains are in a state of disequilibrium in many groundwater systems. GRS-B thus excluded Rn and other natural radionuclides such as ^{40}K for this reason.

The variability of natural systems, even at a local and site level, introduces uncertainty in defining reference values and makes sampling and volume averaging methods very important. Similarly, there is inherent uncertainty in establishing whether the natural systems are, themselves, representative of ‘safe’ conditions. For this reason, GRS-B set reference values to one third of the natural background to capture a conservative safety margin (headroom) and enhance confidence in the safety statement given by the corresponding indicator. No other organisation discussed this issue explicitly in their answers.

In the case of most of the concept-specific indicators and engineering-related indicators (e.g. time to plug closure or container lifetime) a different approach to establishing reference values is needed than for the concentration and flux-related indicators because it is not usually possible to measure reference values directly in natural systems. It is notable that corresponding reference values have not been established for many of these engineering-related performance indicators. According to the SPIN definition, reference values are not essential for comparison with performance indicators (as they are with safety indicators) but they still may aid context and communication depending on their intended use and audience.

The situation is different, however, for engineering-related indicators that are classified as safety function indicators rather than as performance indicators (such as minimum copper thickness or canister strength) because the definition of safety function indicators used by SKB and BGR does require a matching safety function indicator criteria for comparison.

III.6) Please comment on the transferability of the indicator. Do you think it is

- universally applicable, or
- site / formation specific, or
- concept specific, or
- its use is restricted by any other issue?

Most organisations provided an answer to this question. There is a considerable divergence in views with regard to transferability on the basis of the written answers provided. On the one hand, some organisations considered that the majority of complementary indicators are ‘universally applicable’. On the other hand, several considered that the majority of complementary indicators would be specific to particular disposal systems and sites.

It is obvious why many of engineering-related indicators (e.g. time to plug closure or state of stress) are considered to be design or site specific, and not transferrable from one assessment to another. It is less obvious, however, why there is a difference of opinion regarding the concentration and flux-related indicators because conceptually they could apply to most repository systems. By way of example, the commonly referred to indicator radiotoxicity flux from the geosphere was reported to be a universal indicator by some organisations but a site specific indicator by others.

This difference may be due to the way in which some organisations have defined their indicators. Although it is possible to describe many of the indicators generically as was done in the SPIN project (e.g. activity in compartments), some organisations have defined or tailored indicators to meet the particular characteristics of their disposal concepts or host rocks (e.g. flux across the boundary from compartment A to compartment B). It is generally true that the more tailored an indicator is to a particular site and design, the less likely it is to be transferrable to other situations. GRS-B notes that the use of performance indicators is affected by the definition of compartments. The size, geometry and location of the compartments are strongly formation specific but, to some extent, also concept specific. This view was echoed by some other organisations, such as the EA who note that by their nature, complementary indicators are likely to be of narrower applicability than broader safety indicators expressed in terms of dose or risk.

It is possible, therefore, that as repository programmes move from developmental to implementation stages, the complementary indicators used may become progressively focussed on the particular characteristics of the facility design and site (especially if performance indicators are used for design optimisation), and thus less universal in nature. If this were to happen, it would make it increasingly difficult to compare the results of different assessments that had used complementary indicators.

Another reason why indicators may be considered site-specific is to do with the reference values, as suggested by GRS-B. Several of the organisations use, or intended to use, reference values derived from the site or general area in which the repository will be sited for comparison with safety indicators. Given that these reference values are site-specific, it is understandable that some organisations may also consider the indicator to be site-specific and therefore not transferrable. This is less of an issue for performance indicators that do not necessarily require a reference value (as discussed above). The transferability of safety indicators remains an area for further consideration, given the clear divergence of views.

Where indicators are prescribed in regulation, such as in the USA for WIPP and Yucca Mountain, and in Germany with the concept of the ‘containment providing rock zone’, it seems likely that they will be defined in a very site, rock or concept-specific manner and would not be directly transferrable to other situations.

IV) Your Experience

Please comment briefly on your experience of using complementary indicators. For example:

What did your complementary indicators provide that is not provided by dose or risk?

Was it straightforward or did you have to overcome unexpected difficulties?

How did they help you build and demonstrate confidence in the overall safety of the repository?

Did specific indicators work especially well (or otherwise) for communicating safety case findings to specific audiences?

All but three organisations provided an answer to this question.

Overall, the collective experience of using complementary indicators is positive, albeit most organisations considered that further work is necessary to refine the approach (see suggestions for improvements below). Several of the organisations are able to base their positive experience on fully-integrated safety assessments for actual sites and repository systems which adds weight to their claimed benefits.

The most commonly cited advantage of using complementary indicators was the fact that they allow for a much greater understanding of disaggregated system performance, such as the time dependent distribution of radiotoxicity in the various compartments and the retention capacity provided by the different barriers – neither of which is provided by standard dose and risk calculation end-points. The primary advantage of the increased understanding is to build robustness in the safety assessment and confidence in both the repository system and the assessment results. Other 'technical' advantages that were noted include:

- they are most useful for far-future timeframes in which biosphere and aquifer systems have been altered by climate change processes;
- they are subject to fewer assumptions and uncertainties than dose and risk because exposure pathways to humans do not need to be taken into account;
- they provide a linkage between system performance and observations of the site;
- they are relatively simple to use and interpret;
- they can be used to assess different sub-systems and components in the repository;
- they can help develop and understanding of the evolution of the repository over time as different processes dominate in different time periods;
- they help establish a justification for cut-off times for the assessment; and
- they provide a different perspective on environmental safety from dose and risk.

With particular reference to safety function indicators, SKB noted that they played a prominent role in the selection of scenarios in the SR-Can assessment. This is an advantage not explicitly commented on by any other organisation with regards to safety or performance indicators.

Andra commented that their use of performance indicators in the Dossier 2005 assessments was an efficient way to demonstrate that the primary safety functions for the repository components and the whole system can be achieved. They consider that the approach can be extended with other indicators developed to cover lower-level safety functions to assess the performance of secondary repository components and their intrinsic properties, and to optimise design, construction and operational issues.

In addition to the technical advantages, several organisations noted the potential for using complementary indicators for building confidence and communicating with a wide range of audiences, not just the regulatory authorities. Only a few organisations had, however, tried to use complementary indicators in a direct way to communicate with non-technical audiences and, consequently, there is limited reported experience in this area.

In general the calculation of indicators was considered relatively straightforward because they tend to be derived using the same or similar codes and models as the safety assessment. The derivation of appropriate reference values was, however, identified as an area that demands additional effort. This is particularly the case for programmes that have not yet embarked on site characterisation studies and are reliant on generic or proxy data to supply reference values for comparison with safety indicators.

Several organisations did identify limitations associated with particular indicators and the lack of commonly agreed reference values. Some of the limitations noted include:

- the absence of fission products in natural systems can call into question the validity of comparisons between repository-derived concentrations and fluxes with those in nature;
- time-integrated fluxes are potentially confusing because decay is not considered and integrated flux can be much higher than the activity present at any particular time; and
- deciding how to define a representative area/volume of rock to compare with the repository system on a site or local area basis.

Most agreed, however, that these limitations can be offset by using multiple and independent complementary indicators together with dose and risk to provide a more complete picture of the functioning of the repository system. The value comes from the advantages of one indicator balancing the limitations of another.

Referring back to the SPIN project, it was noted (NRG) that some indicators that were tested effectively overlapped and provided similar measures of system performance. For example calculation of radioactivity-based as well as radiotoxicity-based indicators was not considered to deliver any extra value, and the radiotoxicity-based indicators were preferred.

In the case of assessments for the WIPP repository in the USA, it was noted by the USDOE that there is no release and contamination in the undisturbed reference case, and so complementary indicators are not helpful and do not add value to explanations of system safety. This indicates that complementary indicators should be chosen carefully to be consistent with the repository concept and assessment context.

V)	Areas of Uncertainty or Future Development
V.1)	What do you believe are the greatest areas of uncertainty or difficulty with regard to complementary indicators? Please explain your reasoning!

All but two organisations provided an answer to this question.

There was almost universal agreement that the issue subject to the greatest uncertainty and which needs the most development is the definition of reference values, in particular reference values to compare with safety indicators. Some of the comments related to reference values include:

- whether or not reference values are essential (as in the case of the PAMINA definition of a safety indicator) or optional, depending on the different assessment methodologies that may be adopted;
- the need for suitable reference values that have global significance, for example average concentrations of naturally occurring radionuclides/radiotoxicities in different materials;
- addressing the variability inherent in natural systems and its consequences for defining appropriate spatial scales for averaging reference values at global, regional and site scales;
- misleading intercomparisons between assessments that have used different reference values to compare against the same indicator; and
- the relationship between reference values and potential detriment to man and the environment.
- Several other areas of uncertainty were highlighted in the answers, including:

- agreed usage and the potential advantages of radioactivity-based and radiotoxicity-based indicators, across the questionnaire, opinions are divided on which form of indicator provides the most value and which is more useful in communicating system performance to different audiences; and
- deciding how best to use complementary indicators to support a safety case under prescriptive regulatory regimes that specify what calculations to perform.

Although there is broad agreement that complementary indicators have a potentially useful role in communication with non-technical audiences, there is some uncertainty as to which indicators may be best used and how they should be presented. It was noted that several programmes have yet to test the use of complementary indicators with the public, and there is some concern that they could cause confusion if not appropriately presented and explained.

On this topic, BGR noted that there may be issues when presenting assessments that with performance indicators that have demonstrated lack of containment at some sub-system level. The issue here is that the safety of the repository needs to be judged on its overall behaviour and not every single complementary indicator needs to be meet its corresponding reference value for the repository to be deemed to be adequately safe. In other words, not all indicators should be treated as licensing criteria but non-technical audiences may not understand this approach.

V.2)	Do you consider that greater consistency and guidance at an international level would be useful? For example, to derive common terminology (e.g. safety indicator, performance indicator) or a standard set of indicators and 'reference values' that might aid international comparisons? Please explain your reasoning.

All but two organisations provided an answer to this question. The answers to this question reflected those given to the question above. Most organisations considered that guidance on the development and definition of reference values could usefully be done at an international level. There is not, however, any consensus on the need for harmonising reference values so that all programmes could refer to a common database, particularly for comparisons with performance indicators because these are so concept specific.

Many organisations favour making comparisons with local reference values derived from repository sites, because it helps provide context, and consequently a standard set of generic, global averages would not be relevant in these circumstances. ENRESA questioned whether reference values are best derived from the repository site or elsewhere, given that the use of site-specific values could (wrongly) potentially favour sites with high natural radiation levels.

Several organisations did, however, suggest that a catalogue of indicators and reference values used in different assessments could be developed and maintained internationally. This would aid future development and application of the methodology, particularly for programmes at an early stage and looking to establish its assessment methods.

There was also a lack of agreement on the need for international effort in other areas, such as consistency in terminology. Although it is recognised that different terminology is used (e.g. no standardisation in the naming and description of indicators) several organisations didn't consider further guidance was necessary in this area. Reasons given for this view include:

- it is too soon and individual national programmes need more time to test different approaches and build their own practical experience;

- most non-prescriptive regulatory approaches and guidelines usually place emphasis on the implementer justifying how to use complementary indicators in a manner that reflects national and local (to site) circumstances;
- to have international application, terminology would need to be quite general and that would limit its practical use; and
- given that many of the indicators under development are considered to be site or concept-specific, to a greater or lesser extent, it is not useful to define generic indicators at an international level.

That said some other organisations do favour the use of a common terminology because it promotes consistency and understanding.

A few organisations considered that it would be useful to establish a standard set of performance and safety indicators at a generic level, and include common definitions of parameters such as radiotoxicity. Other organisations consider, however, that the increasing development of concept specific performance and safety function indicators would make a common set of indicators inapplicable within a national context.

Overall, the answers to this question suggest that most organisations favour further international discussions and sharing of experiences but are cautious of moving towards developing a common 'standard' for safety and performance indicators. This is probably because, unlike traditional dose and risk calculations, the inherent value of complementary indicators lies in their flexibility to be tailored to the specific attributes of a repository design, site or assessment context.