EUROPEAN COMMISSION
Community research

PAMINA
Performance Assessment Methodologies in Application to Guide the Development of the Safety Case

(Contract Number: FP6-036404)

CONSERVATISM AND REALISM IN PA
MILESTONE (N°: M2.1.C.2)

Author(s): **D.A. Galson (Editor), R.D. Wilmot and M.B. Crawford**
Galson Sciences Limited, Oakham, UK

R. Avila and R. Broed
Facilia, Stockholm, Sweden

Date of issue of this report : **23/03/2009**

Start date of project : **01/10/2006** Duration : 36 Months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the partners of the [PAMINA] project	
CO	Confidential, only for partners of the [PAMINA] project	

Foreword

The work presented in this report was developed within the Integrated Project PAMINA: **P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. This project is part of the Sixth Framework Programme of the European Commission. It brings together 25 organisations from ten European countries and one EC Joint Research Centre in order to improve and harmonise methodologies and tools for demonstrating the safety of deep geological disposal of long-lived radioactive waste for different waste types, repository designs and geological environments. The results will be of interest to national waste management organisations, regulators and lay stakeholders.

The work is organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination of knowledge:

- In RTDC 1 the aim is to evaluate the state of the art of methodologies and approaches needed for assessing the safety of deep geological disposal, on the basis of comprehensive review of international practice. This work includes the identification of any deficiencies in methods and tools.
- In RTDC 2 the aim is to establish a framework and methodology for the treatment of uncertainty during PA and safety case development. Guidance on, and examples of, good practice will be provided on the communication and treatment of different types of uncertainty, spatial variability, the development of probabilistic safety assessment tools, and techniques for sensitivity and uncertainty analysis.
- In RTDC 3 the aim is to develop methodologies and tools for integrated PA for various geological disposal concepts. This work includes the development of PA scenarios, of the PA approach to gas migration processes, of the PA approach to radionuclide source term modelling, and of safety and performance indicators.
- In RTDC 4 the aim is to conduct several benchmark exercises on specific processes, in which quantitative comparisons are made between approaches that rely on simplifying assumptions and models, and those that rely on complex models that take into account a more complete process conceptualization in space and time.

The work presented in this report was performed in the scope of RTDC 2.

All PAMINA reports can be downloaded from http://www.ip-pamina.eu.

Milestone M2.1.C.2
Version 1.0

PAMINA WP2.1C Topic 2: Conservatism and Realism in PA

March 2009

D.A. Galson (Editor), R.D. Wilmot and M.B. Crawford

Galson Sciences Limited, Oakham, UK

R. Avila and R. Broed

Facilia, Stockholm, Sweden

Galson
SCIENCES LTD

5 Grosvenor House, Melton Road, Oakham, Rutland LE15 6AX, UK
Tel: +44 (1572) 770649   Fax: +44 (1572) 770650   www.galson-sciences.co.uk

PAMINA WP2.1.C Topic 2: Conservatism and Realism in PA

Report History

This document has been prepared by Galson Sciences Limited (GSL), AVN, and Facilia as part of the European Commission Project PAMINA FP6-036404.

Draft 1.0 (January 2008) contained an outline for the report and a completed Introduction (Section 1).

Draft 2.0 (September 2008) contained a GSL contribution as Section 2, and a draft Executive Summary and Conclusions (Section 5).

Draft 3.0 (January 2009) contained a further GSL contribution as Section 3 and a revised Executive Summary and Conclusions.

Draft 4.0 (March 2009) contained the Facilia input in Section 4 and was a full review draft.

This is the final version and accounts for comments by GSL and Facilia on Draft 4.0.

PAMINA WP2.1C Topic 2: Conservatism and Realism in PA				
Version:	Date:	Lead Author: D.A. Galson	Reviewed by: P.J. Hooker	Approved by: D.A. Galson
M2.1.C.2 Version 1.0	23 Mar. 2009	Sign ……………………… Date …………………………	Sign ……………………… Date ………………………	Sign ……………………… Date ………………………

Executive Summary

This document reports on activities performed within Topic 2 of PAMINA WP2.1C. The aim of WP2.1C is to explore the relative advantages and disadvantages of different approaches to the quantification of uncertainty in system-wide performance assessment (PA) calculations. This report deals with the question: At what stage of repository development should assessments aim to be more conservative or more realistic?

This report for PAMINA WP2.1C Topic 2 is made up from contributions by **GSL** and **Facilia**.

- **GSL** has evaluated the use of safety functions in terms of its role as a conservative approach. The work is based on interviews conducted with key staff from waste management organisations in Belgium, Sweden, Switzerland, the UK, and the US.

- **GSL** has developed guidance on when conservative and realistic assessment approaches should be used from a regulatory perspective, based on information from the International Atomic Energy Agency (IAEA) project on Application of Safety Assessment Methods for near-surface disposal of radioactive wastes (ASAM) and other sources.

- **Facilia** has carried out assessments illustrating the use of a graded approach for dealing with uncertainties in assessments of complex systems involving many processes and uncertain parameters.

Safety Functions

The work by GSL concluded that, while the principle of using safety functions in the safety case does not bias the safety case towards conservatism or realism, several mechanisms are identified which have the potential to introduce conservatism into the implementation. Examples have been found from the implementation of safety functions in a number of programmes which illustrate these mechanisms.

When using a safety functions approach in PA, introduction of unintended conservatism, or, in the case of scenario development, an unintended bias towards optimism, can be avoided by:

- Accounting for any inter-dependence of safety functions and safety function indicators.

- Applying performance limits for individual safety functions/barrier/sub-systems within the context of the performance limits for the whole repository system.

- Not placing regulatory limits on individual safety functions indicators/sub-system performance criteria.

- Applying complementary methods for scenario development in order to achieve comprehensiveness.

Regulatory Perspective on the Use of Conservative and Realistic PA Approaches

There is an inconsistency with associating the term "realism" with models because models are by their nature only approximations of what is known or surmised about the "real" entity that they intend to approximate. The term "best-estimate" analysis is better used in place of "realistic" to reflect the use of an analysis that attempts to mimic the known behaviour of a system or system element. GSL has considered the role of such "best estimate" analyses and conservative analyses in decision making, demonstrating robustness in safety of the disposal system, and in confidence building. In summary:

- From a regulatory perspective, a conservative approach to PA might be adopted when comparing the results of an analysis to regulatory performance measures for a yes/no decision – supplemented by more realistic approaches to demonstrate system understanding. However, where the decision-making concerns comparison and selection of options, then a more realistic analysis should almost always be considered or, at the very least, a consistent level of conservatism needs to be applied to the analysis of each option.

- Robustness of disposal system safety is generally best demonstrated through the use of conservative PA assumptions and parameter values, to bound uncertainty in the modelling of particular elements or to simplify the PA.

- With regard to confidence-building, conservative and best-estimate PA approaches can be used in tandem to communicate different messages: a conservative analysis provides a robust demonstration of safety; a more realistic analysis can be compared to observation and be used to demonstrate understanding, thereby building confidence in the results.

Graded Approach for Dealing with Uncertainty

Facilia has illustrated the advantages of using a graded approach for dealing with uncertainties in assessment of complex systems involving many processes and parameters. The graded approach consists of making assessments in iterations with an increasing level of realism. This allows for a reduction in scope of any more realistic assessments that may be required, for example a reduction in the number of radionuclides that need to be considered in detailed site-specific assessments. This is especially valuable for long-term assessments that are associated with large uncertainties; these assessments have to rely on predictive models and deal with lack of data and knowledge. A graded approach facilitates and strengthens the demonstration of compliance with regulatory criteria. It also provides an instrument for analysing model uncertainties, and guidance for the development of more realistic site-specific models, where required.

Contents

PAMINA WP2.1C Topic 2: Conservatism and Realism in PA

1 Introduction

This document reports on activities performed within Topic 2 of PAMINA WP2.1C. The aim of WP2.1C is to explore the relative advantages and disadvantages of different approaches to the quantification of uncertainty in system-wide performance assessment (PA) calculations. The task comprises four high-level topics (posed as questions below) that need to be addressed in determining the type of PA to be conducted, and how the results will be presented:

Topic 1 Under what circumstances is it appropriate to use probability to treat uncertainty, and under what circumstances are deterministic approaches more appropriate?

Topic 2 ***At what stage of repository development should assessments aim to be more conservative or more realistic? (this report)***

Topic 3 Do hybrid approaches such as "fuzzy mathematics" offer any advantages over standard probabilistic approaches?

Topic 4 What alternatives are there to presenting the results of PA and associated uncertainties?

The topics are being covered by performing detailed reviews and conducting research by means of case studies taken from the programmes of the organisations taking part. Individual topic reports will be produced, of which this report is one, which will be drawn together into a Task Report by the Task Leader, Galson Sciences Limited (**GSL**). The Task Report will formulate guidance for the treatment of uncertainties with respect to the four topics, as well as summarising reviews and case study results.

This report for PAMINA WP2.1C Topic 2 is made up from two contributions by **GSL** and a contribution from **Facilia**, reported in Sections 2, 3 and 4, respectively. The report concludes with a section (Section 5) that draws together the findings from its component sections into an overview that allows good practice to be identified.

GSL has evaluated the use of safety functions in terms of its role as a conservative approach. The work is based on interviews conducted with key staff from waste management organisations in Belgium (ONDRAF/NIRAS), Sweden (SKB and SKI), Switzerland (Nagra), the UK (NDA), and the US (DOE).

GSL has also developed guidance on when conservative and realistic assessment approaches should be used from a regulatory perspective, based on information from the International Atomic Energy Agency (IAEA) project on Application of Safety

Assessment Methods for near-surface disposal of radioactive wastes (ASAM) and other sources.

Facilia has carried out assessments illustrating the use of a graded approach for dealing with uncertainties in assessments of complex systems involving many processes and uncertain parameters.

2 Conservatism and Realism in the Use of Safety Functions (GSL)

2.1 Introduction

In recent years several national waste disposal organisations have used safety functions in the development of safety cases for the deep geological disposal of radioactive waste. In a European context, examples of safety cases that use safety functions are Opalinus Clay (Nagra 2002a), SAFIR2 (ONDRAF/NIRAS 2001) and SR-Can (SKB 2006).

One of the purposes of PA is to demonstrate how uncertainties are treated in developing a safety case. One approach to the treatment of uncertainty is to adopt conservative assumptions and parameter values. This study aims to determine whether the use of a safety functions approach to PA can lead to a demonstrably conservative PA approach, or whether it could introduce additional, potentially unrecognised, conservatisms to a PA. This study is part of the RTDC-2 component of PAMINA, which is concerned with the treatment of uncertainty, and complements the review of practice that has been performed in relation to safety functions methodology in PAMINA work package WP1.1. This study has also included some programmes that were not covered in WP1.1 (United States and Sweden).

2.2 Methods

There is no single, standardised approach or methodology for using safety functions in a safety case for deep geological disposal of radioactive waste, nor is there a universally recognised terminology: several approaches to using safety functions have evolved independently to deal with regulatory and technical requirements specific to national programmes. To ensure that this study adequately considers all of the ways in which safety functions might be used in safety cases, it was therefore necessary to gather information from a number of different national programmes.

The principal method used to gather information in this study has been to carry out interviews with individuals who have a thorough knowledge of the safety functions methodology that has been applied in particular programmes.

2.2.1 Interview format

A set of questions was developed for use in the interviews to elicit information in line with the aims of the study. For the convenience of interviewees, a telephone interview format was adopted, which lasted on average about one hour. Questions were asked by an Interviewer (Roger Wilmot of Galson Sciences), who also moderated the subsequent discussion. Answers were recorded by a Recorder (Amjad Khursheed of Galson Sciences), who produced the interview record. The interviews were informal, allowing time to dwell on topics of particular importance, and to follow key lines of reasoning. Interviewees were also given the option to produce a main or supplementary response in written form, and this option was taken up in several cases. The interview records in these cases were produced by synthesising the oral and written material as appropriate. In all cases, interviewees were given an opportunity to review and agree on the interview record.

The interview format was trialled in an interview conducted on 18 March 2008 with M. Capouet of the Belgian national waste disposal organisation ONDRAF/NIRAS. The exercise was reviewed internally by GSL and feedback was also sought from the interviewee. While the trial interview format was considered to be broadly successful, the interview *pro forma* was subsequently refined by omitting some questions and changing the order of others.

2.2.2 Questions used in interview

The following set of questions was used in the final interview format:

1) Summarise recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

2) What are the main functions and sub-functions that you use?

3) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, scenario development, or safety case strategy.

4) At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?

5) What possible advantages/disadvantages does a safety functions approach have for *communication* with a range of stakeholders?

6) What safety function indicators do you use and how have they been derived?

7) How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.

8) Which areas of the safety functions approach require further methodological development?

9) Is a safety functions approach to *design* inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

10) Is a safety functions approach to *assessment* inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

11) Please give key references for the safety functions approach that you have used in your recent work.

2.2.3 Experts interviewed in study

The following individuals familiar with the use of safety functions were interviewed in the course of this study:

M. Capouet (ONDRAF/NIRAS).

A. Hedin (SKB, Sweden).

B. Stromberg (SKI, Sweden).

L. Bailey (NDA, United Kingdom).

A. Van Luik (DOE, United States of America)[1].

P. Swift (SNL, United States of America).

J. Schneider (Nagra, Switzerland).

The interview records are reproduced in full in Appendix A. The organisations are all responsible for development of geological repositories, except SKI, which is a regulator. Neither SKB nor DOE/SNL are participants in Pamina, so inclusion of these organisations broadens the scope of work beyond that considered in other parts of the project that also deal with safety functions.

2.2.4 Other sources of information

As well as the interview records presented in Appendix A, the discussion below draws upon material produced for other work packages in the PAMINA project, notably WP1.1, and material already in the public domain.

2.3 Safety functions

2.3.1 The evolution of safety functions

Safety functions are a means of describing how individual repository components, design features and processes contribute to the overall safety of a disposal system.

[1] A. Van Luik and P. Swift were interviewed jointly on the use of safety functions in the Yucca Mountain Project.

Safety functions may also be used as a means of structuring safety assessments. In many respects, the concepts underlying safety functions have been used in safety cases for deep geological disposal for many years. The explicit use of a safety functions approach has, however, introduced a structure to assessments and the safety case that may not have been apparent in earlier assessment reports.

An approach complementary to the use of safety functions is the multiple barrier concept - see, for example, NEA (2003), ASN (1991), and ANDRA (2005). In the multiple barrier concept, a safety case is based on the presence of a series of barriers between the waste and human populations, and the robustness of the safety case is demonstrated by showing that at least one barrier can be disregarded and a safety case still made.

The multiple barrier concept can be viewed as being derived from the concept of "defence-in-depth", an approach transferred from the field of reactor safety and large engineering projects. In the context of reactor safety, defence-in-depth is implemented through several levels of containment and associated control systems, and a demonstration that failure of a single safety system does not compromise overall safety. A direct transfer of the defence-in-depth concept to disposal systems for radioactive waste can, however, be criticised because the barriers that contribute to safety after closure are inter-related, passive systems that may each have more than a single role in the overall safety strategy.

The recognition that barriers in a disposal system may play different, and multiple, roles, and that assuming the complete absence or failure of a passive safety barrier may be unrealistic, has led to the development of the safety function approach. More information on safety functions and their application is provided below.

2.3.2 The formulation of safety functions

The interviews with participants in programmes that are at different stages of development showed that there are several ways in which safety functions are being used in developing safety cases for deep geological disposal of radioactive waste. There are similarities between programmes in the principal safety functions identified, although there remain differences in detail and in the definitions used. One reason for differences in definition lies in whether the safety functions are generic or are design-specific.

All of the programmes studied identify isolation and containment as key generic safety functions in a deep geological disposal system. All programmes also identify the delay of any radionuclides that are released as being important but there are differences in how this process is expressed in terms of one or more safety functions. The remainder of this section summarises how the different programmes formulate safety functions.

Belgium

In Belgium, safety functions have been used extensively since the SAFIR2 safety case (ONDRAF/NIRAS 2001), where they were included in the study at a late stage after the main body of work had been completed. Since then, the safety function approach has been developed further, and now has an integral role in the Belgium programme.

A safety function is defined as (ONDRAF/NIRAS 2007):

> *"an action to be performed or fulfilled by a system or component in order to achieve the fundamental objective of providing long-term safety through the concentration and confinement strategy, while limiting the burden on future generations."*

The current ONDRAF/NIRAS safety strategy for deep geological disposal considers three main safety functions and five sub-functions as given below:

- Isolation (I).
  - I-1 reduction of the likelihood of inadvertent human intrusion and of its possible consequences.
  - I-2 ensuring stable conditions for the disposed waste and the system components.
- Engineered Containment (C).
- Retardation (R).
  - R-1 limitation of contaminant releases from the waste forms.
  - R-2 limitation of water flow through the disposal system.
  - R-3 retardation of contaminant migration.

Switzerland

In Switzerland, safety functions were used explicitly in the Project Opalinus Clay safety case (Nagra 2002a). The approach used is similar to that in Belgium, with safety functions being defined thus:

> *"The disposal system performs a number of functions relevant to long-term security and safety. These are termed safety functions…"*

In Project Opalinus Clay, three main safety functions not specific to repository site or design are defined:

- Isolation from the environment.
- Long-term confinement and radioactive decay within the disposal system.
- Attenuation of releases to the environment.

More recent work has developed the approach (Nagra 2008), and the number of main functions has been increased to five by considering delayed release, and the consequent radioactive decay, as a separate function to long-term confinement, and introducing a safety function for transfer from the geosphere to the environment. Consequently there are now the following main functions:

- Isolation from the human environment and long-term stability.

- Containment of radionuclides.
- Delayed release of radionuclides.
- Radionuclide retention in the near field and in the geosphere.
- Low release rates to the environment.

A more complete definition of these functions is given in the interview notes in Appendix A.

Sweden

In Sweden there was a preliminary consideration of the isolation and retardation safety functions in the SR-97 safety case (SKB 1999), but they were used in a qualitative manner and not developed in a quantitative way. Safety functions were used extensively in the recent SR-Can safety case (SKB 2006). Associated with the safety functions are function indicators and function indicator criteria, defined 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."*

The approach in SR-Can takes the use of safety functions beyond the generalised safety functions that may be provided by more than one component of the disposal system and identifies safety functions that are specific to particular components of the KBS-3 disposal concept. The set of safety functions defined in SR-Can is given in Figure 1, which also presents the safety function indicators that provide a means for quantitatively determining the performance of the safety functions.

Work on the safety functions developed in SR-Can is ongoing, and it is likely that the use of safety functions will be refined in the future, with perhaps the addition of more safety functions.

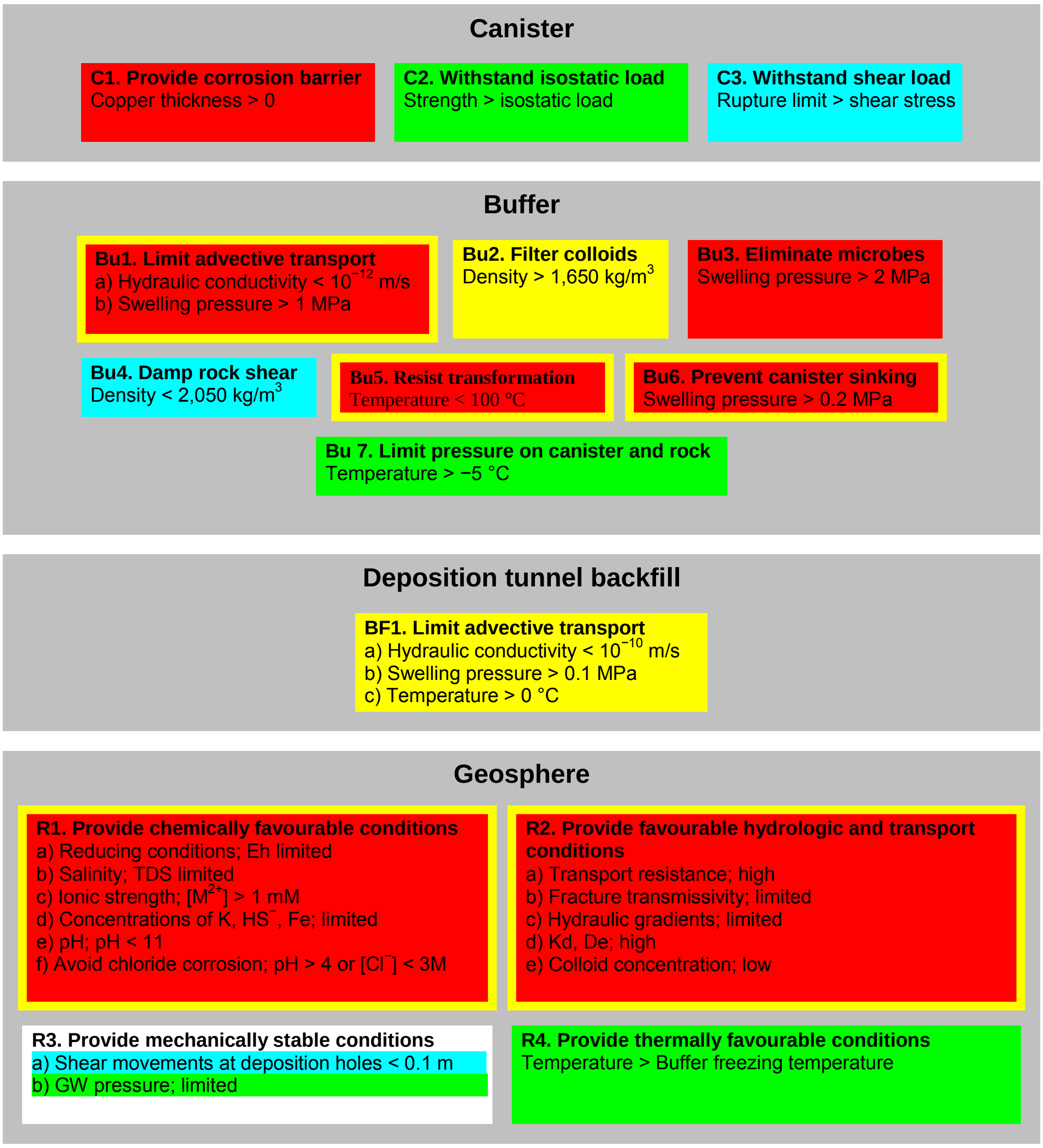

Figure 1. System of safety functions used in SR-Can, comprising safety functions (bold), safety function indicators, and safety function indicator criteria. The colour coding shows how the functions provided by the buffer, backfill and geosphere contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow border).

United States

In the United States, the recently submitted safety case for the Yucca Mountain Project (YMP) (USDOE 2008) uses the concept of "barrier functions" rather than safety functions. These concepts are similar, with the difference in terminology reflecting the distinction between analysing the effects of functions on sub-system performance (barrier functions) and analysing the effects on overall system performance or safety (safety functions).

There is a requirement in current federal regulations 10 CFR 63 (US Nuclear Regulatory Commission) that the proposed Yucca Mountain repository provide the functions of (1) preventing or substantially reducing the rate of movement of water to the waste, (2) preventing or substantially reducing the release rate of radionuclides from the waste, and (3) preventing or substantially reducing the rate of movement of radionuclides from the repository to the accessible environment. The regulations also contain a requirement to identify barriers and associated barrier functions, notably in section 63.115 of the regulations. This states that:

> *"Demonstration of compliance with § 63.113(a) must:*
>
> *(a) Identify those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation.*
>
> *(b) Describe the capability of barriers, identified as important to waste isolation, to isolate waste, taking into account uncertainties in characterizing and modeling the behavior of the barriers.*
>
> *(c) Provide the technical basis for the description of the capability of barriers, identified as important to waste isolation, to isolate waste. The technical basis for each barrier's capability shall be based on and consistent with the technical basis for the performance assessments used to demonstrate compliance with § 63.113(b) and (c)."*

In addition, components of the engineered barrier are required to have a functional lifetime of greater than 10,000 years.

As well as the three main barrier functions noted above, the Yucca Mountain Project has considered using further secondary or contributing functions, including the chemical environment that assures waste package longevity, the geochemical environment that provides sorptive capacity for certain radionuclides, and the waste package internals whose corrosion provides sorptive sites for radionuclides.

United Kingdom

In the United Kingdom, planning for deep geological disposal of higher activity wastes is at an early stage and no decisions have been reached on disposal concepts. Given the range of waste types to be managed, however, two generic concepts for deep geological disposal have been developed:

- A concept for the disposal of intermediate-level waste (ILW) in vaults at a depth of 200-1000 metres.
- A concept for the disposal of high-level waste (HLW) and spent fuel (SF) based upon the Swedish KBS-3 canister design.

Performance of these concepts has been assessed in terms of barrier functions and performance rather safety functions. Nevertheless, the following safety functions can be identified as forming part of the current repository concepts:

- **Containment** - this is considered especially for transport and handling.
- **Isolation** - provided primarily by the geosphere.
- **Retardation** and decay - in terms of the generic parameters describing groundwater flow, this function is provided through the properties of the geosphere that affect travel time (T), and through reducing flow and hence transport through the engineered barrier (Q).
- **Non-dissolution –** this function has particular value for the ILW concept, in which dissolution is controlled by conditioning of the waste and control of the chemical environment surrounding the waste packages.

Experience of using these safety functions is limited so far; it is anticipated that the approach will evolve as site selection proceeds and designs are developed.

2.3.3 Role of safety functions in the safety case

Safety functions can be used in a variety of roles. The interviews with radioactive waste management programmes conducted here discussed how the use of safety functions may contribute to the following aspects of the safety case:

- Repository design.
- PA.
- Safety case organisation/management.
- Qualitative modes of use.
- Quantitative modes of use.
- Communication with stakeholders.
- Scenario development.
- Safety case strategy.

Safety functions may be used as a means of structuring assessments of disposal system and barrier performance by considering, for example, what the effect of different assumptions about safety function performance would be on overall performance. The safety case can build confidence in the overall safety of the disposal system by demonstrating robustness despite the failure or degradation of particular safety functions.

Safety function failure or degradation can also be used in scenario development by focusing scenarios on system behaviour rather than on the causes of particular behaviour. This approach has been used in several programmes, including Belgium and Sweden. It was pointed out, however, that this approach may concentrate too much on extreme, and unlikely, scenarios (e.g., complete failure of safety functions) and insufficiently on more likely, but still significant scenarios involving the gradual degradation of safety functions. An example from the Swedish programme is the buffer erosion scenario, which was not identified by the scenario development exercise in SR-Can, but which independent review has identified as a potentially significant scenario resulting in a higher than expected number of canister failures.

In many assessment programmes, safety functions are currently used in a qualitative manner, for example to order the safety case and to direct the safety case strategy.

Safety functions can also be used quantitatively, as is the case in Sweden, to measure system performance through the specification of safety function indicators (parameters that can be used to characterise the safety function) and comparison with safety function indicator criteria (values that indicate whether the safety function is effective). This approach is discussed further in Section 2.3.5.

In both qualitative and quantitative uses of safety functions, feedback from assessment results to design assumptions can be used to iteratively develop and improve the design. Some care is required in terms of optimisation, however, to ensure that particular sub-system / safety function performance is not optimised at the expense of overall system performance and optimisation.

Safety functions are also used to identify and direct research into priority areas (Belgium). Also in the Belgian programme, safety functions are used to develop a hierarchy of “safety statements” (ONDRAF/NIRAS 2007). At the highest levels these statements are performance requirements for the repository system in order that its further development is justified. At lower levels the statements can be quite specific about the performance of individual components of the Engineered Barrier System (EBS) with respect to performance parameters. An example of such a hierarchy of safety statements is given in Figure 2 below. Safety statements are tested against the “assessment basis” for the repository concept, which is defined in accordance with the definition given by OECD/NEA in its safety case brochure of 2004 (NEA 2004).

The challenges associated with this process are the difficulty in deriving performance criteria, and the need to ensure that the hierarchy of statements is not overly rigid in its requirements, since there is frequently inter-dependence between criteria.

In nearly all interviews, safety functions were credited with aiding communication with stakeholders. An important aspect of safety functions in this respect is their usefulness for passing on the idea that failure of individual barriers, a source of anxiety to lay stakeholders, does not mean failure of the system, since the system has been designed to cope with such failures.

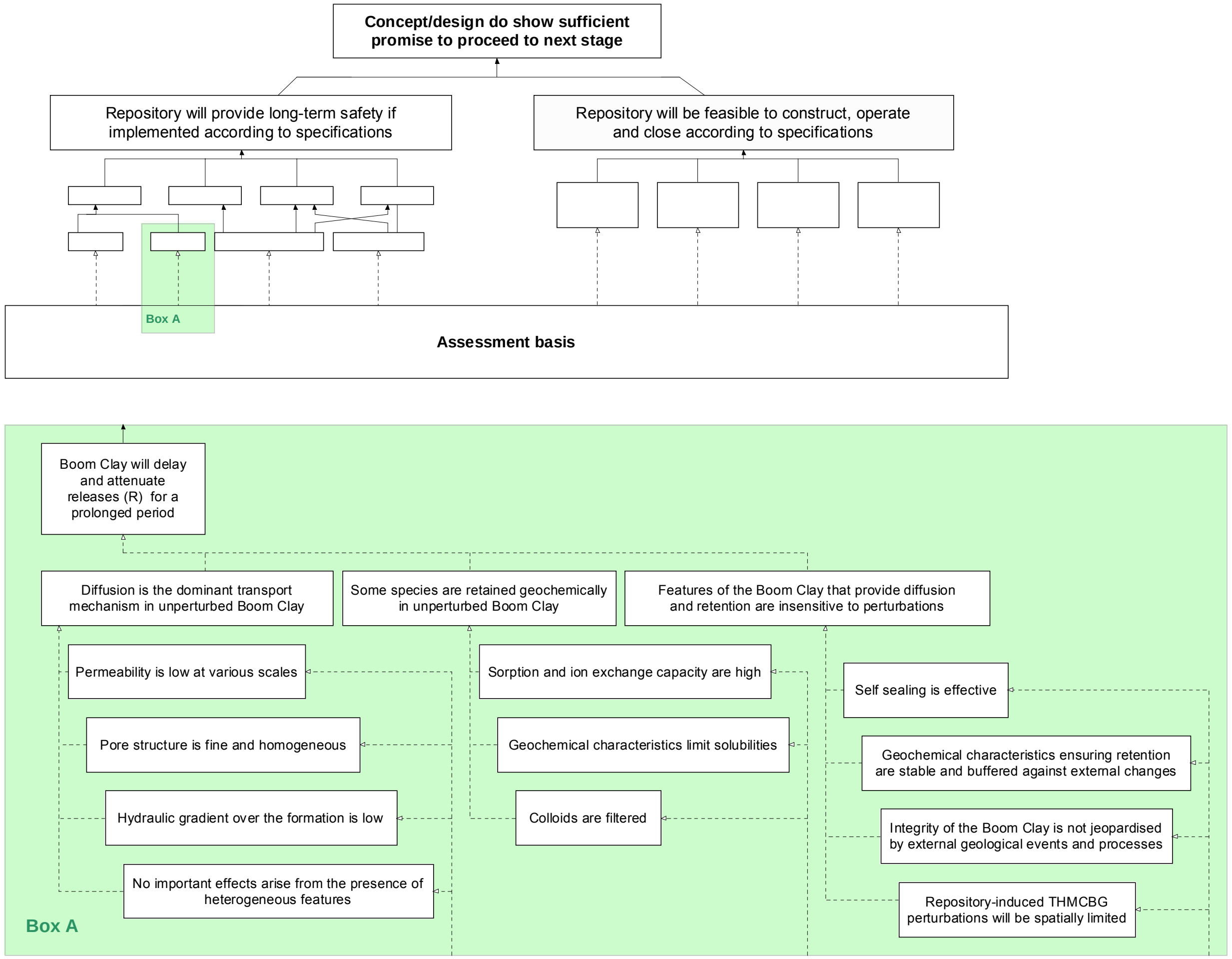

Figure 2. Illustration of hierarchical arrangement of Safety Statements constructed by ONDRAF/NIRAS in Belgium in support of demonstration of feasibility for their repository concept.

2.3.4 Using safety functions at different stages in the development of a programme for deep geological disposal

There was a consensus view among the interviewed experts that safety functions have a role to play in the safety case right through the development and implementation of a programme for deep geological disposal of radioactive waste. However, some thought that their value would increase as the programme entered into its later stages, when site and design had been selected. Use of safety functions early in the programme is likely to focus on broad design issues, while in the later stages their assessment role can be developed more fully. Communication with other stakeholders, notably the host community and regulators, is also likely to become more intense in the later stages of programme, and again safety functions may be useful in this respect.

2.3.5 Safety function indicators and criteria

The quantitative use of safety functions requires the definition of "safety function indicators". There are two types of safety function indicator:

- Properties of a barrier or repository component that provide a safety function (e.g., sorptive capacity of a barrier that provides a retardation safety function).
- Measures of how well a barrier or repository component performs a given safety function (e.g., flux of radionuclides through a barrier that provides a retardation safety function).

A key part of the quantitative use of safety function indicators is the definition of limits or criteria against which performance can be judged. Identification of indicators can be done at almost any stage of the programme once an overall disposal concept has been identified. Setting limits or criteria and assessing performance, however, require information about repository design and site characteristics that is only likely to be known once a programme has achieved a certain degree of maturity. Currently, in Europe, only the Swedish programme is at a sufficiently mature stage to develop quantitative criteria, although several of the interviewees expressed hopes that the quantitative use of safety functions would be developed.

In the Swedish programme, a number of design-specific safety function indicators and associated criteria have been formulated in the SR-Can safety case (see Figure 1). The criteria have been derived independently of any regulatory limits, which apply to the performance of the whole disposal system and not to safety functions or individual barriers. The derivation of these criteria has been the subject of criticism in the response of the Swedish regulator to the safety case submission on the grounds that the values are poorly argued (SKI and SSI 2008). They have also been the subject of criticism from community activists; however, this criticism is focused on the freedom that the implementer has to change the safety function indicator criteria at will without reference to regulation. The lesson to be learnt from this case is that the formal application of safety function indicators needs to be well justified.

The Swedish experience shows that certain safety functions indicators lend themselves to the setting of criteria, while others do not (see SKB interview record). An example of a safety function indicator criterion that can be readily established is for the safety function indicator “ionic strength” (R1d). The R1 safety function for the geosphere is to provide chemically favourable conditions for the canister and buffer, and acceptable values or the criterion for ionic strength as a safety function indicator are/is readily defined. An example of a criterion that is less readily defined is for the buffer temperature safety function indicator (Bu5). At high temperatures, clay mineral transformations may occur within the buffer and change its properties. There is no well-defined temperature limit for this transformation, and the selection of a criterion is a judgement based on information about the rate and significance of any consequent transformation. The value adopted in the SR-Can safety case represents a conservative assumption in the sense that this criterion could be relaxed without significantly affecting the performance of the buffer

These two examples of criteria are representative, in turn, of two types of safety function:

- Safety functions for which there are clear physical limits which determine whether the function is working or not.

- Safety functions for which performance lies along a continuum and which may be regarded as degraded, but not necessarily failed.

There are two examples of the use of the second type of safety function indicators (although, in neither case has the safety function terminology been used):

- In Finland, Guide YVL 8.4 (STUK 2001) gives nuclide-specific constraints for activity releases to the environment.

- In the US, regulations for the WIPP site (USEPA 1993) include requirements on cumulative releases from the controlled area.

The development of alternative safety indicators for repository systems has been the subject of recent European studies (SPIN), which have distinguished between safety indicators and performance indicators (Stork and Becker 2004). Safety indicators provide a statement about the safety of the whole system and are integrated across the whole spectrum of radionuclides. The principal example is the effective dose rate, for which criteria are set in many regulations. Performance indicators provide statements about the whole system or sub-systems and can be integral or nuclide-specific. Performance indicators are identified through a consideration of safety functions and are generally based on measures of activity and concentration in different compartments, travel times through compartments, and fluxes between compartments.

A safety indicator can only provide a statement on safety if it is compared to a suitable reference value. Storck and Becker (2004) give reference values based on regulations or natural concentrations and fluxes. Performance indicators can be used to help understand how the disposal system behaves, to compare options, and to support qualitative arguments on safety. For these purposes, criteria are not necessarily required. Performance indicators can also be compared with quantitative criteria, but similar issues to those noted above for setting criteria on safety function indicators are applicable to setting criteria on performance.

As programmes that currently use safety functions in a qualitative manner (such as in Belgium and Switzerland) progress towards site-specific designs, there will be opportunities to develop quantitative implementations of the safety functions approach. A challenge for programmes that employ general high-level safety functions, such as isolation and retardation, will be to define safety function indicators that are independent and correspond to individual safety functions. The problem can be illustrated by considering defining a safety function indicator for the R3 contaminant retardation sub-function defined by ONDRAF/NIRAS in the Belgian programme. This sub-function may be performed by several components of the system, including the waste form, the bentonite buffer, the backfill material and the surrounding host rock. Assessing the effectiveness of this function is also dependent on the operation of other functions, including the two other retardation sub-functions R1 and R2, and the two isolation sub-functions I1 and I2. Further methodological development of the safety functions approach may be required to provide a means of assessing the effectiveness of particular safety functions.

2.4 Mechanisms by which conservatism may be introduced into a safety functions approach

Conservatism is a well established strategy for treating uncertainty in numerical assessments where the aim of the assessment is to demonstrate compliance with performance limits. The argument put forward is that if compliance with regulatory criteria can be demonstrated when a number of conservative assumptions are made about system behaviour, then it is very likely that the actual performance of the disposal system will satisfy these criteria.

Conservatism has also been used as an initial means of treating uncertainties, adopted when little is known about the characteristics of the uncertainties. The argument put forward in this case is that when there is more information about the uncertainties, more sophisticated means of treating uncertainty can be adopted. A counter argument, put forward in a study commissioned by IAEA as part of its ASAM methodology (Application of Safety Assessment for Near Surface Disposal Facilities) (IAEA 2006), is that in order to achieve conservatism, prior knowledge must be attained about the most likely (realistic) values. If this is the case, then alternative methods for treating uncertainty might also be viable in the first place.

Conservatisms have a role in assessments, provided their limitations are recognised. It is also important that the results of assessments that include conservative assumptions are used appropriately. In particular, optimisation in terms of cost and performance needs to be based on calculations that do not include conservative assumptions or parameter values concerning the optimised component or conditions. Recognising all sources of conservatism within assessments can increase transparency and improve decision-making.

Most of the interviewed experts stated that they did not think that using a safety functions approach in the safety case is inherently conservative, realistic or optimistic. Any bias towards either of these arises from the manner in which safety functions are applied, and from strategic decisions made in the repository programme.

There are several ways in which safety functions, or the way in which they are used, can introduce conservatism into a design or a safety case. These include:

- Selection of conservative values for limits on safety function performance.
- Application of limits on safety function performance without taking into account inter-dependencies between sub-systems and safety functions.
- Regulatory requirements on safety functions/sub-system performance.

It is possible, though less likely, for a safety functions approach to introduce undue optimism into a safety case through the adoption or application of inappropriate values or limits. Of more concern, however, is how a safety functions approach may lead to undue optimism through a lack of comprehensiveness in scenario development.

These mechanisms for the introduction of conservatism or optimism through the use of safety functions are explored in greater depth below, and are illustrated with examples taken from the interviews with experts to support the discussion.

Selection of limits on safety function performance

If a quantitative approach to using safety functions as measures of sub-system performance is adopted, it becomes necessary to set limits or criteria that determine whether a safety function is satisfied by a particular design or set of assessment assumptions.

As discussed in Section 2.3.5, the values adopted for these limits are themselves subject to uncertainty and the need for judgement. If overly conservative values are adopted, this has the effect of requiring better performance from the sub-system providing the safety function. This may lead, in turn, to an over-specification of requirements and properties for the sub-system. If there are already conservative assumptions involved in determining sub-system behaviour, then it will be difficult to determine which parts of the system actually contribute most to safety or to optimise the design.

In the current dialogue between the Swedish regulators and waste implementer, the term “margins” is being used with respect to adopting a systematic approach to treating the uncertainty associated with safety function indicator criteria (the limits on safety function indicators in the SR-Can safety case). The implication of this term is that information is required about how the limits have been derived, the level of in-built conservatism and how sensitive the performance of the function is to deviation from the limits. All of this information is required if judgements are to made about the significance of meeting or not meeting the limits or criteria, or if changes to the limits are to be made in a transparent manner.

One possible approach to deriving safety function indicator limits is to base them on performance limits for the whole system, most obviously regulatory limits on individual dose or risk. This approach may be most appropriate for a mature, site-specific, repository design, since it assumes that many design elements and environmental factors are fixed. It can be argued, however, that it adds no new knowledge to the analysis, and a limit derived in this way is a secondary quantity which depends on an existing analysis of the whole system. Also, any limits derived from an overall performance measure will be influenced by the behaviour of all safety functions and, therefore, not necessarily provide an independent measure of safety function performance.

As an example of deriving limits, work in Finland has been done to use levels of naturally occurring radionuclides to derive limits on radionuclide fluxes originating from repositories. Guide YVL 8.4 (STUK 2001) gives nuclide-specific constraints for activity releases to the environment on the basis that

> *"1) at their maximum, the radiation impacts arising from disposal can be comparable to those from natural radioactive substances; and*
>
> *2) on a large scale, the radiation impacts remain insignificantly low."*

This approach is similar to that of defining safety function indicators in terms of radionuclide fluxes that was evaluated by Storck and Becker (2004). They concluded, however, that the Finnish approach of deriving reference levels was highly dependent on local conditions and the reference levels cannot be transferred easily to other programmes.

Overall, the conclusion is that the derivation of appropriate limits for safety function indicators should, as far as possible, be based on the performance of particular barriers or sub-systems, rather than at a higher level. A systematic, well-argued derivation of limits is needed to avoid undue conservatism and to provide the necessary level of confidence and transparency.

Application of limits on safety function performance

As well as adopting conservative values for limits, conservatism may also be introduced by applying a safety strategy that requires that several or more safety function indicator limits are satisfied independently from each other. This can be illustrated by considering the retardation (R) safety function defined in the safety functions approach used by ONDRAF/NIRAS.

In the ONDRAF/NIRAS approach to the use of safety functions, as set out in ONDRAF/NIRAS (2007), safety functions are applied to the safety case through the formulation of a set of safety statements, which are then supported by the assessment basis for the safety case. The set of safety statements take on a hierarchical form, beginning at the top level with statements that are requirements for the system (see

Figure 2). At the lower levels, these safety statements give rise to quantitative requirements for performance from the whole system, and sub-systems.

As noted in the discussion above (Section 2.3.5), where the retardation sub-function R3 is taken as an illustrative example, this sub-function is provided by several system components and may also be dependent upon the other two retardation sub-functions. Consequently, the set of safety statements produces a set of requirements with a high degree of inter-dependence. If all of these requirements are satisfied independently, through application of limits or criteria, a significant degree of conservatism may be introduced relative to meeting an overall system requirement on retardation.

The derivation of appropriate limits for safety function indicators should take account of interdependencies between sub-systems and between safety functions. To avoid undue conservatism, it may be appropriate to apply qualitative criteria to the performance of individual sub-systems and to apply quantitative limits only to an aggregation of sub-systems.

Regulatory requirements

Conservatisms can be introduced into a PA or into the requirements on sub-system performance by the regulatory regime that operates in the country. Conservatisms in PA may arise through a requirement that conservative values are adopted for parameters used in the assessment. Conservatisms in sub-system performance may arise through the stipulation of conservative performance requirements for the components of the disposal system.

The use of conservative values for parameters is a technique that is widely used in PA when there are large uncertainties that have not been quantified, and it is not restricted to the specification of safety functions and their limits. For example, the current regulatory regimes that apply in Finland and Switzerland specify that conservatism should be built into PA methodology as a default approach for treatment of uncertainties (Finnish Government 1999, HSK/KSA 1993).

As noted above, conservatisms in component performance may arise where a safety functions approach adopts conservative limits or does not consider inter-dependencies. A similar situation may arise where regulations require components to meet specified criteria. Generally, regulations are established independently of detailed information about the disposal concept or site, and so few national regulators appear to favour the use of regulatory limits on sub-system performance. An example of the effect of requirements on sub-system performance is provided by the evolution of regulations for Yucca Mountain.

In developing the generic regulations for high-level waste disposal (10 CFR 60), the US Nuclear Regulatory Commission (NRC) prescribed minimum performance standards for each of the major system elements (as they were envisioned at the time) as well as an overall system performance objective. It was argued that barriers could be prescribed, generically, which would act “independently,” and that generic performance measures for these “independent” barriers could be selected that would reduce calculational uncertainty. Identification of such sub-system performance measures was expected to be a helpful input to the repository design process, without being overly restrictive. Moreover, it was believed, at the time, that compensation for uncertainties in assessing the system's overall performance could only be achieved by introducing conservatism. Intentional addition of conservatism, either by making the measure of performance unduly stringent or by using worst-case, bounding assumptions in the evaluation, was argued to be impractical from a regulatory point of view.

It is now recognised that the NRC attempted to define barrier performance criteria on the basis of limited existing knowledge, without the benefit of research and site-specific information that was later acquired during characterisation of a specific site at Yucca Mountain. This meant that the requirements were seen as overly prescriptive, lacking in both a strong technical basis and a clear technical nexus to the overall performance objective, and unclear in their wording

As a result of the concerns raised concerning the generic regulations, the NRC's site-specific regulations for Yucca Mountain (10 CFR 63) now require an evaluation of the behaviour of barriers important to waste isolation in the context of the performance of the geologic repository, without specific numerical goals for the performance of individual barriers. These regulations require an analysis that:

- Identifies those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation.
- Describes the capability of these barriers to isolate waste, taking into account uncertainties in characterising and modelling the barriers.
- Provides the technical basis for the description of the capability of these barriers.

These regulations also include a requirement to demonstrate that the geologic repository comprises multiple barriers, but do not prescribe which barriers are important to waste isolation or the methods to describe their capability to isolate waste.

It is interesting to note the change from concerns regarding undue conservatism, if only overall performance is considered, to the recognition that the specification of sub-system performance criteria in regulations also introduces conservatisms that can be avoided.

Scenario development

Safety functions have been used in several programmes as a means of developing alternative scenarios for the long-term evolution of a disposal system. Proponents of a safety functions approach have found this to be one of the most useful roles for safety functions. Consideration of the "time frames" over which safety functions are active, latent or fail leads to the identification of a set of scenarios for analysis in a PA. This approach is considered to be good for identifying performance-limiting scenarios, and to be more efficient than using lists of features, events and processes (FEPs), many of which may be irrelevant to scenario development (see Nagra interview record).

However, in the regulator's response to SKB's recent SR-Can safety case, which used a safety functions approach for scenario development, one of the most significant deficiencies was noted to be the absence of a scenario for buffer erosion (see interview record for SKI). This scenario could result in a significantly higher rate of canister failure than others that have been analysed in the SR-Can safety case. This suggests that the safety functions approach to scenario development may concentrate too much on extreme, and unlikely, scenarios (i.e., complete failure of safety functions) and insufficiently on more likely, and still potentially significant, scenarios involving the more gradual degradation of safety functions. Omitting this type of scenario may introduce an unintended bias towards optimism in the PA.

2.5 Conclusions

The increasing use of safety functions is a positive development in safety case methodology, which has the potential to strengthen safety cases for the deep geological disposal of radioactive waste, and improve communications with a variety of stakeholders.

Approaches using safety functions contain elements of previous approaches which explain repository performance in terms of barriers, but develop these elements and use them to structure safety arguments. There is no established convention in the application of safety functions, rather a variety of approaches has developed in response to regulatory requirements and past experiences in individual countries.

A safety functions approach is a valuable tool that can be used in various ways to support the analysis of the repository design/concept, and development of the safety case. However, using safety functions in a quantitative manner in, for example, optimisation studies, is limited by the need to identify meaningful limits or criteria on safety function performance.

It is concluded that, while the principle of using safety functions in the safety case does not bias the safety case towards conservatism or realism, several mechanisms are identified which have the potential to introduce conservatism into the implementation. Examples have been found from the implementation of safety functions in a number of programmes which illustrate these mechanisms.

When using a safety functions approach in PA, introduction of unintended conservatism, or, in the case of scenario development, an unintended bias towards optimism, can be avoided by:

- Accounting for any inter-dependence of safety functions and safety function indicators.

- Applying performance limits for individual safety functions/barrier/sub-systems within the context of the performance limits for the whole repository system.
- Not placing regulatory limits on individual safety functions indicators/sub-system performance criteria.
- Applying complementary methods for scenario development in order to achieve comprehensiveness.

2.6 References

ANDRA 2005. Dossier 2005 Argile: Safety Evaluation of a geological repository. ANDRA Report no. 782, Paris, France. (Published in English in 2007).

ASN, 1991. Regle Fondamentale de surete RFS.III.2.f relative aux objectifs a retener dans les phases d'etudes et de travaux pour le stockage definitive des dechets radioactifs en formation geologique profonde afin d'assurer la surete la periode d'exploitation du stockage (10 Juin 1991), French Nuclear Safety Authority (ASN), Paris, France.

Becker, D. *et al.* 2003. Testing of safety and performance indicators (SPIN). European Commission Report EUR 19965EN, Brussels, Belgium.

Finnish Government 1999. Decision 478 Council of state decision on safety of disposal of nuclear fuel (478/1999). Helsinki, Finland.

HSK/KSA 1993. Protection objectives for the disposal of radioactive waste, HSK-R-21/e. Swiss Federal Nuclear Safety Inspectorate (HSK) and Federal Commission for the Safety of Nuclear Installations (KSA), Villigen-HSK, Switzerland.

IAEA 2006. Application of Safety Assessment Methodologies for Near Surface Disposal Facilities (ASAM). Common Application Aspects Working Group. Position Paper. Roles of Conservatism and Realism. International Atomic Energy Agency (IAEA), Vienna, Austria (December 2006).

Nagra 2002a. Project Opalinus Clay: Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05. Nagra, Wettingen, Switzerland.

Nagra 2002b. Project Opalinus Clay: Models, codes and data for safety assessment. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-06. Nagra, Wettingen, Switzerland.

Nagra 2008. Vorschlag geologischer Standortgebiete für ein SMA- und ein HAA-Lager: Begründung der Abfallzuteilung, der Barrierensysteme und der Anforderungen an die Geologie – Bericht zur Sicherheit und Machbarkeit, Nagra Technical Report NTB 08-05. Nagra, Wettingen, Switzerland. (Expected publication date: 2nd half of 2008.)

NEA 2003. Engineered barrier systems and the safety of deep geological repositories. OECD Nuclear Energy Agency (NEA), Report no. EUR 19964, Paris, France.

NEA 2004. Post-closure safety case for geological repositories: nature and purpose. OECD Nuclear Energy Agency (NEA) Report no. 3679, Paris, France.

ONDRAF/NIRAS 2001. SAFIR 2: Safety Assessment and Feasibility Interim Report 2. ONDRAF/NIRAS, Report NIROND 2001-06 E, Brussels, Belgium.

ONDRAF/NIRAS 2007. The ONDRAF/NIRAS Long-term Safety Strategy for disposal of high level waste. NIROND-TR 2006-04 E, Brussels, Belgium.

SKB 1999. SR 97 - Deep repository for spent nuclear fuel. SR 97 - Post-closure safety. Main report - Vol. I, Vol. II and Summary. SKB Technical Reporteport TR-99-06, Stockholm, Sweden.

SKB 2006. SKB. Long-term safety for KBS-3 repositories at Forsmark and Laxemar - a first evaluation. Main report of the SR-Can project. SKB Technical Report TR-06-09, Stockholm, Sweden.

SSI and SKI 2008. SKI:s och SSI:s gemensamma granskning av SKB:s Säkerhetsrapport SR-Can. Granskningsrapport. SSI rapport 2008:04/SKI 2008:19, Statens strålskyddsinstitut (SSI) / Statens kärnkraftinspektion (SKI), Stockholm, Sweden.

Storck R. and Becker D.-A. 2004. R. Testing of safety and performance indicators and their relevance to the safety case. Euradwaste '04 Conference, Luxemburg.

STUK 2001. Long-term safety of disposal of spent nuclear fuel. Finnish Nuclear Safety Regulator (STUK) Guide no. YVL 8.4, Helsinki, Finland.

USDOE 2008. Yucca Mountain Repository license application: safety analysis report. United States Department of Energy (DOE), Washington DC, United States.

USEPA 1993. 40 CFR 191 - Title 40 Code of Federal Regulations Part 191: Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes; Final Rule. Federal Register, Vol. 58, No. 242, pp. 66398-66416. Office of Radiation and Indoor Air, Washington DC, United States.

USNRC. 10 CFR 60 - Title 10 Code of Federal Regulations Part 60: Disposal of high level radioactive wastes in geologic repositories. United States Nuclear Regulatory Commission (NRC), Washington DC, United States.

USNRC. 10 CRF 63 - Title 10 Code of Federal Regulations Part 63: Disposal of high level radioactive wastes in a geologic repository at Yucca Mountain, Nevada. United States Nuclear Regulatory Commission (NRC), Washington DC, United States.

3 A Regulatory Perspective on the Use of Conservative and Realistic Assessment Approaches (GSL)

3.1 Introduction

The International Atomic Energy Agency's (IAEA) coordinated research project (CRP) "Improving Long-Term Safety Assessment Methodologies for Near-Surface Radioactive Waste Disposal Facilities" (ISAM) was launched in 1997 and completed in the year 2000. The main outcome of the project was the development of a harmonised methodology for carrying out post-closure safety assessment of near-surface disposal facilities that can be applied iteratively to provide for the various purposes required of such a safety assessment. Following ISAM, the IAEA organised a further CRP "Application of Safety Assessment Methodologies for Near-Surface Radioactive Waste Disposal Facilities" (ASAM). This CRP considered the practical application of the ISAM methodology to a range of near-surface disposal facilities, and the development of practical approaches to assist regulators, operators and other specialists reviewing safety assessments.

Under ASAM, one topic addressed by a Common Application Aspects Working Group was the roles of conservatism and realism in safety assessments. A position paper was produced covering (IAEA 2006):

- The application of conservatism and the application of realism in regulatory frameworks, in international guidance, and in safety assessments for near-surface disposal facilities.
- The advantages and disadvantages of the various approaches.
- Areas of consensus and recommendations on how to address conservatism and realism in safety assessments.

This chapter reviews the findings of the ASAM working group in the context of safety assessments or performance assessments (Pas) for deep geological disposal facilities and considers when conservative and realistic assessment approaches might be used from a regulatory perspective.

3.2 Definitions

IAEA (2006) provides the following definitions:

> *Conservatism – The conscious decision, made in light of the current state of system knowledge and associated uncertainties, to represent an element of the system (scenario, model or data) such that it provides an under-estimate of system performance attributable to that element and thereby an over-estimate of the associated radiological impact (i.e. dose or risk).*

Realism – The representation of an element of the system (scenario, model or data), made in light of the current state of system knowledge and associated uncertainties, such that the safety assessment incorporates all that is known about the element under consideration and leads to an estimate of the expected performance of the system attributable to that element. The associated level of knowledge must be able to be justified robustly to stakeholders and be quantifiable in a practicable sense as part of the safety assessment.

These definitions are appropriate for assessment modelling for deep geological disposal, but with two caveats. First, a distinction needs to be made between elements of the disposal system, such as features, events and processes (FEPs) that the PA simulates, and elements of the PA, such as scenarios, models and parameters, that are used to simulate the system. Conservatism or realism is generally applied to the PA elements to effect a conservative or realistic representation of the disposal system elements. Second, more than one element of the system might be represented conservatively or realistically, leading to the whole analysis being termed conservative or realistic.

With regard to the second point, IAEA (2006) notes that there is an inconsistency with associating the term "realism" with models because models are by their nature only approximations of what is known or surmised about the "real" entity that they intend to approximate. The term "best-estimate" analysis is better used in place of "realistic" to reflect the use of an analysis that attempts to mimic the known behaviour of a system or system element. "Realism" is better applied to convey the conceptual decision to model the system or system element using all that is currently known about that system or system element.

3.3 Use of conservative and realistic approaches to PA

Table 3.1 is reproduced from IAEA (2006) and summarises the advantages and disadvantages of conservative and realistic approaches in PA. There are no absolute rules for using one or another approach. Consequently, it is important to be clear in setting out the assessment context which approach has been taken and with what objectives. The considerations regarding which approach to use are discussed below from a regulatory perspective in terms of the objectives of decision-making, building a robust PA, and building confidence in the PA.

3.3.1 Decision making

As noted under definitions, a conservative approach can be applied to individual elements of a PA or it can be applied to the entire analysis. From a regulatory perspective, the latter might be adopted when comparing the results of an analysis to regulatory performance measures - such as annual individual dose or risk - for a yes/no decision; conservatism can build confidence in the robustness of the comparison. A decision can also be taken regarding the benefit of further, possibly more detailed development and analysis for a system that is compliant when modelled conservatively.

Table 3.1. Advantages and disadvantages of conservatism and realism in PA (from Table 1 of IAEA (2006).

Approach	Advantages	Disadvantages
Conservatism	- Often considered easier to perform and defend analyses using conservative assumptions, models and/or parameters than it is to perform and defend realistic analyses. - Conservative model and/or data can be used in presence of incomplete data and/or knowledge. - Can prove beneficial in supporting confidence building if the estimated system performance conforms to the regulatory criterion. - Considered to provide a pessimistic estimate of system performance and, therefore, also provide a margin of safety relative to the "best-estimate" analysis of system performance. - Can allow quick decisions early in a project, based on a limited amount of information.	- Requires a sufficient understanding of the disposal system to be able to demonstrate that the analysis is truly conservative. - Does not allow demonstration of a scientifically robust understanding of the disposal system. - If "best-estimate" analyses are needed to demonstrate compliance when the conservative estimate violates the regulatory criterion, non-technical audiences may lose confidence despite demonstrating sufficient safety for the regulatory authorities unless sufficient emphasis is placed on communication to these audiences. - A conservative approach for one exposure pathway (or radionuclide) may not be conservative, but instead could be optimistic, for another exposure pathway (or radionuclide). - Inappropriate for the calibration of models. - Might result in sub-optimal or erroneous decisions.
Realism	- Allows demonstration of a scientifically robust understanding of the disposal system and so builds confidence. - Limits non-physical representations of the disposal system and over-estimation of impacts. - Provides the information necessary for making informed decisions. Optimisation of such things as the facility design, waste loading and site characterisation cannot be performed without a "best-estimate" analysis. - In concert with sensitivity and uncertainty analyses, provides a means for targeting robust data collection suited for uncertainty reduction and decision making. - Provides some scope for calibrating and validating "best-estimate" models.	- Requires a sufficient understanding of the present-day and future disposal system to justify that the analysis is truly a "best estimate". - Demonstration of realism over long periods of time is questionable. - It may be impossible or very expensive to collect sufficient data or supporting information for the entire spatial or time domain of interest.

In a highly legalistic setting and approach to decision making (e.g. as in the United States), there is a need to consider which approach to PA is least likely to be subject to legal challenge. For example, could a conservative approach to PA be argued by lawyers to lead to "wrong" PA results (even if the decision based on the results is itself well founded)? Would "realism" as implemented in a best-estimate approach be less subject to legal challenge? Of course, such considerations are also important even in less legalistic settings, where there is often a (regulatory) need to demonstrate a scientifically robust understanding of the disposal system, in addition to compliance with regulatory performance measures. Therefore, in presenting analyses for decision-making purposes, there is an argument to present realistic results, to demonstrate system understanding, and conservative approaches, for confidence building and to demonstrate robustness of the repository system. This dual approach could also help avoid the situation where different parties to a decision engage in unnecessary debate arising from the use of results based on different assumptions.

However, if the decision-making concerns comparison and selection of options, then a more realistic analysis should almost always be considered or, at the very least, a consistent level of conservatism should be applied to the analysis of each option.

Where conservatism is applied at a more detailed level in the assessment, possibly resulting in a mix of conservatism and realism across the PA model, care must be applied in using the PA results to decide on future work and development. A conservative model may mask uncertainties and the possible effects of reducing those uncertainties. A lack of detail in the model tends to obscure the interpretation of the results and can make it difficult to evaluate and demonstrate optimisation of the system. However, developing a more realistic model will involve resources, and these have to be balanced against the potential benefits from optimisation.

3.3.2 Robustness

Conservative assumptions and parameter values might be adopted to bound uncertainty in the modelling of particular elements or to simplify the PA. Simplification might be used where a FEP is not considered sufficiently important to model in detail, or where the intention is to use the analysis to enhance understanding and communication.

3.3.3 Confidence building

There are two viewpoints on the benefits of a conservative analysis versus a realistic analysis in terms of confidence-building. One view is that the simplicity and cautious nature of a conservative analysis of total system performance provides a robust demonstration of safety. The other view is that a realistic analysis can be compared to observation and demonstrates understanding, thereby building confidence in the results. These two viewpoints could be considered to be opposing; however, they do not rule out the use of both types of analyses to communicate the two different messages.

If the results of a conservative analysis fail to meet regulatory performance measures, then this might erode confidence. Further, it might undermine confidence in the results of more realistic models of the same system that show regulatory compliance.

3.4 Conclusions

There is an inconsistency with associating the term "realism" with models because models are by their nature only approximations of what is known or surmised about the "real" entity that they intend to approximate. The term "best-estimate" analysis is better used in place of "realistic" to reflect the use of an analysis that attempts to mimic the known behaviour of a system or system element. We have considered the role of such "best estimate" analyses and conservative analyses in decision making, demonstrating robustness in safety of the disposal system, and in confidence building. In summary:

- From a regulatory perspective, a conservative approach to PA might be adopted when comparing the results of an analysis to regulatory performance measures for a yes/no decision – supplemented by more realistic approaches to demonstrate system understanding. However, where the decision-making concerns comparison and selection of options, then a more realistic analysis should almost always be considered or, at the very least, a consistent level of conservatism needs to be applied to the analysis of each option.

- Robustness of disposal system safety is generally best demonstrated through the use of conservative PA assumptions and parameter values, to bound uncertainty in the modelling of particular elements or to simplify the PA.

- With regard to confidence-building, conservative and best-estimate PA approaches can be used in tandem to communicate different messages: a conservative analysis provides a robust demonstration of safety; a more realistic analysis can be compared to observation and be used to demonstrate understanding, thereby building confidence in the results.

3.5 References

IAEA 2006. Application of Safety Assessment Methodologies for Near Surface Disposal Facilities (ASAM). Common Application Aspects Working Group Position Paper - Roles of Conservatism and Realism. IAEA, Vienna, Austria (1 December 2006).

4 A Graded Approach for Dealing with Uncertainties in Assessments of Complex Systems (Facilia)

4.1 Introduction

this chapter considers the advantages of using a graded approach for dealing with uncertainties in assessments of complex systems involving many processes and uncertain parameters. The approach is illustrated using a graded approach to a dose assessment for a geological repository. However, the analysis of the merits of the graded approach is valid for any stage of a PA.

Applying a graded approach in the assessment process implies that the assessment is seen as an iterative process, which starts with conservative assessments that are followed by more realistic assessments when required. For example, if the conservative assessments demonstrate that doses are well below the relevant dose constraints, there may be no need for further detailed assessments to demonstrate compliance with regulatory criteria. Several graded methods have been developed and are available for application (e.g. IAEA 2001, NCRP, 1996). These methods have been developed for assessments of operational facilities, with existing or potential releases of radionuclides to the atmosphere and surface waters over relatively short periods (less than 100 years). Dose assessments for geological repositories cover longer timeframes and deal with different release pathways into the environment, mainly groundwater releases. Hence, this study adapted existing screening methods for use in dose assessments for radioactive waste repositories (Sections 4.2 and 4.3).

The procedure developed was applied to two hypothetical scenarios of radionuclide releases into the biosphere from a geologic repository for spent nuclear fuel. We show how this screening procedure can be used to demonstrate compliance with regulatory criteria (Section 4.4), and to guide the development of more realistic site-specific models and the analysis of assessment uncertainties (Section 4.5).

4.2 Description of the graded approach to assessments

The graded approach to dose assessments illustrated here (Figure 4.1) consists of two-tiers, where performing a screening study using simple conservative models (Tier 1) may be followed by more realistic, but still conservative, assessment (Tier 2), when required. In each Tier, doses are calculated and divided by a Reference Screening Dose to obtain a Risk Quotient (RQ). The Tier 1 and Tier 2 assessment approaches must be sufficiently conservative that there is a high degree of confidence that if the RQ is below 1, then the doses are below the relevant regulatory limit. The Reference Screening Dose itself should be set at a value less than the regulatory dose limit, depending on the desired degree of conservatism in the evaluation.

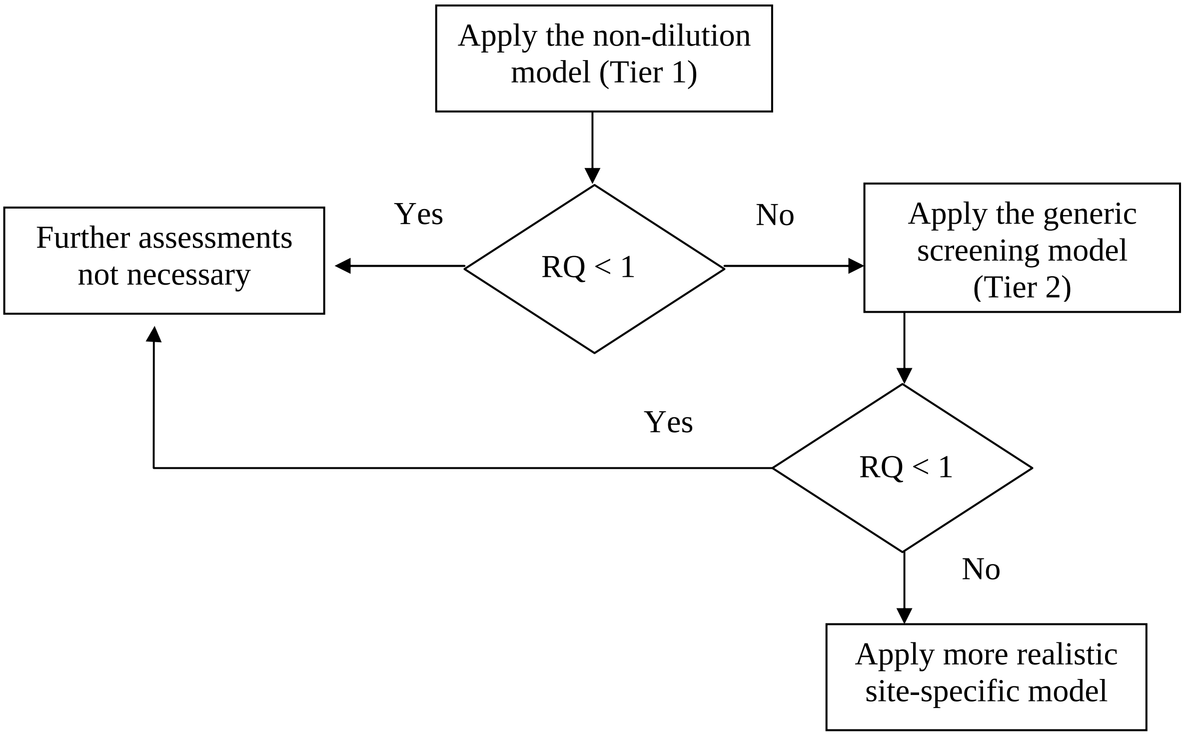

Figure 4.1. Illustration of the proposed graded approach to assessment, consisting of two sequential Tiers. The decision after each Tier depends on the value obtained for the Risk Quotient (RQ), defined as the calculated dose divided by a Reference Screening Dose.

The procedure is similar to the one recommended in IAEA (2001) for use in assessing the impact of discharges of radioactive substances to the environment. At the first Tier, a conservative calculation is performed, in which it is assumed that a hypothetical individual is exposed over one year to the whole integrated release via ingestion and inhalation. The same individual is also exposed externally to the release, assuming that it accumulates in 1 m^2 and that the individual is exposed during the whole year. This set of highly conservative assumptions is called "the non-dilution model".

The only parameters required by this model are the dose coefficients for inhalation, ingestion and external exposure. The dose coefficients given in Avila and Bergström (2006) for adults can be used. The use of dose coefficients for adults is consistent with ICRP (2006) recommendations, where it is stated that: "*In the case of disposal of long-lived radioactive waste, where dose to the public may be incurred in the far future over the entire life of the individual….it is then reasonable to calculate the annual dose/risk averaged over the lifetime of the individuals*". This means that it is not necessary to calculate doses to different age groups; the average over a lifetime of exposure can be adequately represented by the annual dose/risk to an adult.

If the RQ calculated in Tier 1 is greater than 1, then it is necessary to continue the assessments. In Tier 2 a generic screening model is applied, which is less conservative than the non-dilution model used in Tier 1, but still sufficiently conservative for the screening purpose. The screening model used in Tier 2 does not require site-specific parameters and therefore is called "generic". This model is described in more detail in the next section. If the RQ obtained from the application of this model is less than 1, then it can be concluded that more detailed site-specific assessments are not required.

4.3 The generic screening model

A schematic representation of the radionuclide transfer pathways considered in the generic screening model used in Tier 2 is presented in Figure 4.2. The radionuclide releases from the geosphere are directed to a well and a small lake, and from the lake to a small terrestrial area (SOIL) via runoff, and from the well radionuclides reach the vegetation via irrigation. Losses of radionuclides in the well and the lake are neglected and, therefore, the whole release reaches the terrestrial area, where radionuclides accumulate. Hence, this simple model includes all possible biosphere receptors.

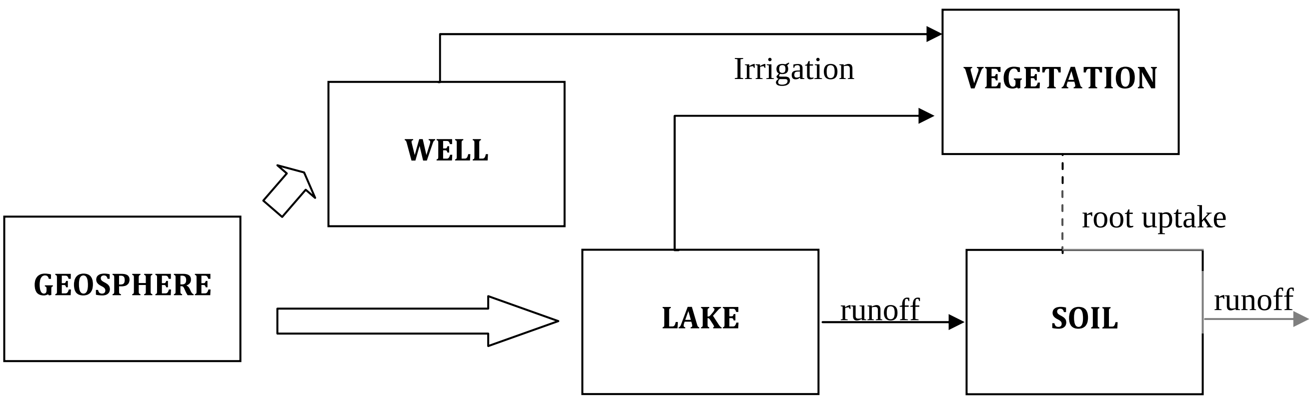

Figure 4.2. Schematic representation of the generic screening model.

For each of the biosphere receptors, the estimates of radionuclide concentrations in environmental media are maximised. This is achieved by making conservative assumptions, which are briefly outlined below.

4.3.1 Conservative assumptions for estimating the environmental concentrations

Radionuclide concentrations in the well water are obtained by dividing the release rate by the well capacity. Radionuclide losses from the water by adsorption in the walls of the well are conservatively neglected. A small value of the well capacity is used, but in the dose calculations it is assumed that there is sufficient well water available for all possible uses of the well water: drinking, irrigation and watering of domestic animals.

To calculate the concentrations of radionuclides in the lake water, it is assumed that the releases are directed to a very small lake. The area of the lake is taken as the minimum area needed to provide a person with the yearly demand of food and drinking water, assuming a high productivity. The depth of the lake is assumed to be only 0.5 m. The water flux from the lake is set at a minimum value, calculated as the product of the runoff and the area of the lake. Losses of radionuclides from the lake water, for example by sedimentation, are neglected.

All radionuclide discharges from the lake reach a small area of land. The area of the land is calculated in the same way as the area of the lake. The depth of the soil is taken as the depth of the rooting layer. The runoff of radionuclides from the land is calculated in the same way as for the lake, but the retention in the soil is maximised by using a high distribution coefficient (K_d) to calculate sorption of radionuclides.

Radionuclide concentrations in food are conservatively estimated by multiplying the radionuclide concentrations in the lake water and the soil by the highest transfer factor reported for aquatic and terrestrial food, respectively. For terrestrial foods the direct contamination of the vegetation surface by irrigation is also considered. It is assumed that the highest concentrations of water (from the well or the lake) are used for irrigation. Although not represented in Figure 4.2, radionuclide concentrations in animal food are also considered. These are calculated assuming that animal food consists of the vegetation with the highest radionuclide concentrations.

For C-14 a specific activity model (Avila and Pröhl 2008) is used, which produces conservative estimates. The conservative assumptions made in this model are described in detail in Avila and Pröhl (2008).

4.3.2 Conservative assumptions for estimating doses

The following assumptions are made to obtain conservative estimates of the doses to humans:

- Doses are calculated to a hypothetical individual that spends 100% of the time on the contaminated land and is exposed via inhalation and externally.
- The exposed individual obtains 100% of the ingested water and food from the contaminated environmental media. All consumed food and water are assumed to have the highest radionuclide concentrations.

4.4 Example of application in a graded approach for demonstrating compliance with regulatory criteria

We next describe an example application of the screening procedure. It is assumed that the overall purpose of the assessments is to demonstrate compliance with regulatory criteria. As in Section 4 of PAMINA Milestone Report M2.1.C.1, (corresponding to Topic 1 of this Work Package; Galson *et al.* 2009), we use the following hypothetical criteria: 100 µSv/y for the most exposed members of the public and 1 µSv/y for other members of the public. The Tier 1 Screening Reference Dose (see Section 4.2) is set at 10 nSv/y, i.e. equal to the lowest dose criterion (1 µSv/y) divided by 100. Hence, the screening procedure can be applied to each released radionuclide separately. As the number of radionuclides in the releases is less than 100, even if the Risk Quotient (RQ) for each radionuclide is exactly 1, the total dose at Tier 2 will be lower than the lowest dose criterion (1 µSv/y). For radionuclides with RQs below 1, there is no need to perform more realistic dose assessments. Equally, if all RQs are below 1 for one scenario, then there is no need to consider this scenario in more detailed dose assessments.

4.4.1 Description of the study cases

We considered two release scenarios, with the following radionuclides present in the releases: Ag-108m, Am-241, Am-243, C-14, Ca-41, Cl-36, Cm-244, Cm-245, Cm-246, Cs-135, Cs-137, Ho-166m, I-129, Mo-93, Nb-94, Ni-59, Ni-63, Np-237, Pa-231, Pb-210, Pd-107, Po-210, Pu-239, Pu-240, Pu-242, Ra-226, Se-79, Sm-151, Sn-126, Sr-90, Tc-99, Th-229, Th-230, Th-232, U-233, U-234, U-235, U-236, U-238 and Zr-93. The release rates from the geosphere for the two scenarios are presented in Figures 4.3 and 4.4. The analysis of the radionuclide releases from the geosphere is outside the scope of this study and is given here only for illustrative purposes. The release rates are presented for the first 15,000 years, as this is the period for which demonstration of compliance is required in the adopted hypothetical regulatory framework.

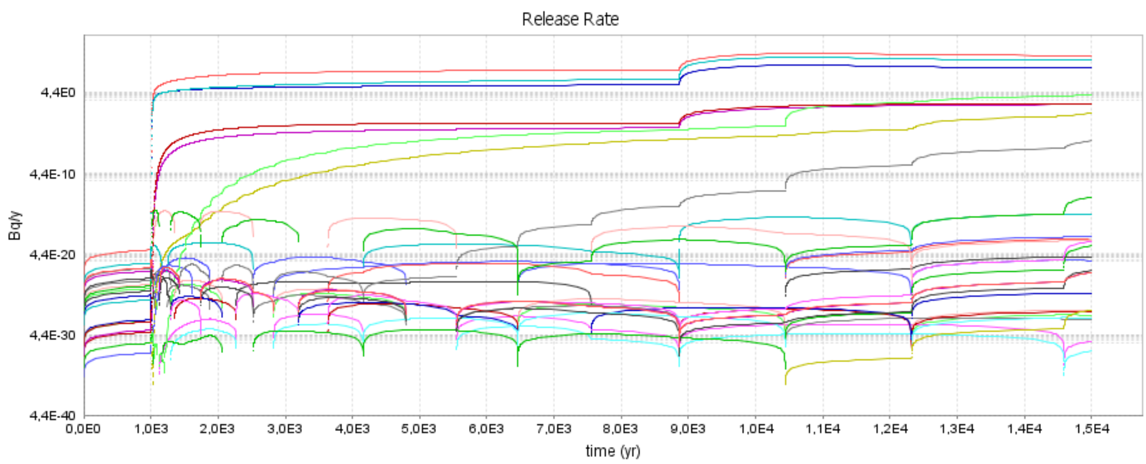

Figure 4.3. Hypothetical release rates from the geosphere for the first studied scenario (Scenario 1), corresponding to the most probable evolution of the system. Each curve corresponds to one of the released radionuclides.

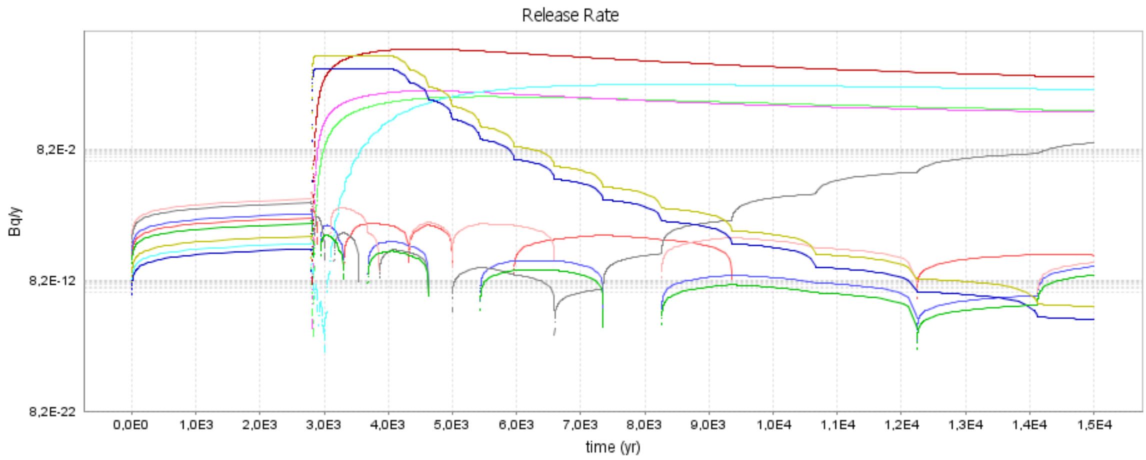

Figure 4.4. Hypothetical release rates from the geosphere for the second studied scenario (Scenario 2), corresponding to the evolution of the system for an event with low probability of occurrence. Each curve corresponds to one of the released radionuclides.

4.4.2 Results from the screening procedure

The results of the screening procedure at Tier 1 for the two studied scenarios are presented in Figures 4.5 and 4.6. Even for these extremely conservative calculations, RQ was above 1 only for eight radionuclides. For Scenario 1, the RQs for C-14, I-129 and Cl-36 were much higher than for other radionuclides and RQs above one were observed already 1000 years after the start of the releases to the biosphere. For Scenario 2, RQs above 1 were observed after 3000 years. One main difference between the two studied scenarios is that C-14 has the highest RQ for Scenario 1, but zero value for Scenario 2, as in this later scenario C-14 is not present at all in the releases to the biosphere. Also, Mo-93 had a much higher RQ in Scenario 2.

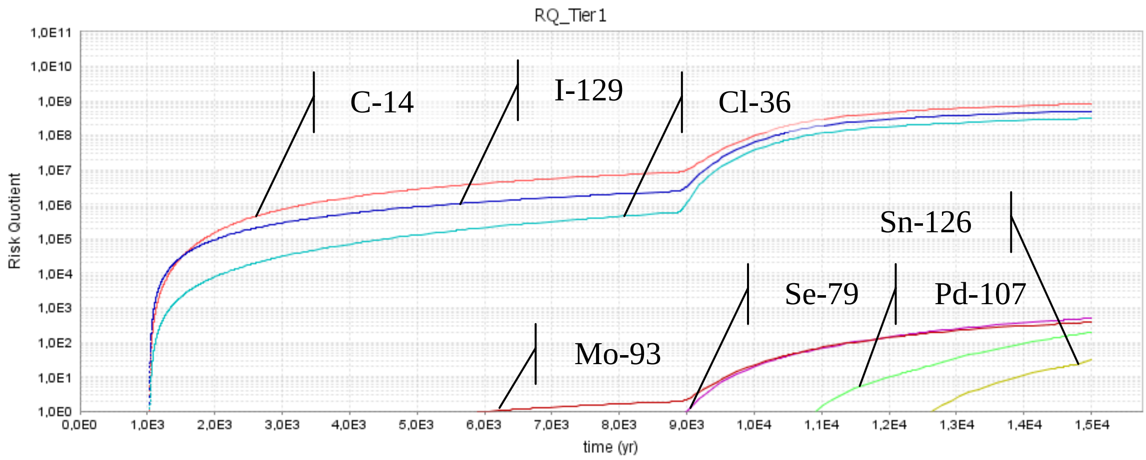

Figure 4.5. Risk Quotients obtained in Tier 1 of the screening procedure for Scenario 1. Only values above 1 are shown.

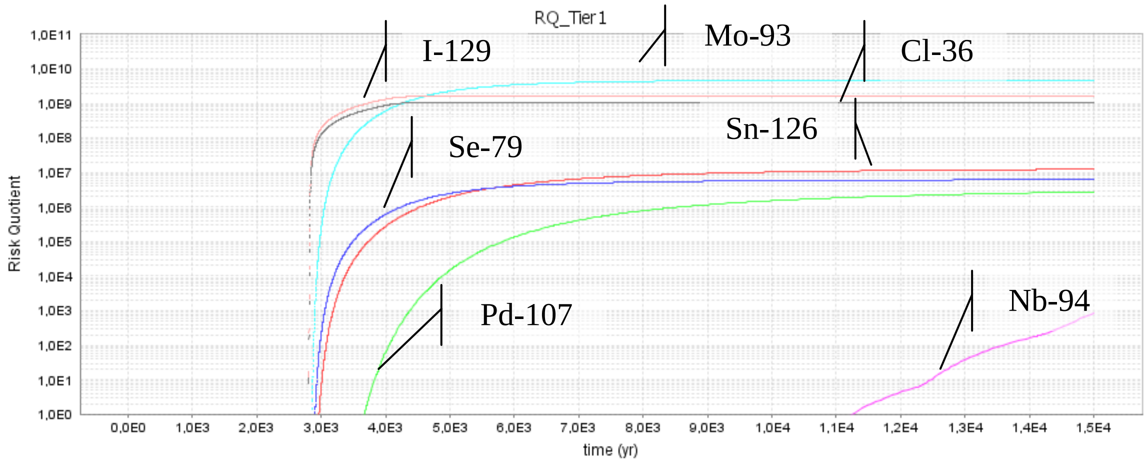

Figure 4.6. Risk Quotients obtained in Tier 1 of the screening procedure for Scenario 2. Only values above 1 are shown.

The main conclusion from Tier 1 calculations is that there is no need to continue to Tier 2 or to carry out more detailed assessments for any radionuclide with RQ below 1. For these radionuclides, compliance has been demonstrated independently of the properties of the biosphere to which their releases might occur or of their behaviour within the biosphere.

In the screening procedure proposed here, the next step is to move to Tier 2, i.e. carry out a less conservative assessment applying the generic screening model (Section 4.3) for those eight radionuclides whose RQs are above 1. This means that radionuclide-specific parameter values are only needed for these radionuclides. This is an added benefit of this two-tiered screening procedure, as it reduces the number of parameter values required. In this study, we performed the Tier 2 calculations for all radionuclides independently of whether or not RQs where higher or lower than 1 in Tier 1.

The results of the Tier 2 calculations are presented in Figures 4.7 and 4.8. The number of radionuclides for which the RQ was above 1 is lower than in Tier 1, three radionuclides in Scenario 1 and six in Scenario 2. The calculated RQs in this Tier are several orders of magnitude lower than the values reported in Tier 1, which illustrates the extreme conservatism implicit in Tier 1 of the screening procedure.

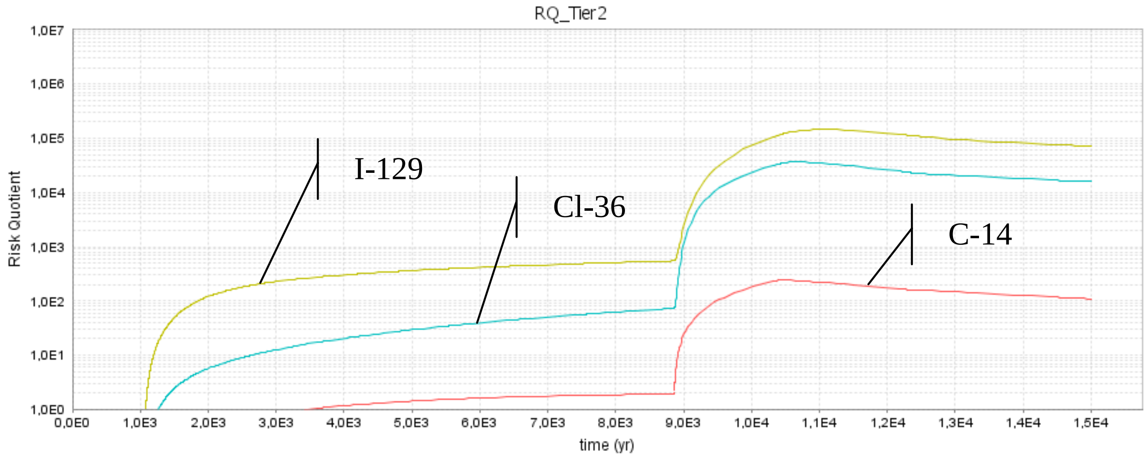

Figure 4.7. Risk Quotients obtained in Tier 2 of the screening procedure for Scenario 1. Only values above 1 are shown.

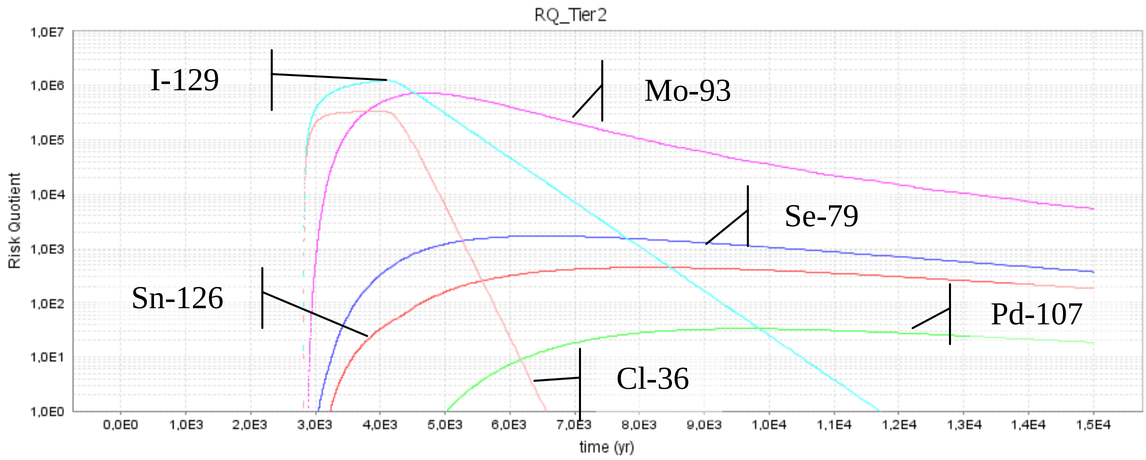

Figure 4.8. Risk Quotients obtained in Tier 2 of the screening procedure for Scenario 2. Only values above 1 are shown.

An overview of the Tier 1 and 2 results from the screening procedure is presented in Table 4.1. Radionuclides - and the respective RQs - for which further assessment is required are highlighted in red. For all other radionuclides considered,, it can be considered that compliance with both dose criteria has been demonstrated.

Furthermore, it can be concluded that more realistic assessments are required for both scenarios. For convenience, the complementary more realistic assessments could be carried out for all eight radionuclides with RQ above 1 irrespective of the scenarios. This would allow a comparison between the two scenarios and would not require collection of complementary information or parameter values, as the same model can be used for both scenarios.

Table 4.1. Summary of Risk Quotients with values above 1 obtained at Tier 1 and 2 of the screening procedure for the two studied scenarios. Radionuclides - and the respective RQs - for which further assessment is required are highlighted in red.

Radionuclide	Scenario 1		Scenario 2	
	Tier 1	Tier 2	Tier 1	Tier 2
I-129	5.0E+08	1.5E+05	1.6E+09	1.2E+06
Cl-36	3.1E+08	3.6E+04	1.0E+09	3.3E+05
C-14	8.2E+08	2.5E+02	0.0E+00	0.0E+00
Se-79	5.0E+02	1.7E-01	6.2E+06	1.7E+03
Mo-93	3.8E+02	3.5E-02	4.8E+09	7.3E+05
Pd-107	2.0E+02	7.2E-03	2.7E+06	3.3E+01
Sn-126	3.0E+01	2.3E-03	1.2E+07	4.5E+02
Nb-94	8.7E-03	4.7E-07	8.1E+02	4.2E-02

It should be emphasized that if a RQ above 1 is obtained in Tier 2, this does not mean that the dose is above the regulatory criteria. Tier 2 is also designed to sufficiently overestimate doses to guarantee, with a high degree of confidence, that if the RQ is below 1 then the dose is below the regulatory criteria. If the RQ is above 1 in Tier 2, this merely indicates that compliance with the criteria could not be demonstrated with this simple conservative approach and, therefore, more detailed and less conservative assessments are required.

To carry out less conservative assessments, usually more realistic models are required. One possible approach is to develop a site-specific model that describes more realistically the environmental behavior of the potentially released radionuclides. An example is the landscape model that was used in the studies presented in Section 4 of PAMINA Milestone Report M2.1.C.1, corresponding to Topic 1 of this Work Package (Galson *et al.* 2009). However, “realistic” models can easily become very complex and might require a large number of parameters. Complex models might be difficult to use in practice and the interpretation of results can be challenging. This could play a negative role in the process of building confidence in the assessment results. Hence, when selecting a model that is “fit for purpose”, a compromise between model realism and model complexity is often required. As shown in the next section, the results of the screening study can provide guidance in the development of more realistic models with an adequate level of complexity.

4.5 Application to model development and uncertainty analysis

The results from the screening calculations in Tier 2 can be used to identify the most important exposure pathways. Table 4.2 presents the contribution of different exposure pathways to the total doses obtained in Tier 2. Note that this contribution is the same for both scenarios. It can be seen that, for all radionuclides with RQs above

1, the doses from food ingestion dominate the exposure. For Nb-94 the doses are dominated by the external exposure, but for this radionuclide the RQs in Tier 2 were below 1 for both scenarios. For other radionuclides, like Pu-239, the inhalation pathway could have the highest contribution to dose. Hence, the importance of the different exposure pathways will depend on which radionuclides dominate the releases and the doses.

Table 4.2. Relative contribution of the different exposure pathways to the total doses in Tier 2 from all potentially important radionuclides, identified from the screening procedure for both studied scenarios.

Radionuclide	External	Inhalation	Water ingestion	Food ingestion
I-129	1.2E-05	8.9E-08	4.7E-05	1.0E+00
Cl-36	4.1E-05	8.7E-07	1.6E-05	1.0E+00
C-14	1.5E-07	4.3E-04	2.6E-04	1.0E+00
Se-79	9.3E-07	3.0E-06	1.6E-05	1.0E+00
Mo-93	1.0E-05	4.2E-07	8.7E-05	1.0E+00
Pd-107	0.0E+00	3.0E-05	6.8E-05	1.0E+00
Sn-126	1.7E-02	2.2E-05	1.5E-04	9.8E-01
Nb-94	9.6E-01	3.7E-05	1.1E-04	4.3E-02

For this study, we can conclude that for the more realistic dose assessments the focus should be on exposure via food ingestion.

Table 4.3 presents the radionuclide concentrations in aquatic and terrestrial food obtained with the screening model. The results show that for all radionuclides except C-14, the concentrations in terrestrial food are higher than in aquatic food. For C-14 the opposite situation is observed. It can also be observed from Table 4.3 that the contribution of irrigation to radionuclide concentrations in terrestrial food is less than 10% for all radionuclides. This information again provides an indication of which processes should be given more attention in the more realistic assessments.

The information provided by the screening model is also useful in uncertainty analysis. The screening model can be seen as a way of treating uncertainties, where practically all uncertainties have been treated by introducing conservatism in the model. This opens the way for a step-by-step analysis of the different sources of uncertainties for the important radionuclides and exposure pathways. Each conservative assumption in the screening model can be iteratively removed one by one, or in groups. After any one such iteration, we will obtain a more realistic model, which can be used to make new predictions. We can then compare the new predictions with the predictions made with the screening model. This will provide an indication of the significance of the different uncertainties for the model predictions. Such studies will also show which of the more realistic assumptions and choice of parameters have the highest impact on dose, in comparison with the values obtained with the “uncertainty-free” (Tier 2) screening model. It should be noted that such an approach to the assessment is consistent with ICRP (ICRP 2006) and IAEA (IAEA 2001) recommendations for assessments of the impact of discharges to the environment. For example, in ICRP (2006) it is stated: "*The assessment generally begins with more conservative assumptions for sources, parameter values, habit data, and population size. The results from each iteration are used to determine if more site-specific and realistic information is needed. The use of detailed information is particularly important when the magnitude of the calculated doses approaches the relevant constraint*".

Table 4.3. Maximal activity concentrations (Bq/kg) in aquatic and terrestrial foods obtained in Tier 2 for all potentially important radionuclides, identified from the screening procedure for both studied scenarios. The percentage contribution of irrigation to the activity concentrations in terrestrial foods is also indicated.

Radionuclide	Aquatic	Terrestrial	Irrigation*
I-129	7.3E-01	5.9E+01	0.086%
Cl-36	1.7E+00	1.5E+03	0.030%
C-14	1.7E+01	5.2E-02	0.81%
Se-79	2.3E-04	5.3E-03	0.029%
Mo-93	1.6E-04	1.0E-03	0.16%
Pd-107	1.6E-04	1.8E-02	0.12%
Sn-126	2.7E-05	4.3E-05	0.28%
Nb-94	1.1E-09	4.7E-10	10%

4.6 Conclusions

In this study we have illustrated the advantages of using a graded approach for dealing with uncertainties in assessment of complex systems involving many processes and parameters. The graded approach consists of making assessments in iterations with an increasing level of realism. This allows for a reduction in scope of any more realistic assessments that may be required, for example a reduction in the number of radionuclides that need to be considered in detailed site-specific assessments. This is especially valuable for long-term assessments that are associated with large uncertainties; these assessments have to rely on predictive models and deal with lack of data and knowledge. A graded approach facilitates and strengthens the demonstration of compliance with regulatory criteria. It also provides an instrument for analysing model uncertainties, and guidance for the development of more realistic site-specific models, where required.

4.7 References

Avila, R., and Bergström, U. 2006. Methodology for calculation of doses to man and implementation in Pandora. Posiva Oy Report 2006-56 (Finland) and Svensk Kärnbränslehantering AB report SKB R-06-68 (Sweden).

Avila R and Pröhl G. 2008. Models used in the SFR1 SAR-08 and KBS-3H safety assessments for calculation of C-14 doses. SKB report R-08-16.

Galson, D.A. (Editor), Hooker, P.J., Wilmot, R.D., Nordman, H., Avila, R. and Broed, R. 2009. The treatment of uncertainty using probability. PAMINA Milestone M2.1.C.1.

IAEA 2001. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment. Safety Report Series 19. Vienna.

ICRP 2006. Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and the Optimization of Radiological Protection. ICRP Publication 101, Elsevier, April 2007.

NCRP 1996. Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground, Rep. 123 I, NCRP, Bethesda, MD.

5 Conclusions

Safety Functions

The work by GSL concluded that, while the principle of using safety functions in the safety case does not bias the safety case towards conservatism or realism, several mechanisms are identified which have the potential to introduce conservatism into the implementation. Examples have been found from the implementation of safety functions in a number of programmes which illustrate these mechanisms.

When using a safety functions approach in PA, introduction of unintended conservatism, or, in the case of scenario development, an unintended bias towards optimism, can be avoided by:

- Accounting for any inter-dependence of safety functions and safety function indicators.
- Applying performance limits for individual safety functions/barrier/sub-systems within the context of the performance limits for the whole repository system.
- Not placing regulatory limits on individual safety functions indicators/sub-system performance criteria.
- Applying complementary methods for scenario development in order to achieve comprehensiveness.

Regulatory Perspective on the Use of Conservative and Realistic PA Approaches

There is an inconsistency with associating the term “realism” with models because models are by their nature only approximations of what is known or surmised about the “real” entity that they intend to approximate. The term “best-estimate” analysis is better used in place of “realistic” to reflect the use of an analysis that attempts to mimic the known behaviour of a system or system element. GSL has considered the role of such “best estimate” analyses and conservative analyses in decision making, demonstrating robustness in safety of the disposal system, and in confidence building. In summary:

- From a regulatory perspective, a conservative approach to PA might be adopted when comparing the results of an analysis to regulatory performance measures for a yes/no decision – supplemented by more realistic approaches to demonstrate system understanding. However, where the decision-making concerns comparison and selection of options, then a more realistic analysis should almost always be considered or, at the very least, a consistent level of conservatism needs to be applied to the analysis of each option.
- Robustness of disposal system safety is generally best demonstrated through the use of conservative PA assumptions and parameter values, to bound uncertainty in the modelling of particular elements or to simplify the PA.

- With regard to confidence-building, conservative and best-estimate PA approaches can be used in tandem to communicate different messages: a conservative analysis provides a robust demonstration of safety; a more realistic analysis can be compared to observation and be used to demonstrate understanding, thereby building confidence in the results.

Graded Approach for Dealing with Uncertainty

Facilia has illustrated the advantages of using a graded approach for dealing with uncertainties in assessment of complex systems involving many processes and parameters. The graded approach consists of making assessments in iterations with an increasing level of realism. This allows for a reduction in scope of any more realistic assessments that may be required, for example a reduction in the number of radionuclides that need to be considered in detailed site-specific assessments. This is especially valuable for long-term assessments that are associated with large uncertainties; these assessments have to rely on predictive models and deal with lack of data and knowledge. A graded approach facilitates and strengthens the demonstration of compliance with regulatory criteria. It also provides an instrument for analysing model uncertainties, and guidance for the development of more realistic site-specific models, where required.

Appendix A: Interview Summaries – The Use of Safety Functions

A.1 Interview Summary – M. Capouet, ONDRAF/NIRAS, Belgium

Present in Galson Sciences Limited offices: A. Khursheed (record keeper), R. Wilmot (interviewer) and D. Galson.

Present in ONDRAF/NIRAS offices: M. Capouet.

This note is a record of a telephone interview conducted by Galson Sciences Limited (GSL) on 18 March 2007 with M. Capouet of the Belgian waste disposal organisation ONDRAF/NIRAS on the use of safety functions in the safety case for deep geological disposal of radioactive waste. The interview was also used to test the interview format and set of questions before its application to a small number of experts[2].

1) Summarise recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

ONDRAF/NIRAS has recently revised their system concept for a deep geological disposal facility in Belgium. The use of safety functions is a key element in the revised system concept. Recent experience of the use of safety functions:

- Clarifies the way in which safety functions change over time.
- Has led to a new scenario development methodology that is based upon the operation of safety functions over time.

ONDRAF/NIRAS is still developing an assessment methodology and exploring the application of safety functions to the safety concept. Refinements to the methodology and its application are expected.

2) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, and/or scenario development.

ONDRAF/NIRAS sees safety functions as the “cornerstone” of the safety and feasibility case (SFC1) that is planned for 2013. SFC1 aims to build a safety case for a repository situated at an unspecified site in Boom Clay. Safety functions form the top tier of the safety strategy; they are underpinned by “safety statements”, which in turn are supported by detailed scientific arguments and assessment. The result is

[2] Note that the set of questions was revised for subsequent use with experts from other waste disposal organisations, so that this response has a slightly different form than the other responses.

essentially a "top down" approach to the safety strategy, where the use of safety functions is ultimately supported by the assessment basis for the safety case.

The safety case being developed for SFC1 will use safety functions in several aspects of the case. Safety functions are considered to have an important role in establishing design criteria for the repository concept. For example, the characteristics of candidate buffer materials can be evaluated against performance criteria provided by analysis of safety functions. Such criteria might be qualitative or quantitative; in the case of the latter a small number of safety function indicators are being developed, although this work is still in its early stages.

The "top down" approach adopted in the safety strategy means that a consideration of safety functions is driving the assessment basis of the safety case, which is optimised in relation to analysis of safety functions. The treatment of uncertainty within the assessment, however, is a "bottom-up" approach that starts from elements of the assessment basis with uncertainties propagated up to the safety functions. The complementary use of the two approaches is a key element of the use of safety functions.

The use of safety functions in the safety case is also seen to benefit communications with stakeholders. Experience gained in this area to date suggests that safety functions help give stakeholders a clear conceptual background to the disposal concept, and that discussions with stakeholders progress more quickly when safety functions are used in descriptions of a facility and its performance.

3) At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?

Safety functions are useful early in the programme in the context of defining the repository concept, i.e. when used in a design mode. In addition, their value to the assessment basis for the safety case has increased with the maturity of the programme, as the assessment basis has become more developed.

ONDRAF/NIRAS sees safety functions as playing an important role in the safety case at all stages of their programme. The stages at which safety functions are seen as being most useful within the ONDRAF/NIRAS programme are:

- Defining the repository concept in the early stages.
- Using safety functions as inputs to a scenario development methodology.
- Using analysis of safety functions to refine the repository design.
- Using safety functions to structure information in the assessment basis for the safety case.
- Defining sensitivity studies for investigating the role of safety functions in the overall repository system.

The use of safety functions will probably decrease as construction of the repository nears.

4) What advantages/disadvantages over alternative approaches does a safety functions approach have for waste disposal implementers?

The answer to this question depends on what you compare a safety functions approach to. There was some discussion of what the alternatives are. The respondent questioned whether any geological disposal programmes are using approaches that do not employ safety functions once differences in terminology are accounted for. Galson and Wilmot suggested that prior to the common usage of a safety functions approach, an orthodox approach was to derive a repository design concept (perhaps using sub-system performance requirements that would now be termed safety functions), but to carry out overall system performance assessments against regulatory limits/constraints such as individual dose or risk and not explicitly consider the detailed behaviour of individual elements of the design. It was also pointed out (Khursheed) that the review conducted in RTDC-1 of the use safety functions in different programmes suggested that they are not universally used, in name at least.

The following potential advantages of the safety functions approach were cited:

- Improved communication with scientifically literate stakeholders.
- Providing direction to the R&D programme, e.g. R&D meetings are organised around particular safety functions.
- Giving structure to the assessment basis for the safety case.
- Providing a clear route for the development of scenarios.
- Allowing a set of performance indicators to be derived from the safety functions (in early stages at present).

The following potential disadvantages were cited:

- Compartmentalisation of the safety case, potentially leading to omissions.
- Interactions between safety functions not fully treated or understood.
- Temporal variations in the repository system can be challenging to interpret in terms of safety functions, which will also need to have time-dependent qualities.
- Difficulty in putting across an essentially abstract concept when communicating with a lay audience.

5) What advantages/disadvantages over alternative approaches does a safety functions approach have for waste disposal regulators?

This question was considered to be not relevant to the experience of ONDRAF/NIRAS.

6) What possible advantages/disadvantages over alternative approaches does a safety functions approach have for communication with a range of stakeholders?

This question was addressed in the answers to Questions 2 and 4.

7) What are the main functions and sub-functions that you use?

The three main safety functions, with their sub-functions, are:

- Isolation (I)
  - I-1 reduction of the likelihood of inadvertent human intrusion and of its possible consequences.
  - I-2 ensuring stable conditions for the disposed waste and the system components.
- Engineered Containment (C)
- Retardation (R)
  - R-1 limitation of contaminant releases from the waste forms.
  - R-2 limitation of water flow through the disposal system.
  - R-3 retardation of contaminant migration.

There is also a range of “supplementary functions”, effective at certain times, but whose performance cannot be quantified, e.g. immobilisation of radionuclides within the waste form matrix. This supplementary function was originally included in the R-1 sub-function, but is now used only in supporting, qualitative, arguments. It was suggested that another example of a supplementary safety function is dilution in the far field and biosphere (Wilmot). ONDRAF/NIRAS recognises that dilution will affect calculated doses, but does not treat it as a safety function in siting or design studies.

8) What safety function indicators do you use and how have they been derived?

Safety function indicators are being developed in the current programme. At the time of the SAFIR2 study (published December 2001), only a “containment factor” indicator was developed. Recent work being conducted within PAMINA WP3.4 by Marivoet (SCK/CEN) develops indicators in relation to the R-1 and R-3 sub-functions. It is anticipated that the safety case for SFC1 will also draw upon indicators that were defined and tested in the EC SPIN project.

9) How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.

The regulatory framework for geological disposal of radioactive waste has not yet been developed in Belgium, so there are consequently no limits/constraints related to safety function indicators. Furthermore, little effort has been given to this to date.

The point was raised that designers need to use reference levels for safety function indicators (Wilmot), and the question was asked whether, in practice, they adopted conservative values to solve the problem of deriving such reference levels from regulatory limits on dose or risk? This may be a means by which an inherent conservatism is introduced into the safety case. Experience some 15-20 years ago of applying the then extant US Nuclear Regulatory Commission sub-system performance criteria (in 10 CFR 60) to a prospective HLW repository at Yucca Mountain suggested that over-reliance on sub-system performance measures had the potential to result in a sub-optimal design for the total system (Galson).

The approach adopted by STUK in Finland was also raised for comparison (Wilmot). In Finland, individual nuclide-specific activity fluxes have been developed as regulatory constraints for the long-term performance of the engineered barrier system, mainly on the basis of comparisons to naturally occurring radionuclide fluxes (in Regulatory Guide YVL8.4). The derivation of such regulatory constraints, however, requires a significant number of assumptions to be made, which may not be appropriate to particular sites at the time an assessment is performed.

10) Which areas of the safety functions approach require further methodological development?

No particular topics were highlighted specifically under this question. However, it was noted that the issue of how to use supplementary functions was unresolved, and may benefit from further development.

It is also noted (Khursheed) that several other topics for further development are included in the answers to other questions. These are:

- The compatibility of a quantitative treatment of system uncertainty with a safety functions approach. ONDRAF/NIRAS is attempting such an exercise and is exploring the relationship between the “top down” approach based on safety functions that is used to define the safety strategy, and the “bottom up” approach that is used to propagate uncertainties within the system model.
- Using a safety functions approach to communicate with stakeholders – there is the impression that it helps, but can this be tested objectively and developed further?
- Relating the values of safety function indicators to references values (as discussed for Question 9).
- Interactions between safety functions over time (Question 4).

11) Is a safety functions approach to design inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

The view in ONDRAF/NIRAS is that the safety function approach is neither inherently conservative nor realistic. The choice regarding whether an approach is conservative or realistic is made in the safety statements, and how these are supported, and in the assessments used to make the safety case. It was noted that there are certain conservative assumptions in the system concept, e.g. the choice of a conservative container lifetime, which are reflected in the safety functions, but the containment safety function is not itself inherently conservative. Overall, it is important to be clear about where conservative assumptions are introduced in the safety case.

12) Is a safety functions approach to assessment inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

This question was addressed in the answer to Question 11.

13) To what extent can an assessment approach based on safety functions replace a PA that uses individual dose and risk as performance indicators?

ONDRAF/NIRAS sees no conflict between the two approaches. However, experience is limited since the programme is still at an early stage (i.e., feasibility studies), and the regulatory system is not yet in place.

14) Please give key references for the safety functions approach that you have used in your recent work.

References were forwarded later along with a written response, which was used in developing this note.

A.2 Interview Summary – A. Hedin, SKB, Sweden

Present in Galson Sciences Limited offices: A. Khursheed (record keeper) and R. Wilmot (interviewer).

Present in SKB offices: A. Hedin.

The answers to the questions were provided primarily by a written response from Allan Hedin on 25 April 2008. They were supplemented during the course of a telephone conference held on 17 June 2008.

1) Summarise your recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

Safety functions played a prominent role in our most recent safety assessment, SR-Can, published in November 2006 as SKB Technical Report TR-06-09. They were introduced as a means of structuring the safety case in a more distinct and transparent manner. Prior to their use, the arguments used in safety assessments were based more directly on FEPs and FEP interactions. The development of a safety functions approach in Sweden has been largely independent of similar activities in other countries, and, although similar to other approaches the SKB approach adopted is programme-specific.

In the SR-Can assessment safety functions were used

- to identify important safety related issues early in the assessment;

- to structure the account of long-term safety in different time frames of a comprehensive main scenario (based on a reference evolution); and
- as a basis for identifying scenarios in addition to the main scenario

2) What are the main functions and sub-functions that you use?

We use the following definitions (see further chapter 7 of TR-06-09):

- A safety function is a role through which a repository component contributes to safety.
  - Example: The canister should withstand isostatic load.
- 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.
  - Example: Isostatic stress in canister.
- 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.
  - Example: Isostatic stress < isostatic collapse load.

The main safety functions, safety function indicators and safety function indicator criteria are shown in Figure A.1.

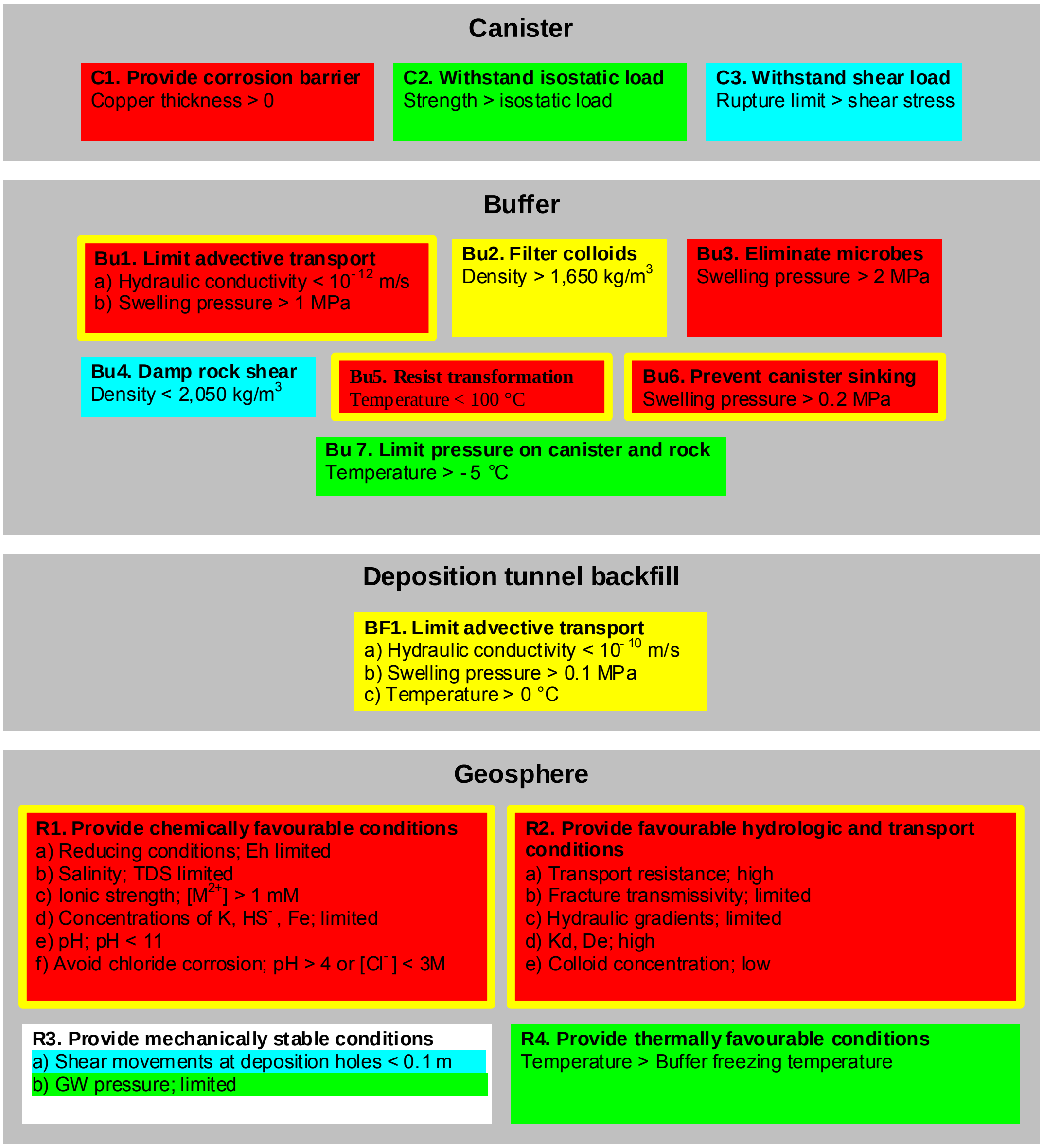

Figure A.1. Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like “high”, “low” and “limited” are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).

3) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, scenario development, or safety case strategy.

So far, we have used the safety functions as indicated in the answer to Question 1. Although the most important role of the safety functions turned out to be in the development of scenarios, their use has had an effect on all aspects of the safety case. See further chapter 11 of SKB TR-06-09 for details on their use for scenario development.

The KBS-3 concept predates the use of safety functions. Although major design decisions were not directly influenced by a safety function analysis, results from SR-Can provide important feedback on the proposed repository design, which can be used to refine the design concept in the next safety case.

4) At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?

Safety functions on a high level should be possible and fruitful to apply already in the conceptual development. Sub-level functions, function indicators and criteria could presumably be gradually developed and implemented as a programme reaches more mature stages.

At all stages, but particularly early in a programme development, it could be expected that application of safety functions in a safety assessment would aid in identifying critical issues to be further evaluated. At later stages, safety functions could probably play a more important role in compliance demonstration.

In short, safety functions could presumably be useful in all stages of a programme, but their role would change as the role of the safety assessment changes.

5) What possible advantages/disadvantages does a safety functions approach have for communication with a range of stakeholders?

In our experience, it has been straightforward to communicate our safety functions approach to the general public. Also, in a recently completed review of our most recent safety assessment, the safety functions were seen as important and useful components in the safety assessment methodology, although requiring some refinement to be apt for use in a licence application.

No significant disadvantages have been noticed with respect to using safety functions to communicate with stakeholders, although specific references and descriptions of safety functions have been limited. This in part is because the overall KBS-3 concept appears to be well understood by the concerned municipalities and other stakeholders.

6) What safety function indicators do you use and how have they been derived?

The indicators used are shown in Figure A.1 above. Note that none of these are directly related to release rates or fluxes of radionuclides.

The pillars on which the derivation of safety functions is built are: i) the two principal safety functions isolation and retardation on which the design of the KBS-3 repository is based; and ii) the scientific understanding of the long-term evolution of a KBS-3 repository. Throughout decades of research related to the long-term safety of a KBS-3 repository, safety functions or barrier requirements have been discussed and established successively. See further section 7.2 of TR-06-09, subheading "Derivation of safety functions, indicators and criteria".

7) How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.

As mentioned in the answer to Question 6, the indicators are not directly related to release rates or fluxes of radionuclides. There are (thus) no regulatory limits/constraints to compare to. Rather, the safety functions allow a disaggregation of the complex analyses that lead to results that can be compared to regulatory limits.

Many of the safety function indicator criteria are set at values where the safety function changes from "on" to "off", and these criteria can be used in a quantitative approach, with limits defined by the implementer. In cases where limiting values are hard to obtain, the criteria are used in a qualitative way, by focussing the assessment on a particular safety relevant issue. Hydraulic gradients – which should preferably be limited but for which a quantitative limit can not be formulated – is an example of this. In cases where there is no threshold behaviour and where a criterion has been set with a margin to acceptable performance, for example the upper temperature limit on the buffer for avoiding unfavourable transformations, there is room for a more developed treatment of the margin.

8) Which areas of the safety functions approach require further methodological development?

In our particular application, it is desirable to further develop the description of how safety functions are derived, and possibly their completeness. Also a more developed approach to margins to desired performance when determining safety function indicator criteria would be a valuable development (see response to Question 7).

9) Is a safety functions approach to design inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

It is neither. If safety functions are used in a qualitative sense, then the question is irrelevant. If they are used in a quantitative sense, the issue of conservatism or realism depends on how you apply criteria for safety function evaluation. In SR-Can, the approach taken has depended upon specific safety functions and system characteristics, in practice being a mixture of conservatism and realism. For example, when using the safety function indicator for ionic strength, R1d, there are well defined limits for acceptable values, and a realistic approach will result. However, for other safety function indicators, such as temperature of the buffer, Bu5, the limits are not so well defined, and a conservative approach will result if a broad margin to the limit is adopted, as was the case in the SR-Can assessment.

10) Is a safety functions approach to assessment inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

See answer to Question 9. (The division between design and assessment between Question 9 and Question 10 is however, not obvious. A design needs to be evaluated in an assessment and one way of doing this is by a safety functions approach.)

11) Please give key references for the safety functions approach that you have used in your recent work.

See reference given in the answer to Question 1. In particular chapters 7, 11 and 12 of SKB TR-06-09 are relevant.

A.3 Interview Summary – B. Stromberg, SKI, Sweden

Present GSL: A. Khursheed (recorder), R. Wilmot (interviewer).

Present SKI: B. Stromberg.

This note is a record of a telephone interview conducted by Galson Sciences Limited (GSL) on 18 June 2008 with Bo Stromberg of the Swedish nuclear regulatory authority SKI. The interview followed that conducted for the Swedish waster implementer SKB on the previous day. To avoid unnecessary repetition, some of the factual questions on the Swedish programme which were answered fully by SKB were treated in a brief manner.

1) Summarise your recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

SKI has reviewed recent safety cases for deep geological disposal of radioactive waste in Sweden, notably SR-Can (2007), which made extensive use of safety functions. Before SR-Can, general safety functions, such as isolation and retardation, were considered in the SR-97 safety case, but it was not specified in a formal and detailed way what had to be fulfilled.

In the recently completed review of SR-Can, the safety functions set out in the safety case were reviewed by Swedish regulators in depth, one by one. Some deficiencies were noted with respect to the definitions for the functions, which are brief and, in some cases, not backed up by sufficient arguments. The most serious deficiencies, however, were noted in relation to the use of safety function indicator criteria. Where used quantitatively, the limits were not explained or justified to a sufficient degree.

2) What are the main functions and sub-functions that you use?

The safety functions used in the SR-Can safety case were defined in detail in the interview with SKB, and were consequently not discussed here (see Figure A.1).

3) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, scenario development, or safety case strategy.

The safety functions approach has made a positive contribution to the safety case. It has been found to be an effective aid to communications between the waste disposal implementer and regulators on how the repository concept functions. Safety functions have been a useful tool for organising review work, as important processes can be identified in relation to safety functions. The safety functions approach has also benefited scenario development in the safety case – in this respect it has a greater value than the use of lists of FEPs, since many of these prove to only have a very minor influence on the repository performance. A possible weakness of a safety functions approach to scenario development is lack of comprehensiveness – some scenarios that are characterised by intermediate performance of repository components can be missed.

It is also considered that some safety functions have greater value in the safety case than others. For the SR-Can study, the containment-related safety functions are more useful than those for retardation, since meaningful numerical values are harder to come by for the latter.

4) At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?

Since the Swedish programme is already well advanced, and choices have been largely made, this question was thought to be of limited relevance.

5) What possible advantages/disadvantages does a safety functions approach have for communication with a range of stakeholders?

SKI has presented the findings of its review on SR-Can to the municipalities, and found safety functions to be a useful tool in this respect. There has been criticism from environmental organisations of the way that safety function indicator criteria have been set up in SR-Can, and the freedom there appears to be for the waste disposal implementer to change the limits without involvement from the regulator. There are doubts within SKI, however, about the value of imposing limits on subsystem performance in regulation – experience shows that the use of subsystem performance limits can detract from the performance of the whole system, and also takes responsibility away from the waste disposal implementer for building a sound and comprehensive safety case.

6) What safety function indicators do you use and how have they been derived?

This is answered by the responses to Question 2.

7) How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.

In the Swedish programme there are no direct links between limits applied to safety function indicator criteria and regulatory limits. Nevertheless, in order to achieve transparency, discussion and arguments are required from the waste disposal implementer to demonstrate how limits on safety indicator criteria have been derived.

8) Which areas of the safety functions approach require further methodological development?

The definition of the safety functions used in the Swedish programme would benefit from further development and justification. Certain safety functions are useful and can be easily quantified e.g. the isostatic load function (C2). Others are not as well defined, such as canister corrosion (C1), which is subject to the effects of buffer erosion.

Another example of the way in which the definition of functions can be improved is the absence of a safety function for retention in the waste form, which is needed to describe leaching of radionuclides from the waste form.

9) Is a safety functions approach to design inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

The safety functions approach in itself does not give a bias towards realism or conservatism – this results from the manner in which the approach is implemented. In the Swedish programme, safety functions related to isostatic loads on the canister involve a considerable degree of conservatism, while safety functions related to corrosion failure of canister tend more towards realism, such as in the establishment of assessment assumptions concerning groundwater flow and corrosion rates.

This issue is connected to that of “safety margins”, which has been raised in connection to the review conducted for SR-Can. Effort is required to develop further the concept of safety margins in the safety case.

10) ***Is a safety functions approach to assessment inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.***

This was answered in the previous question.

11) Please give key references for the safety functions approach that you have used in your recent work.

The review SKI has carried out for the SR-Can safety case will shortly be published.[3]

A.4 Interview Summary – J. Schneider, Nagra, Switzerland

Present GSL: A. Khursheed (recorder), R. Wilmot (interviewer).

Present Nagra: J. Schneider.

This note is a record of a telephone interview conducted by Galson Sciences Limited (GSL) on 19 June 2008 with J. Schneider of the Swiss national nuclear waste disposal organisation, Nagra. Written material was also supplied by the interviewee, which has been used to supplement that gathered in interview.

1) Summarise your recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

The answer to this question is informed principally by Project Opalinus Clay (Entsorgungsnachweis), and the current focus in the Swiss programme on site selection. With respect to the latter, the Swiss programme is in an active phase of work, driven by the recent publication of a Sectoral Plan to further site selection. This essentially starts off with a blank map of Switzerland. The first stage is to identify those regions that are potentially suited to site a deep geological repository on geological grounds and without consideration of economic and societal factors. Criteria for site selection are given in the Sectoral plan and based in part on a consideration of safety functions. It was noted in discussion that this approach differs from that in the UK, where local communities were recently invited to volunteer as hosts for a repository prior to an assessment of potential geological suitability.

The use of safety functions was integral to certain aspects of the safety case constructed in Project Opalinus Clay, notably in deriving the "Pillars of Safety" and in Chapter 2 (Guidance and Principles for Choosing the Disposal System and Evaluating Safety). However, it was also noted that the safety functions approach methodology

[3] SSI and SKI 2008. SKI:s och SSI:s gemensamma granskning av SKB:s Säkerhetsrapport SR-Can. Granskningsrapport. SSI rapport 2008:04/SKI 2008:19, Statens strålskyddsinstitut (SSI) / Statens kärnkraftinspektion (SKI), Stockholm, Sweden.

being used in Switzerland has evolved further since that report, which was published nearly six years ago (December 2002).

2) What are the main functions and sub-functions that you use?

The disposal system performs a number of functions relevant to long-term security and safety, which are termed safety functions. The following descriptions are translated from the German text:

- *Isolation from the human environment and long-term stability:* The safety and security of the waste, including fissile material, is ensured by placing it in a repository located deep underground, with all access routes backfilled and sealed, thus isolating it from the human environment and reducing the likelihood of any undesirable intrusion and misapplication of the materials. Furthermore, there is the absence of any currently recognised and economically viable natural resources that might result in conflict with future infrastructure projects that can be conceived at present, thereby reducing the likelihood of inadvertent human intrusion. Finally, appropriate siting ensures that the site is not prone to disruptive events and to processes unfavourable to long-term stability.

- *Containment of radionuclides:* Much of the radioactivity initially present decays while the wastes are totally contained within the primary waste containers, particularly in the case of spent fuel (SF) and high-level waste (HLW), for which the high integrity canisters are expected to remain unbreached for several thousand years thanks to the favourable geochemical and rock-mechanical conditions. Even after the canisters are breached, they still fulfil a barrier function against radionuclide transport in that they limit water access to the waste matrix and in that their corrosion products have favourable sorption properties for many radionuclides.

- *Delayed release of radionuclides:* Even after the canisters are breached, the stability of the waste matrix in the expected environment (reducing conditions), the slowness of groundwater flow and a range of geochemical immobilisation and retardation processes ensure that radionuclides continue to be largely confined within the engineered barrier system and the immediately surrounding rock, so that further radioactive decay takes place. This applies specifically to SF (stable UO_2 matrix) and HLW (stable glass matrix), but also to ILW and L/ILW for which a large fraction of the radionuclides is embedded in slowly corroding steel.

- *Radionuclide retention in the near field and in the geosphere:* After radionuclides are released from the waste matrix, they are transported through the near field and the geosphere at very low rates thanks to a number of favourable properties of the engineered and natural barriers. During transport, further decay takes place; this further reduces radionuclide releases from the repository to the human environment.

- *Low release rates to the environment:* A number of additional processes attenuate releases during transport towards the surface environment, and limit the concentrations of radionuclides in that environment. These include radioactive decay during transport and the spreading of released radionuclides in time and space by, for example, diffusion, hydrodynamic dispersion and dilution.

3) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, scenario development, or safety case strategy.

Safety functions have an important role to play in all of the above aspects of the safety case. In certain roles they are used indirectly, such as for PA (if used synonymously with safety assessment) and safety case organisation/management.

4) At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?

At each stage in a repository programme, safety functions are useful. However, safety functions may be developed in more and more detail as a programme progresses from one stage to the next.

5) What possible advantages/disadvantages does a safety functions approach have for communication with a range of stakeholders?

Safety functions have been found to be a very useful communication tool. To a lay audience they have been used to explain how the proposed repository would function.

For researchers or engineers involved in the programme who might be one step removed from development of the safety concepts, they have been useful too. For example, in talking to construction engineers involved in the plans for the tunnels for the HLW repository, safety functions were used to explain why the design does not need shotcrete. In communications with researchers, safety functions can help focus research on those phenomena that should be studied with high priority, and those that have a potential to undermine the proper operation of the safety functions. In communications with exploration geologists, they can guide the search for adequate sites / host rocks.

Another stakeholder for whom safety functions may be a useful communications tool is the regulator. However, discussions with the regulator in Switzerland are currently at an early stage and the use of safety functions has not been tested in this situation.

No disadvantages have been noted.

6) What safety function indicators do you use and how have they been derived?

The descriptions of the role and applicability of safety functions (see Question 2) effectively provide qualitative safety function indicators. There has been no quantitative use of safety function indicators in the Swiss programme to date; however, the situation is in a state of flux, and the development of such indicators is being considered.

Swiss regulations have requirements to demonstrate an understanding of the functioning of barriers, but have no limits on performance other than those on dose and risk.

7) How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.

There are no examples to date.

8) Which areas of the safety functions approach require further methodological development?

Nagra is currently developing a methodology for applying a safety functions approach to scenario development. It is hoped that this methodology will tackle issues of scenario comprehensiveness.

See also the answer to Question 6 regarding use of safety function indicators.

9) Is a safety functions approach to design inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

The use of a safety functions approach with respect to design and assessment is neither conservative, realistic nor pessimistic. The adoption of conservatism or realism is a result of strategic decisions, rather than an intrinsic property of using a safety functions approach.

This point may be illustrated by considering the case of containment of radionuclides in the first few thousand years (SF/HLW). A SF/HLW canister has to be designed in such a way that convincing arguments can be made that, under all conceivable repository conditions (geochemical, rock mechanical), the canister will fulfil the safety function of containment. In this example, the safety functions approach to design cannot be said to be either conservative, realistic or pessimistic.

10) Is a safety functions approach to assessment inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

The safety functions approach to assessment cannot be said to be conservative, realistic or pessimistic.

Safety functions are considered to have a key role in safety assessment; they help to identify the key safety-relevant phenomena using a full scientific understanding of the repository system and the various processes that operate and that will drive repository evolution. An important point is the issue of completeness; a methodology should be used that minimises the likelihood that any safety-relevant phenomena have been overlooked (e.g. a cross-comparison of the project-specific FEP database with independently-derived FEP databases). The effects of uncertainties in the key safety-relevant phenomena are evaluated in a broad range of assessment cases. Again, arguments have to be made why the range of assessment cases is wide enough (systematic methods for checking that all safety-relevant phenomena are adequately reflected by the chosen set of assessment cases).

11) Please give key references for the safety functions approach that you have used in your recent work.

Project Opalinus Clay: Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungs-nachweis). Nagra Technical Report NTB 02-05. Nagra, Wettingen, Switzerland (2002).

Project Opalinus Clay: Models, codes and data for safety assessment. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-06. Nagra, Wettingen, Switzerland (2002).

FEP management for the Opalinus Clay safety assessment. Nagra Technical Report NTB 02-23. Nagra, Wettingen, Switzerland (2002).

Vorschlag geologischer Standortgebiete für ein SMA- und ein HAA-Lager: Begründung der Abfallzuteilung, der Barrierensysteme und der Anforderungen an die Geologie – Bericht zur Sicherheit und Machbarkeit, Nagra Technical Report NTB 08-05. Nagra, Wettingen, Switzerland (2008). Expected publication date: 2nd half of 2008.

A.5 Interview Summary – L. Bailey, NDA, UK

Present GSL: A. Khursheed (recorder), R. Wilmot (interviewer).

Present NDA: L. Bailey.

This note is a record of a telephone interview conducted by Galson Sciences Limited (GSL) on 21 May 2008 with L. Bailey of the UK's Nuclear Decommissioning Authority (NDA).

1) Summarise your recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

The UK programme to develop a deep geological disposal facility for higher-radioactivity wastes is at the pre site-selection stage. Work to date has focussed on developing generic concepts, to demonstrate the feasibility of the deep geological disposal strategy and build confidence in safety. This approach is described in the Disposal System Safety Case (DSSC), which is due for publication late 2009.

Two deep geological disposal concepts have been developed:

a) a concept for the disposal of intermediate-level waste (ILW) in vaults at a depth of 200-1000 metres; and

b) a concept for the disposal of HLW and spent fuel based upon the Swedish KBS-3 canister design.

Hitherto, performance assessment of the generic concepts has been structured according to the roles of the barriers in each concept rather than to overall safety functions. However, in the case of the ILW concept, safety functions have been considered in relation to transport and handling of waste packages.

2) What are the main functions and sub-functions that you use?

As stated in the previous answer, to date the methodological framework has focused on the barriers in the repository concept. However, the following four safety functions can be identified in the current repository concepts:

- containment - this is considered especially for transport and handling;
- isolation, provided primarily by the geosphere;
- retardation and decay - in terms of the generic parameters (Q, T, and F) describing groundwater flow, this function is provided not only through the properties of the geosphere that affect travel time (T), but also through reducing flow and hence transport through the engineered barrier (Q);
- non-dissolution – this function has particular value for the ILW concept, where dissolution is controlled by conditioning of the waste and control of the chemical environment surrounding the waste packages.

3) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, scenario development, or safety case strategy.

At the present stage of development, the focus within the UK programme is on communication with stakeholders and building confidence, often through the use of qualitative arguments. Consequently, safety functions have not been used much in a quantitative way.

4) *At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?*

It is anticipated that, as the site selection process progresses, safety functions will play a greater part in the safety case, including their use in a quantitative way. At present the generic repository concepts are being used to define the beneficial characteristics that a good repository site would have. An overview of how the performance assessment is expected to develop in relation to the repository programme is set out in NDA Report 117.

5) *What possible advantages/disadvantages does a safety functions approach have for communication with a range of stakeholders?*

Communications with stakeholders is an important element of the safety case and the NDA programme. NDA is exploring how qualitative arguments i.e. "words" rather than "numbers", can aid communication with non-technical audiences. Communication of the repository design has been in terms of barriers, and their associated safety functions.

6) *What safety function indicators do you use and how have they been derived?*

It is too premature for NDA to consider the use of safety function indicators. First, a site needs to be selected and then a repository design developed for that particular site. These steps will progress iteratively, and the present stage is considered to be some cycles away from a detailed design for a specific site.

7) *How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.*

There are no examples to date.

8) *Which areas of the safety functions approach require further methodological development?*

NDA will consider developing an approach to safety function indicators when the repository programme is sufficiently mature.

9) *Is a safety functions approach to design inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.*

It is likely that safety functions will play a role in the detailed design for a repository. For example, in the HLW repository design, an approach that employs safety functions could be useful for analysing the spatial relationship between deposition holes.

In reviewing the use of safety functions in the safety case in other deep geological disposal programmes, it is observed that there is the potential for the approach to result in conservatism when there is a requirement for all barriers to pass tests set on safety function indicators independently. NDA would consider a holistic approach, whereby failure of one test would be weighed against credits elsewhere in the analysis. This would be particularly important for ILW designs where there is less emphasis on containment by a single barrier and more emphasis on the complementary safety functions of different barriers over different timeframes.

10) Is a safety functions approach to assessment inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.

This was answered in the previous question.

11) Please give key references for the safety functions approach that you have used in your recent work.

The DSSC overview report is due to be published this summer. The complete Generic DSSC is due to be published late 2009.

A.6 Interview Summary – A. Van Luik, DOE, and P. Swift, SNL, US

Present GSL: A. Khursheed (recorder), R. Wilmot (interviewer).

Present DOE, SNL: A. Van Luik (DOE, Nevada), P. Swift (SNL, New Mexico).

This note is a record of a telephone interview conducted by Galson Sciences Limited (GSL) on 21 May 2008 with A. Van Luik, US Department of Energy (DOE) and P. Swift, Sandia National Laboratories (SNL). The questions had been distributed prior to the interview, and, at the interviewee's request, an additional question on definitions (no. 0) was included.

0) Please define the terms used in the US programme with respect to the use of "safety functions"

The term "safety functions" is used to describe the roles that may be played by barriers and/or their components in the safety case for the deep geological disposal of radioactive waste. The intent is to use these words to show a continual focus on safety as one thinks through the components of a repository system. They are good words.

However, they do carry some baggage. It implies that each barrier or component safety function is something that has been evaluated in terms of its quantitative impact on safety. In many instances, a safety function such as radionuclide retardation is provided by several repository components, such as degraded waste package components, waste form secondary minerals, a buffer material, fracture coatings in the host rock, or another feature further down the travel path. In many instances, such functions are not quantitatively evaluated until the total system is being analysed.

It is because of this implication that the contribution to safety from each safety function has been analysed and quantified that the US DOE has decided to use the words “barrier function” instead. In many instances, the delay or potential delay of a point release from one area of the repository to another has been evaluated to judge the importance of a barrier function on a small scale, but many such functions are integrated at the repository-level in a total-system performance assessment that evaluates safety. Therefore, the US DOE uses the words “barrier function” in much the same way the international community uses the words “safety function.” That this is so can be seen from reading this paragraph from *An International Peer Review of Safety Report 97: Post-closure Safety of a Deep Repository for Nuclear Spent Fuel in Sweden*, Section 2.0, where the Swedish barrier system is described this way:

> *These barriers have multiple safety functions: for example, the bentonite buffer provides mechanical protection and restricts water access to the canister and would also retard the movement of contaminants away from the canister in the event of it being breached. Some functions are supplied by more than one barrier: for instance, radionuclide migration can be delayed by sorption effects both in the bentonite buffer and in the surrounding rock.*
>
> Reference: Nuclear Energy Agency (NEA) 2000,
> http://www.nea.fr/html/rwm/reports/2000/nea2468-sr97.pdf

This usage is essentially equivalent to our usage of the words “barrier functions” in our most recent documents. For example, in our recent *Total System Performance Assessment for the License Application* (MDL-WIS-PA-000005 Rev 0.0), the Executive Summary states the following (acronyms were previously defined in this document: EBS is engineered barrier system, WPs are waste packages, DSs are drip-shields, and the UZ is the unsaturated zone above and below the repository):

> **ES6.2 Engineered Barrier System**
>
> The EBS includes the engineered components and the physical and chemical environment surrounding and within the engineered elements of the repository. Figure ES-19 illustrates the primary components of the EBS that are the WPs containing the waste, the DSs that protect the WPs from dripping water and falling rocks, and the crushed-tuff invert and support structures beneath the WPs and DSs. **The barrier functions of the EBS are** to isolate the waste forms from migrating water and chemical conditions leading to mobilization of the radionuclides in the waste forms. The EBS helps divert water from the UZ above the repository to the invert and to the UZ below the repository. The WP and DS Degradation Model Component simulates the response of these engineered systems to heat, humidity, seepage, geochemical environment, and moisture. The Waste Form Degradation and Mobilization Model Component simulates the dissolution of the waste forms and the amount of water released from breached WPs. The EBS Flow and Transport

Model Component simulates the flux of fluid and radionuclides from the repository to the UZ below the repository.

Section 8.3.2.1 of the same report states that:

Within the repository horizon, ambient unsaturated flow and thermo-hydrologic processes are favorable to the natural barrier function of preventing or substantially reducing the movement of water into emplacement drifts.

Although these are the only two places where "barrier function" is used, many other statements in fact are describing such functions. The primary location for this discussion is under section 8.3.2 which does not use the words "barrier" and "function' together, but makes clear that is the subject at hand:

8.3.2 Identification of Barriers for Yucca Mountain Repository System

As noted earlier, the Yucca Mountain Repository system is comprised of three barriers, namely, the Upper Natural Barrier, the EBS, and the Lower Natural Barrier (Figure 8-1). Collectively, these three barriers function to: (1) prevent or substantially reduce the rate of movement of water or radionuclides from the repository to the accessible environment, or (2) prevent or substantially reduce the release rate of radionuclides from the repository. A brief description of these barriers and their features is given below:

1. Upper Natural Barrier—Barrier features include the topography and surface soils of the mountain, the unsaturated tuff units above the repository, and the rock in which the repository is constructed.

2. EBS—Barrier features include the emplacement drifts, DSs, WPs, waste forms, cladding (associated with CSNF, DSNF, and NSNF), WP pallets, and ballast in the emplacement drift inverts.

3. Lower Natural Barrier—Barrier features include the volcanic rock in the UZ beneath the repository and the volcanic rock and alluvial material in the SZ between the repository and the accessible environment.

It is important to clarify that the Upper Natural Barrier is the portion of the geologic strata that extends from land surface to the bottom of the repository emplacement horizon. The Lower Natural Barrier extends from the base of the repository horizon to the water table and includes the SZ below the water table that extends from the repository footprint to the accessible environment boundary at approximately 18 km.

For the Upper Natural Barrier, the **capability of the barrier features is described with respect to how they prevent or substantially reduce the rate and amount of water that may seep into the repository drifts and, ultimately, to the accessible environment**. In contrast, **the capability of the EBS features is described with respect to how they prevent or substantially reduce the release rate of radionuclides from the WPs**. In the case of the Lower Natural Barrier, **the <u>capability of the barrier features</u> is described in terms of how they prevent or substantially reduce the rate of movement of radionuclides from the repository to the accessible environment**.

In the above paragraphs, the bolded/underlined words are the equivalent of the "safety functions" words in accepted international usage, but here "capability" is used in place of "function." The intent is the same, but note how the definition of the Upper Natural Barrier is stated in two parts: restriction of water entering drifts, and ultimately control of water reaching the accessible environment. Some barrier capability evaluations stop at calculation midpoints that are not expressed in terms of dose or risk hence safety. There may be evaluations of how much radioactivity is located at various points in the repository, for example, to illustrate the type of contribution a barrier function is making, but without calculating system safety. Hence the reluctance to use the words "safety function" in the US programme.

1) Summarise your recent experience of using safety functions in the safety case for the deep geological disposal of radioactive waste.

In the latest documents describing the total system performance assessment for the proposed Yucca Mountain repository (see Question 11 for reference), there is substantial attention to the issue of being able to demonstrate that there are multiple barriers that provide functions that contribute to safety. This is carried down to the component level in a qualitative sense, or in a quantitative sense by showing radionuclide delay and retention in portions of the engineered and natural systems. However, these quantitative calculations do not address the expected dose to the hypothetical dose recipient in the very far future. They are designed to demonstrate a barrier capability or contribution at the process or sub-system level, and are not typically rolled up separately into dose calculations.

Note that an important distinction is made, with respect to the use of safety functions, between post-closure and pre-closure phases of repository operation. The remarks made above apply to the post-closure phase. For the pre-closure phase, safety functions are used in way that is closer to that in several European programmes (see presentation of Preclosure Safety Analysis by M. Frank to Nuclear Waste Technical Review Board on 19 September 2007).

2) What are the main functions and sub-functions that you use?

The performance assessment methodology chosen for the recent Yucca Mountain license application closely follows the regulatory guidelines set out in 10 CFR 63, issued by the US National Regulatory Commission. These regulations contain a requirement to identify barriers and associated barrier functions. In addition, components of the engineered barrier are required to have a functional lifetime of greater than 10,000 years.

The primary functions are the delay of the movement of groundwater and radionuclides. Secondary or contributing functions may include the chemical environment that assures waste package longevity, the geochemical environment that provides sorptive capacity for certain radionuclides, and the waste package internals whose corrosion provides sorptive sites for radionuclides.

In a summary form, the barriers of the proposed Yucca Mountain repository provide the functions of: (1) preventing or substantially reducing the rate of movement of water to the waste; (2) preventing or substantially reducing the release rate of radionuclides from the waste; and (3) preventing or substantially reducing the rate of movement of radionuclides from the repository to the accessible environment

3) Please indicate the roles in the safety case where you consider safety functions to have most value, giving examples where appropriate. Your answer might refer to repository design, PA, safety case organisation/management, qualitative modes of use, quantitative modes of use, communication with stakeholders, scenario development, or safety case strategy.

Safety/barrier function discussions can play a role in each of the listed items. Design has to be aware of what functions their designs are to provide, and performance assessment needs to evaluate a system composed of barriers with specific functions. Creating and managing a safety case over time derives benefit from more becoming known about barrier capabilities over time. A combination of descriptive and quantitative evaluations can be a powerful tool in communications.

In the work done for the recent license submission for Yucca Mountain, safety functions played notable roles in the organisation of the safety case and for communication with stakeholders. Safety functions have been particularly helpful for passing on a conceptual understanding of the barrier concept in communications with lay stakeholders; they help make the significant point that physical “failure” of barriers (inevitable at some in the system’s evolution) does not necessarily mean that the safety functions do not work. It is noted in this respect that disruptive events are an integral part of the reference case for the evolution of the Yucca Mountain site.

Safety functions have also played a valuable role in the computational design of the performance assessment, by allowing efforts to concentrate on key processes that affect risk to individuals. Their importance for barrier design, however, is mitigated by the 10,000 year containment requirement that regulations stipulate for barrier performance.

While safety functions can be useful in scenario development, their use in this way has been limited in recent work performed for the Yucca Mountain project.

4) At what stage of development would a deep geological disposal programme benefit the most from a safety functions approach in the safety case e.g. conceptual development/feasibility, site selection, site-specific studies, construction, operation, post-closure? How would you expect the way in which safety functions are used to change as the programme advances from one stage to another?

Safety/barrier functions ought to be the defining focus right from the start. As repository concepts and designs change in response to evolving knowledge of the natural system and the proposed engineered system's characteristics, new components and features, new processes, even new unexpected events may be determined to either be plausible or needed. This has been the experience at Yucca Mountain, where initial concepts were developed for a site with very little moisture. Understanding of the site and the design of the facility have evolved to the stage where it is now assumed that there is a high degree of moisture at the proposed repository site.

5) What possible advantages/disadvantages does a safety functions approach have for communication with a range of stakeholders?

Safety- or barrier-function displays and explanations are very effective in taking the mystery out of why a repository ought to work. They are quite effective in giving audiences insight into not only how a repository is expected to function, but also why it is possible to model the expected behaviour, and the expected behaviour in response to unexpected events. They show that failure of system components is not fatal for the proper functioning of the system.

6) What safety function indicators do you use and how have they been derived?

Barrier functions have been derived primarily from regulatory language indicating that a barrier is anything that slows or stops the movement of either water or radionuclides in a repository. The regulator's approach was one that makes common sense. The question was asked (and answered): what can go wrong in a repository (waste packages fail and water contacts waste and it migrates)? The barrier functions then had to be the prevention or delay of those dominant processes.

The following pictures help illustrate this approach (for the early failure and nominal cases only, not considering volcanic disruptive events or larger earthquakes). Note that none are expressed in terms of dose to a receptor, each examines a limited domain within the repository only. This first illustration (Figure A.2) shows the total activity in the inventory decreasing with time (black line) and the activity of specific radionuclides as well as the total activity released from the engineered barrier system (EBS) over time (95% of the inventory does not leave the engineered system over a million years).

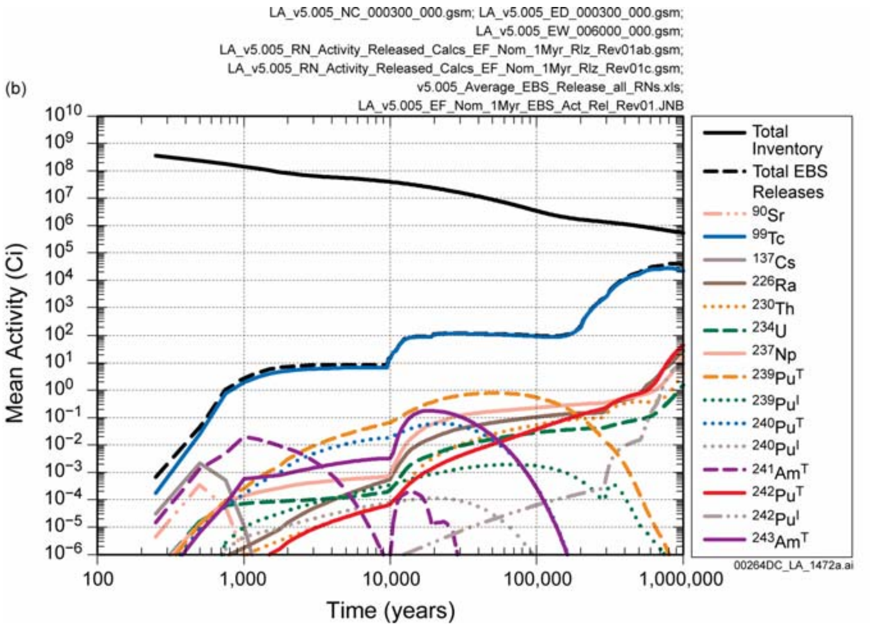

Figure A.2. Inventory decay and releases from the Yucca Mountain EBS over time.

Similarly the next illustration (Figure A.3) shows the same EBS releases but now at the end of the combined unsaturated/saturated zone pathways crossing the accessible environment boundary.

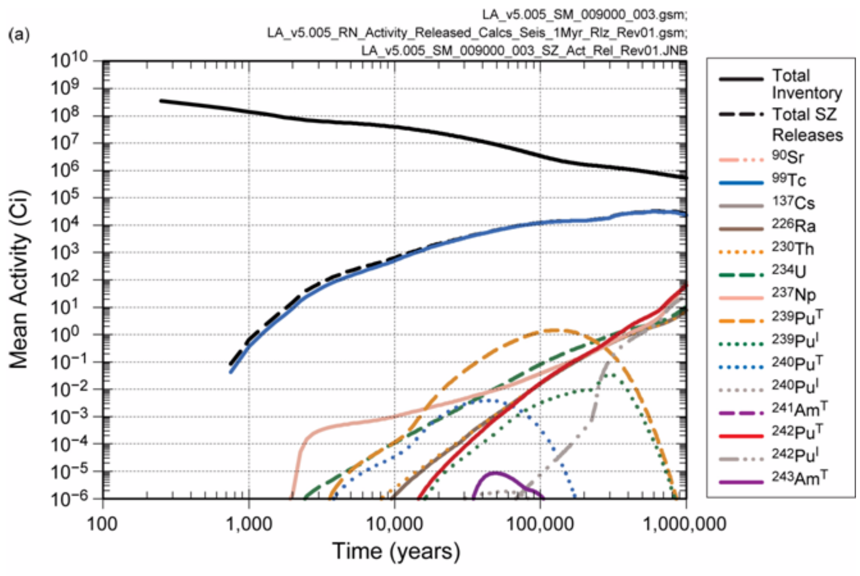

Figure A.3. Releases to the accessible environment over time from the Yucca Mountain repository.

Although the release of ~6*10^4 Curies a million years into the future seems like a high number in the abstract, given the specific radionuclides involved and the pathways in the biosphere, this translates to a dose to the hypothetical individual defined by regulation of less than 0.02 mSv/year. If that connection had been made in these illustrative calculations, then these could have been described as safety function analyses rather than barrier function analyses.

7) *How would you propose to relate the values of these indicators to regulatory limits/constraints? Please illustrate with examples.*

The regulatory requirements at the system level are quantitative. The requirements at the subsystem level are qualitative, and it is at that level that barrier functions are evaluated to show that there are in fact multiple barriers contributing to overall system safety.

8) *Which areas of the safety functions approach require further methodological development?*

This is a concept-specific question; in the case of Yucca Mountain it is not so much methodological development that is needed as it is gaining further insight into the long-term environments and component behaviours through continuing testing and observation.

9) *Is a safety functions approach to design inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.*

None of these. Design considers safety, efficiency, and manageability of the operational side of the equation. Items of importance to safety (items with a demonstrable and direct function assuring worker and public safety), and items of importance to waste isolation (items directly or substantively but indirectly affecting the ability of the repository to contain its waste) are separate categories in the design of the repository and of the safety evaluation of the repository before and after permanent closure. Naming these components is followed by analyses of their durability, reliability, and eventual failure (safety assessments). Naming them, in and of itself, does not assure that safety assessments will be either realistic or pessimistic or optimistic.

10) *Is a safety functions approach to assessment inherently conservative, realistic, pessimistic or none of these? Please give examples to support your case if appropriate.*

None of these. Safety functions (barrier functions) are mid-point evaluations of contributions and capabilities of specific components and barriers made up of such components. In and of themselves, “safety functions” do not dictate the decisions to be made in modelling that in turn determine whether an evaluation is pessimistic or optimistic.

11) *Please give key references for the safety functions approach that you have used in your recent work.*

SNL (Sandia National Laboratories), *Total System Performance Assessment Model/Analysis for the License Application,* MDL-WIS-PA-000005 Rev 00, AD 01, U.S. Department of Energy Office of Civilian Radioactive Waste Management, Las Vegas, Nevada (2008).