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Engineered Barrier Systems (EBS): Design Requirements and Constraints

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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EXECUTIVE SUMMARY

Radioactive waste disposal systems typically comprise a series of barriers that act to protect the environment and human health. The presence of several barriers enhances confidence that the waste will be adequately contained. In deep geological disposal systems, the barriers include the natural geological barrier and the engineered barrier system (EBS). The EBS may itself comprise a variety of sub-systems or components, such as the waste form, canister, buffer, backfill, seals and plugs.

The Integration Group for the Safety Case (IGSC) of the OECD Nuclear Energy Agency (NEA) is co-sponsoring a project to develop a greater understanding of how to achieve the necessary integration for the successful design, construction, testing, modelling and performance assessment of engineered barrier systems.

This report presents a synthesis of information and findings from a workshop on repository design requirements and constraints, which was hosted by Posiva Oy in Turku, Finland, in August 2003.

The following principal conclusions were drawn:

- Designing, constructing and operating a radioactive waste disposal system is a complex project that has to take account of the many requirements that the disposal system has to fulfil. Requirements management systems and tools can assist in the successful completion of such complex projects. Key advantages of requirements management systems are that they formalise the repository design process; ensure that the design takes adequate account of the various requirements and constraints placed on the disposal system; and help to achieve the goals of clear communication and traceable, justified decision making.

- Requirements management systems and tools are complementary to safety and performance assessment techniques and tools. Requirements management and performance assessment share some common inputs (e.g. site characterisation information, regulations), methods (iteration, change control), goals (transparency), and needs (quality assurance, traceability, successful integration of project teams, stakeholder dialogue – see below), but each provides important and distinct outputs (e.g. detailed specifications that would allow the construction of an engineered barrier, estimates of potential dose). Thus, while the perspectives of requirements management systems and performance assessment are slightly different, both form logical parts of the overall safety case for the disposal facility.

- Active stakeholder dialogue is a key element contributing to the success of processes for selecting waste management options and developing design solutions. Ensuring clear communication between project teams is also of high importance.

Noting the potential offered by requirements management systems and the need to gain further experience in their application to radioactive waste management, the workshop recommended that the IGSC establish a project to (i) undertake initial steps in the development of a prototype requirements management tool, and (ii) develop a grid of high-level requirements common to all waste management programmes. The tools developed by this project would feed into the final workshop of the EBS series.

Acknowledgements

On behalf of all participants, the NEA wishes to express its gratitude to Posiva Oy, which hosted the workshop in Turku, Finland, as well as to the EC for its co-operation to the workshop. Special thanks are also due to:

- The members of the Workshop Programme Committee who structured and facilitated the workshop were: Timo Äikäs, (Posiva Oy, Finland); David Bennett, (Galson Sciences Limited, UK); Jean-Paul Boyazis, (ONDRAF/NIRAS, Belgium); Frank Hansen, (SNL, USA); Alan Hooper, (United Kingdom Nirex Limited, UK); Robert Mackinnon, (SNL, USA); Nina Müller-Hoeppe, (DBE, Germany); Frédéric Plas, (Andra, France); Öivind Toverud, (SKI, Sweden); Hiroyuki Umeki, (NUMO, Japan); Sylvie Voinis, (OECD/NEA) and Henning von Maravic, (EC).

- The working group chairpersons and rapporteurs who led and summarised the debates that took place in the five working groups.

- The speakers for their interesting and stimulating presentations, and all participants for their active and constructive contributions.

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1. INTRODUCTION

Radioactive waste disposal systems typically comprise a series of barriers that act to protect the environment and human health. The presence of several barriers enhances confidence that the waste will be adequately isolated and contained.

In deep geological disposal systems, the barriers include the natural geological barrier and the Engineered Barrier System (EBS). The EBS may itself comprise a variety of sub-systems or components, such as the waste form, canister, buffer, backfill, seals, and plugs. The purpose of an EBS as a whole is to prevent and/or delay the release of radionuclides from the waste to the repository host rock. Each sub-system or component has its own requirements to fulfil. For example, the canister must ensure initial isolation of the waste. The engineered barriers must also function as an integrated system and, thus, there are requirements such as the need for one barrier to ensure favourable physico-chemical conditions so that a neighbouring barrier can fulfil its intended function. For example, in some disposal systems the buffer has a role in minimising canister corrosion.

The specific role that an EBS is designed to play in a particular waste disposal system is dependent on the conditions that are expected (or considered possible) to occur over the period of interest, on regulatory requirements (e.g. for waste containment), and on the anticipated performance of the natural geological barrier. To be effective, an EBS must be tailored to the specific environment in which it is to function. Consideration must be given to factors such as the heat that will be produced by the waste, interactions between different materials in the waste and the EBS, the groundwater chemistry (e.g. pH and redox conditions) and flux, the mechanical behaviour of the host rock, and the evolution of the disposal system.

Designing an EBS to fulfil all of the requirements requires integration of data from site- and waste-characterisation studies, as well as from research and analysis on the engineering and physico-chemical properties of the barriers and their materials. These data may be gathered from a range of sources, including laboratory tests and tests performed in underground facilities, and may be interpreted and integrated through modelling studies.

1.1 The NEA EBS Project

The Integration Group for the Safety Case (IGSC) of the Nuclear Energy Agency (NEA) is co-sponsoring the EBS project to develop a greater understanding of how to achieve the necessary integration for successful design, construction, testing, modelling, and performance assessment of engineered barrier systems. It was decided to start by one workshop in order to get further information in the view of a series of workshops. To this end a first workshop (named “Oxford workshop” in the further chapters) was held under the joint auspices of the EC and the NEA, hosted by United Kingdom Nirex Limited (Nirex), at Keble College, Oxford on 25-27 September 2002[1].

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[1] Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case; Workshop Proceedings; Oxford, United Kingdom; 25-27 September 2002; EC-NEA, 2003.

In line with the successful outcomes and findings of the Oxford workshop, there was strong support for a series of four workshops, to be held at a frequency of one per year, and to be continued with co-sponsorship by the NEA and the EC in order to have a good platform for an integration of understanding on the EBS and its role in the overall safety case.

The EBS project is being conducted via a series of workshops:

- Design Requirements and Constraints (Turku 2003).
- Process Issues (Las Vegas 2004):
  - Thermal management and analysis.
  - Alteration of non-metallic barriers and evolution of solution chemistry.
  - Radionuclide release and transport.
- Role of Performance Assessment and Process Models (Spain 2005).
- Design Confirmation and Demonstration (Japan 2006).

Recognising the diversity in engineered barrier systems in various national programmes, as shown by the recent state-of-the-art report (NEA-EC, 2003), the IGSC-EBS project is seeking through these workshops, to achieve the following high-level aims:

- To promote interaction and collaboration among experts responsible for engineering design, characterisation, modelling, and performance assessment of engineered barrier systems.
- To develop a greater understanding of how to achieve the integration needed for successful design, construction, testing, modelling, and performance assessment of engineered barrier systems, and to clarify the role that an EBS can play in the overall safety case for a repository.
- To share knowledge and experience about the integration of EBS functions, engineering design, characterisation, modelling and performance evaluation in order to understand and document the state of the art, and to identify the key areas of uncertainty that need to be addressed.

Throughout its work, the EBS project is considering the engineered barrier system from four perspectives:

- Engineering design (e.g. how can a component be (re)engineered to improve performance or ease of modelling?).
- Characterisation (e.g. how can the properties of the EBS and the conditions under which it must function be measured or otherwise characterised?).
- Modelling (e.g. how well can the relevant processes be modelled?).
- Performance assessment (e.g. how can the performance of the EBS and/or its components be evaluated under a wide range of conditions?).

This approach is designed to enable participants to characterise more clearly the confidence in the contribution of the EBS to long-term safety within a suitably structured safety case.

This report presents a synthesis of information and findings from the 2003 workshop on repository design requirements and constraints.

1.2 Background to the Workshop on Design Requirements and Constraints

The design of a disposal system needs to take account of stakeholder's views regarding the objectives and requirements of the system. It must also be possible to demonstrate that the disposal system design provides an acceptable solution of the waste management problem.

In developing the details of the design for an EBS, various requirements and constraints have to be considered. Relevant constraints include disposal site characteristics, the nature of existing waste packages, the waste inventory, available technologies, available understanding of processes and related uncertainties, and the need for operational safety and flexibility. Although safety has the highest priority in the process of repository development, business requirements also have to be considered. There may be various alternative ways of fulfilling the requirements but at significantly different costs.

In September 2002 at the Oxford workshop (NEA 2003), the EBS project noted that several national disposal programmes were selecting between alternative options, refining concepts and undertaking detailed design work. The project decided, therefore, to hold a workshop in August 2003 on the topic of design requirements and constraints.

1.3 Report Structure

This report is structured as follows:

Section 2:	Workshop objectives.
Section 3:	Summary of presentations and discussions on the opening day of the workshop.
Section 4:	Summary of results from working group sessions and discussions held during the second and third days of the workshop.
Section 5:	Conclusions.
Section 6:	References.
Appendix A:	Workshop agenda.
Appendix B:	Papers/Overheads presented to the workshop.
Appendix C:	Membership of the working groups.
Appendix D:	List of participants.

2. WORKSHOP OBJECTIVES AND STRUCTURE

The workshop began with welcoming addresses from Sylvie Voinis (NEA), Michel Raynal (EC) and Timo Äikäs (Posiva Oy).

Timo Äikäs noted that the issue of requirements management was becoming increasingly topical as waste management programmes approached licensing and implementation, and raised the question of whether a formalised requirements management tool was necessary for linking between the repository design process and performance assessment (PA).

Hiroyuki Umeki (NUMO) described the background to the NEA IGSC-EBS Project (Section 1), and the specific objectives of the workshop as follows:

1. To state the design requirements for disposal systems and identify their basis, including the evolution of these requirements.
2. To promote common understanding of design requirements, and of methods for linking stakeholders' needs and regulatory requirements to practical design concepts and detailed design decisions.
3. To promote methods for achieving and maintaining transparency and traceability in establishing and developing the design basis for the EBS, and to seek ideas on how to assess whether the requirements have been fulfilled.
4. To share ideas and experiences on working with challenging requirements and constraints, and in accounting for uncertainty.
5. To understand better the basis for differences in national EBS designs.

The workshop continued with a plenary session devoted to presentations on the theme of the workshop and short discussions. The plenary session began with an invited keynote presentation on "*Systematic Management of Requirements: Theory and Practice*" by Lena Morén, SKB. This was followed by several further invited presentations on national practical examples of requirements management for EBS subsystems/components. The plenary session ended with a general discussion. Section 3 summarises key points from the presentations and discussions in these workshop sessions. The supporting papers or overheads on which the presentations were based are presented in Appendix B.

The second day and the early part of the morning on the third day were devoted to working group sessions. Four working groups were convened to consider the following topics:

Working Group A:	Practical Approaches to Ensuring Traceability in Design Requirements Management.
Working Group B:	Practical Approaches to Defining Design Requirements and Accounting for Uncertainty and Constraints.

Working Group C:	Practical Approaches to Developing/Evaluating/Selecting between Alternative Design Options and Refining Selected Designs.
Working Group D:	Practical Approaches to Linking “High-level” Requirements to Detailed Design Requirements/Specifications.

Section 4 presents (i) the issues that were discussed by each working group session, (ii) the results from the working groups and (iii) key points of discussion that arose when the results were presented to the subsequent plenary session.

Conclusions and recommendations are presented in Section 5.

3. REQUIREMENTS MANAGEMENT: THEORY, PRACTICE AND EBS EXAMPLES

An invited “keynote” paper on requirements management theory and practice (Section 3.1) was followed by a series of invited papers discussing examples of requirements management for EBS components (Section 3.2).

3.1 Requirements Management: Theory and Practice

Lena Morén (SKB) made a keynote presentation entitled “Systematic Management of Requirements: Theory and Practice”. The presentation outlined recent work by SKB on requirements management, in developing a disposal system for spent nuclear fuel, which is building upon expertise in systems analysis and PA. The slides from the presentation are included in Appendix B.

SKB defines a requirement as an “*expression describing a desired function, capability, characteristic, property or quality”*. Requirements thus provide a clear statement of objectives and define the problem or need that is to be satisfied. Requirements can be used to define the characteristics of the set of acceptable solutions and to provide guidance in the selection of an appropriate solution.

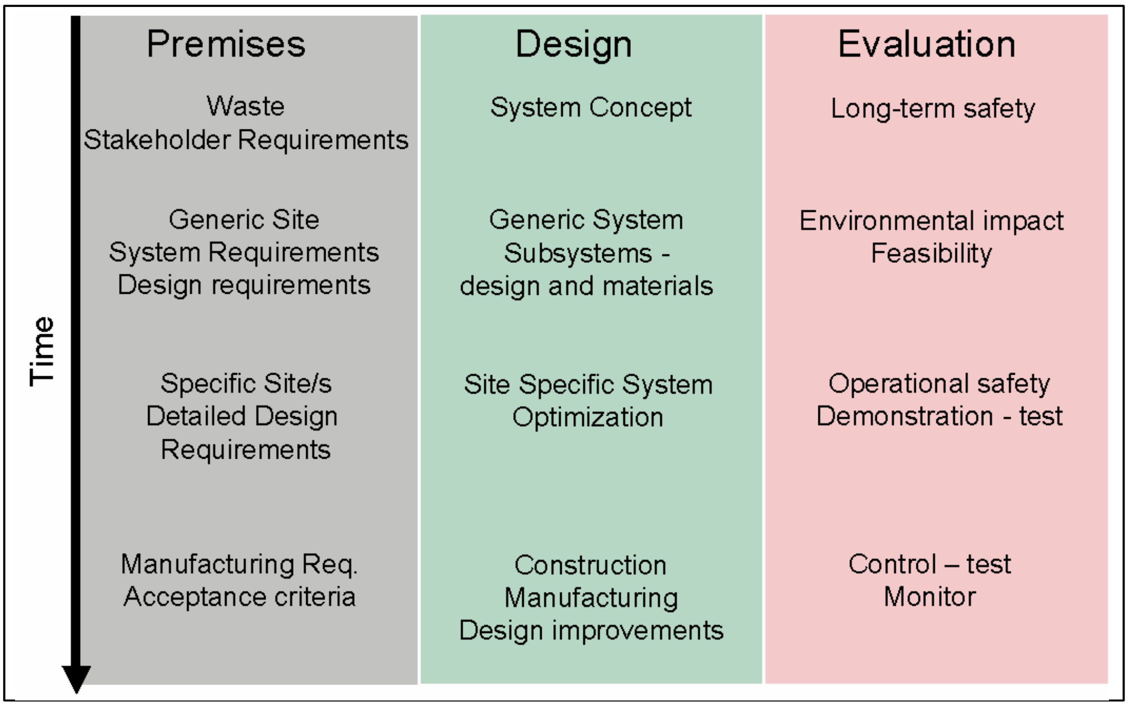
SKB has identified a hierarchy of requirements as follows:

Stakeholder Requirements	e.g. multi-barrier system
System Requirements	e.g. the repository shall isolate the waste from man and environment. If the isolation is broken, the repository shall retard the transport of radionuclides so that when the nuclides reach the biosphere they will cause no harm.
Sub-system Requirements	e.g., the canister must enclose the spent fuel and prevent dispersion of radioactivity to the surroundings, be watertight, withstand corrosion processes, and withstand mechanical stresses.
Design Requirements	e.g. the canister shall withstand mechanical stresses during handling, storage, transport and deposition. The canister shall withstand the water pressure at repository depth and the swelling pressure from the buffer. The canister shall withstand the pressures occurring due to glaciations. The canister shall withstand mechanical stresses caused by earthquakes.

Figure 3.1 illustrates the progressive identification and evaluation of design requirements and criteria, through several stages of disposal system design.

SKB is using the DOORS requirements management software to categorise and trace the evolution of the requirements and constraints on the design of the KBS-3 disposal system. The software system helps to facilitate communication (e.g., of the definition of the problem and its scope), design (e.g. by documenting optimisation and risk management steps taken, and ensuring change control), and quality assurance (e.g. traceability).

Figure 3.1. The Progressive Identification and Evaluation of Design Requirements and Criteria for Several Stages of Disposal System Design



Premises	Design	Evaluation
Waste Stakeholder Requirements	System Concept	Long-term safety
Generic Site System Requirements Design requirements	Generic System Subsystems - design and materials	Environmental impact Feasibility
Specific Site/s Detailed Design Requirements	Site Specific System Optimization	Operational safety Demonstration - test
Manufacturing Req. Acceptance criteria	Construction Manufacturing Design improvements	Control – test Monitor

Discussion around the presentation focused on the following points:

- **Terminology**. It was noted that there was inconsistency between the terminology and definitions proposed in the workshop programme document and that used in the Swedish work. Lena Morén suggested that the key point was that there should be a common understanding of terms within the project team. It was noted that the group “working on the project” could be considered to include a wide range of stakeholders, including the regulators.
- **Application of requirements management theory**. It was noted that requirements management theory is relevant generally to product design and that the theory needs to be tailored to the particular product in question (in this case a waste repository). Different waste disposal programmes might be expected, therefore, to apply the theory in slightly different ways to suit their particular context.
- **Requirements evolution**. It was recognised that during a repository development programme, which will typically last for several decades, stakeholder requirements are likely to change. Responding effectively to such changes will require continuous dialogue amongst the project team and the stakeholders and, in particular, close contact between repository designers and performance assessors. The need for “data freezes” prior to the

conduct of PA calculations was noted, with the implication that careful management is needed to ensure clear communication of project positions, particularly on issues that may be evolving actively in response to stakeholder input.

- **Institutional, corporate or project memory**. The potential for requirements management systems to help in preserving long-term project memory had been highlighted in the keynote presentation. Questions were asked as to whether this had been demonstrated in the specific context of radioactive waste disposal. It was noted that much of the experience in applying requirements management systems derives from the defence and telecommunications industries, but that relevant work had also been undertaken within the US WIPP (Waste Isolation Pilot Plant) Project.

3.2 Practical Examples of Requirements Management for EBS Components

3.2.1 Waste Packages in the US-DOE Yucca Mountain Project

Robert Mackinnon (SNL/US-DOE) described the requirements of the waste package for waste disposal at Yucca Mountain and discussed how the requirements and the design had evolved during the project (Appendix B).

The Yucca Mountain Project (YMP) has undertaken several iterative cycles of PA, data collection and design work. PA calculations had been reported by the YMP in 1991, 1993, 1995, 1998, 2000 and 2001. During these cycles, EBS component designs have evolved. For example, in the 1998 Viability Assessment, the waste package design included an Alloy 22 inner shell and a structurally strong, carbon-steel outer shell. The 2000 Site Recommendation design, however, included a 20-25 mm Alloy 22 outer shell and a structurally strong, 50 mm stainless-steel inner shell.

Within the YMP, design requirements are documented and managed using a hierarchical series of formal reports, including the:

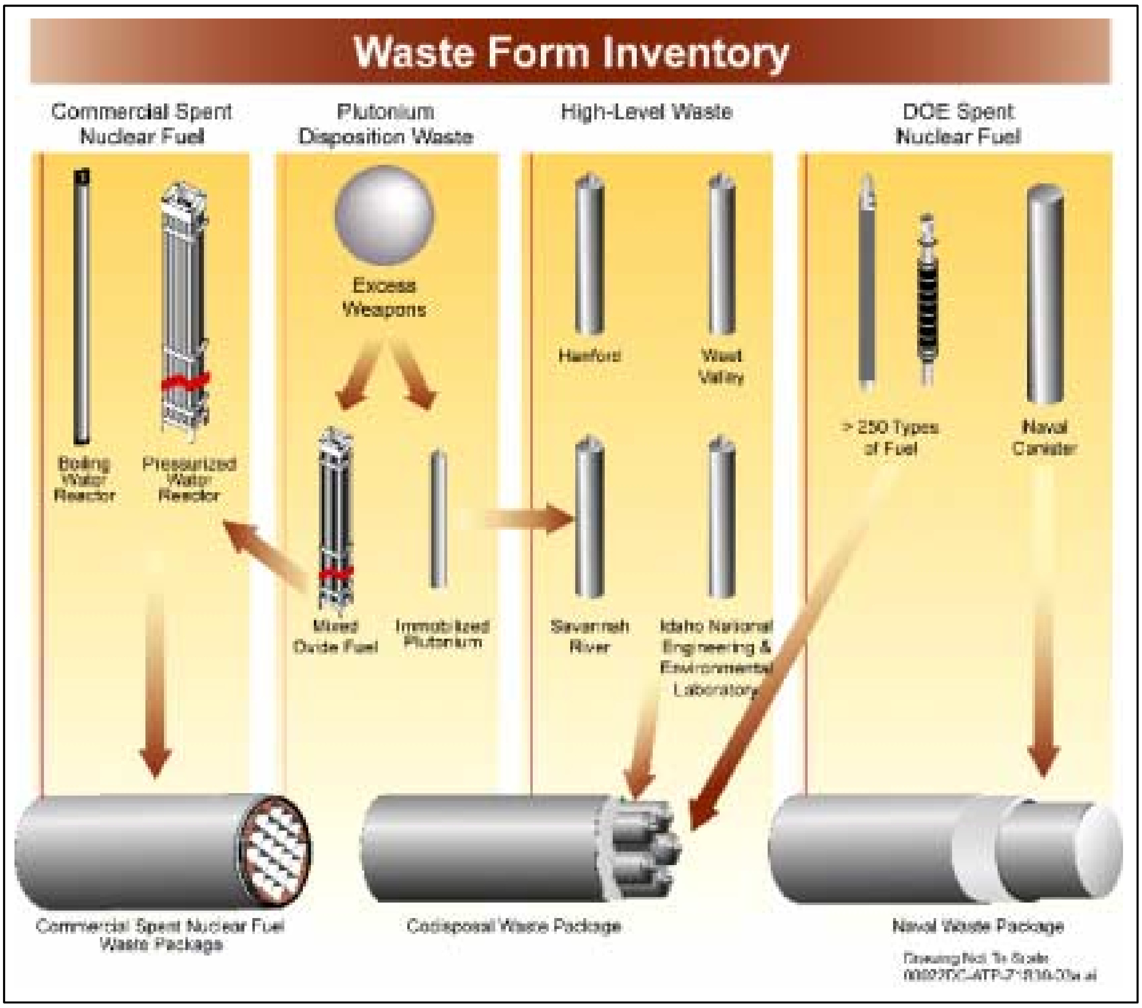
1. Civilian Radioactive Waste Management System Requirements Document.
2. Monitored Geologic Repository Requirements Document.
3. Project Description Document.
4. System Description Documents (SDD).

The SDDs are living documents that describe the system functions and design criteria, and detail the design of each EBS component. A change control board oversees the EBS design process, consults with stakeholders, including the US-DOE, the NWTRB (Nuclear Waste Technical Review Board) and the USGS (US Geological Survey), and approves revisions to the SDDs.

Statutory and regulatory requirements demand that:

- Expected waste forms are accommodated (Figure 3.2).
- Worker and public health and safety are protected during operations and before final closure of the repository.
- Long-term system performance objectives are satisfied.

Figure 3.2. Accommodation of Expected Waste Forms at Yucca Mountain



One of the biggest challenges so far in the design process has been ensuring adequate communication between the many organisations involved in the project. Work toward a licence application will include pre-closure and post-closure assessments of representative waste packages.

Discussion around the presentation focused on the following points:

- **Scheduling implications**. It was noted that the YMP is adhering to a strictly defined schedule, leading to a licence application in 2004 and the scheduled first receipt of waste in 2010. In answer to a question as to whether the schedule allowed sufficient time for scientific investigation, it was noted that the schedule had precluded consideration of certain materials (e.g. cement) for use within the EBS, for which it was judged that too much further R&D effort would be necessary.
- **Design changes**. It was noted that although some effects of design changes could be predicted and considered at the time of revising the design, other effects only became apparent during implementation (e.g. construction, emplacement).
- **The extent of the waste management system**. Questions were raised at to whether repository design might influence waste production and, by implication, reactor operation.

It was noted that although the YMP assumes a particular level of reactor fuel burn-up, this does not constrain reactor operation. More generally, it was noted that radioactive waste management programmes are typically being developed in a *post hoc* manner, subsequent to the decisions allowing waste generation. In practice, therefore, the waste generation processes impose requirements and constraints on the waste management system but requirements and constraints are not propagated in the opposite direction.

3.2.2 Buffer and Backfill in the Finnish/Swedish KBS-3 Repository Concept

Planning for the Finnish repository follows the KBS-3 concept, for disposal of spent nuclear fuel, which is being developed in a collaborative effort between SKB in Sweden and Posiva Oy in Finland. A closely similar concept is also being considered in Japan. Johanna Hansen (Posiva Oy) described the requirements and design of the buffer and backfill in the KBS-3 repository concept (Appendix B).

Posiva's planning for the ONKALO underground rock characterisation facility was also summarised. The ONKALO underground facility will be constructed at Olkiluoto, as a pre-cursor to a repository for Finland's spent nuclear fuel (Figure 3.3).

Figure 3.3. Layout of the Finnish ONKALO Underground Rock Characterisation Facility

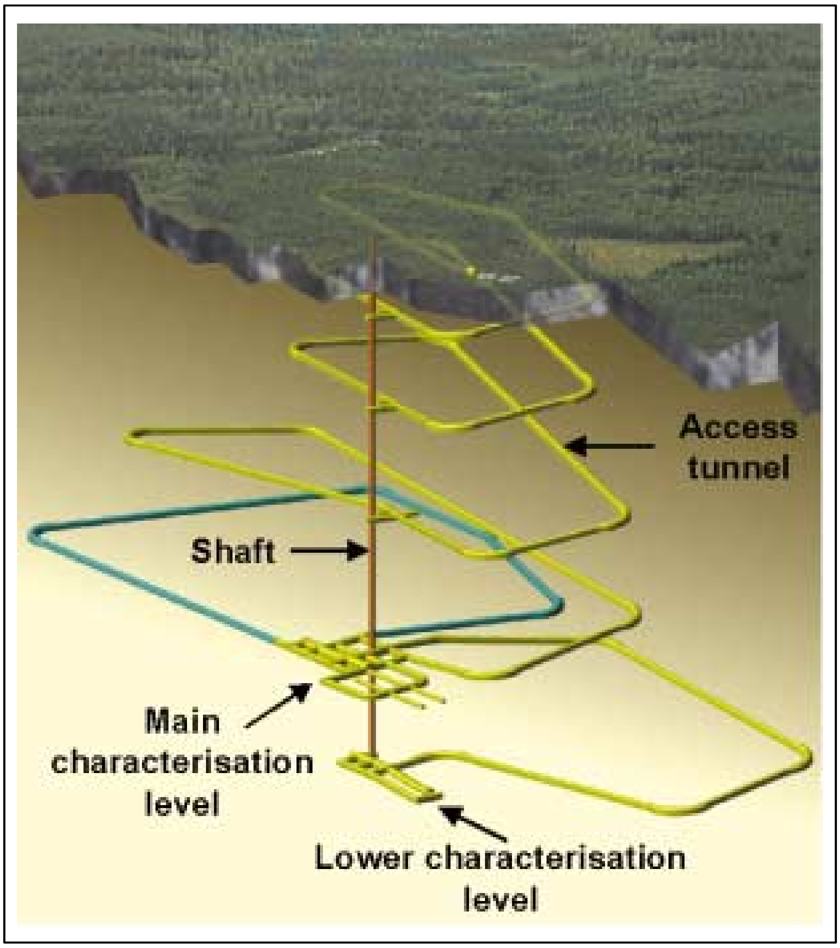
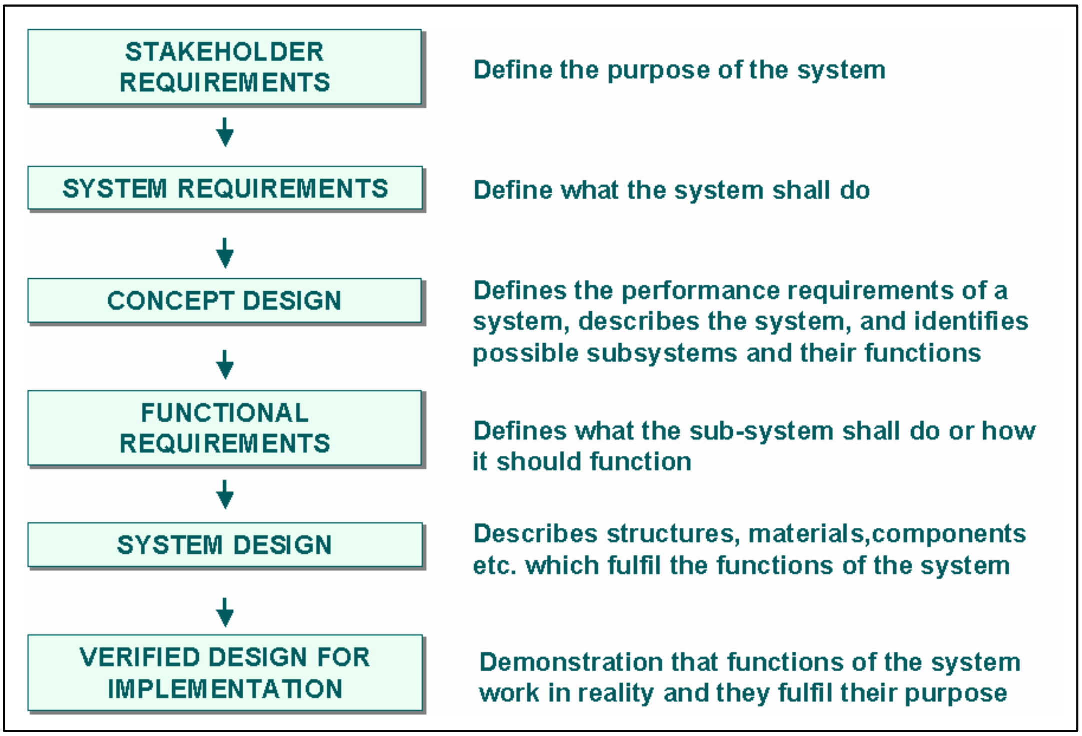


Figure 3.4 illustrates the design process being followed and the role of requirements in that process.

Figure 3.4. Role of Requirements in the Finnish Repository Design Process



Given current thinking on the requirements of the disposal system and the conceptual repository design, functional requirements have been identified for each component of the EBS, including the buffer and the backfill.

Seven different combinations of backfill material and backfill emplacement method have been evaluated in attempts to achieve a sufficiently high material density (and therefore swelling pressure and hydraulic performance) to withstand the effects of saline groundwaters. Partly because of the practicalities of backfill emplacement (see Section 3.2.6) and partly to reduce the amount of backfill that would be needed, consideration is now being given to a variant conceptual design known as KBS-3H, in which the waste canisters would be emplaced horizontally.

Difficulties in the requirements management process were identified. These included poorly specified requirements; ambiguous, unclear and contradictory requirements; and a lack of traceability in the ownership and basis for requirements.

Discussion around the presentation focused on the following points:

- **Sequencing of design decisions**. It was noted that early “high-level” decisions on the design of a facility inevitably influence subsequent more detailed design decisions. For example, for the ONKALO facility an early decision was the selection of an access ramp in preference to an access shaft (Figure 3.3). Once the ramp approach had been decided upon it was then possible to consider the precise location of the facility according to the geological characteristics of the site.

- **The use of Performance Assessment in repository design**. There was discussion as to how much the repository design process can or should rely on results from PA models. It was noted that the answer depended on the maturity of the disposal programme, the PA models, and the design in question. Ideally, over time, the iterative process of PA and repository design work should lead to a situation where the design has matured and become stable (relatively unchanging with each new iteration) and is consistent with the PA models. The same iterative process should lead to mature PA models that provide a reasonable (not overly simplified) representation of the disposal system.
- **Safety culture**. It was noted that all personnel involved in the design process needed to consider the relevance of their work to disposal system safety, and that the safety culture needed to be organisation wide.

3.2.3 Requirements and Design of French Waste Packages

Stefan Mayer (Andra) described the procedure being followed by Andra to identify requirements and constraints on disposal system design, considerations pertaining specifically to French waste disposal packages (WDPs), and the status of current waste package design concepts.

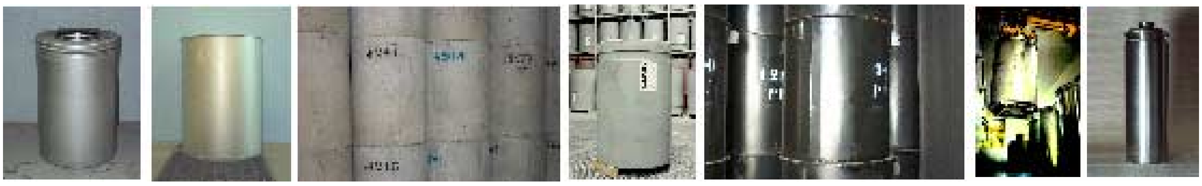
Andra is following an iterative approach to identifying design requirements and constraints for the repository system. High-level requirements derive from consideration of pre-closure and post-closure safety, as well as the need to make provisions for reversibility (see NEA, 2001). Andra's approach begins with an initial analysis and interpretation of stakeholder needs and requirements, and is continuing to evolve as understanding of site-specific characteristics improves, and as increasingly detailed design concepts and experimental and modelling results are obtained.

Andra's iterative approach is supported by functional analysis, process analysis and safety analysis. Functional analysis helps to manage requirements and constraints by ensuring that the overall approach followed is both systematic and comprehensive.

Requirements and constraints applicable to the WDPs are derived from functional analysis, from consideration of the interfaces between WDPs and other repository components, and from scientific understanding of WDP behaviour in the repository environment.

In practice, the primary constraints on the WDP design derive from the waste inventory and the variety of primary waste packages (Figure 3.5).

Figure 3.5. Primary Waste Packages for French Intermediate-level Radioactive Waste



Discussion around the presentation focused on the following points:

- **Effects of uncertainty on design**. It was suggested that design decisions that help to ensure that the conditions under which EBS components have to operate correspond to those where process interactions are relatively well understood could help to circumvent problems relating to limitations in scientific understanding. An example might be a design decision to separate the locations for ILW and HLW disposal and, thereby, circumvent the need to fully understand the potentially complex interactions that might occur in a co-disposal system as an alkaline plume migrating from a cementitious ILW vault began to interact with waste in a HLW vault. It was noted that, in addition to limitations in scientific understanding, a range of other uncertain factors affects programmatic decisions, including cost, time and the capabilities of existing models.
- **Fitness-for-purpose**. It was noted that there is a continual need to evaluate whether the level of understanding and extant modelling capabilities are fit for their intended purpose. Models used to support a decision-in-principle on the potential feasibility of a particular concept, for example, may not need to be as fully developed as models used to support a licensing decision or final safety case.

3.2.4 Seal Requirements and Design for Repository in Salt Host Rock

Nina Müller-Hoeppe (DBE) described the evolution of the designs drift seals (tunnel seals) in the German radioactive waste disposal programme (Appendix B), relying on the former German decision to focus on developing a repository in rock salt. Evidence from old German salt mines indicated that drift seals could be constructed successfully and would provide adequate tunnel sealing performance for at least 25 years. To this end, site investigations were conducted at Gorleben, over an extended period up to 2000, when a political decision was taken to look for alternative sites.

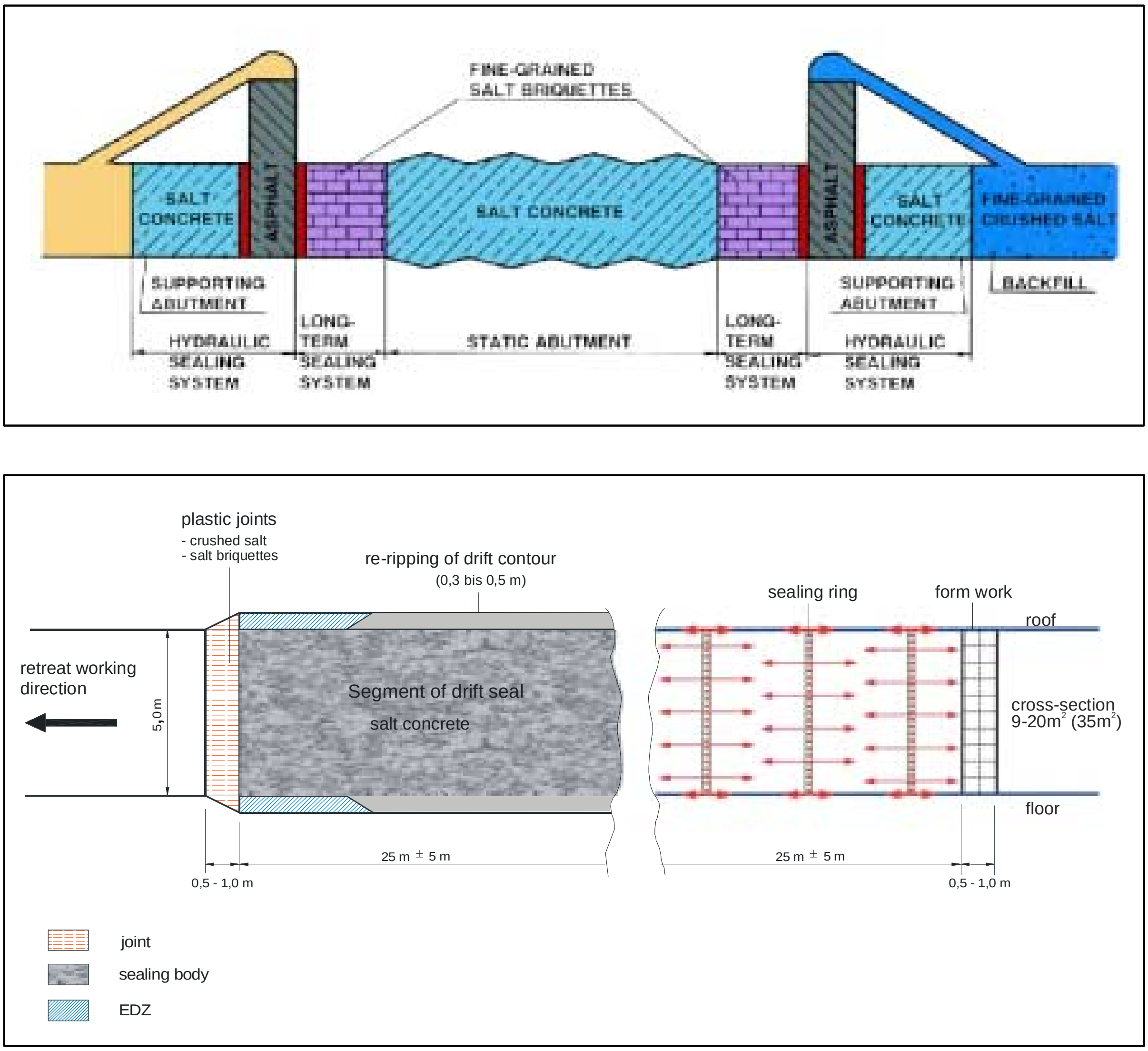
Changes to sealing requirements were made to increase the period over which the seals had to provide adequate performance from 25 years to 500 or 1 000 years, depending on the circumstance. Further changes to the sealing requirements generally derived from a decision to dispose of spent fuel as well as vitrified high-level waste (HLW) produced from reprocessing of spent nuclear fuel.

Elements of prototype seals were constructed and investigated in the Asse underground rock laboratory (URL). The Asse tests were, however, considered to have provided an insufficient demonstration of seal performance because the results obtained were too complex and only addressed the short-term. As such, it was considered that these URL results could not easily be extrapolated to a repository situation.

After the end of the investigations at Gorleben, work on the EBS was focused to the Morsleben repository. A conceptual design for a tunnel seal made of bentonite was developed. This was subsequently rejected because of a lack of physical understanding and reliable a mathematical description of bentonite behaviour in a salt environment and other uncertainties. An alternative means of tunnel sealing was then developed based on the use of salt-concrete. Figure 3.6 shows the evolution of a prototype design of a salt-concrete tunnel seal. The requirements for the salt-concrete seal were specified as a maximum permeability of 10^{-18} m^2 and a minimum lifetime of between 5 000 and 30 000 years.

Work is continuing to develop a sufficient demonstration of repository safety. Safety analysis is being used as the principal means of linking design and engineering work with high-level stakeholder requirements on the repository and site-specific constraints.

Figure 3.6. Evolution of German Prototype Design for a Tunnel Seal Composed Primarily of Salt-concrete for use in a Salt Host Rock
(above: Site Independent design; below: Morsleben Site Specific Design)



Discussion around the presentation focused on the following points:

- **Quality assurance and standards**. It was noted that repository licensing necessarily relies upon a quality assurance (QA) system and QA procedures. It was further noted that EBS components are often required to function, and be shown to function, for periods of the order of hundreds to thousands of years but that existing standards governing construction work do not account for the extended timescales of concern to radioactive waste disposal programmes.

3.2.5 Concepts for the Disposal of Belgian Vitrified High-Level Radioactive Waste

Johan Bel (ONDRAF/NIRAS) described the application of a multi-criteria decision analysis approach for comparing and helping to select between alternative technical concepts for the disposal of Belgian vitrified HLW (Appendix B).

The Belgian programme considers that it is essential to record the reasons for each design choice. To this end the programme has made a thorough analysis of the top-level design requirements and constraints on the disposal system. For example, locating the repository in plastic clay, such as the Boom Clay, means that use of a concrete liner is effectively the only option for holding tunnels open during the repository operational phase. Other constraints on the design include the need to avoid the creation of unusual rock stresses by minimising the number of tunnel crossing points.

The programme is currently assessing three alternative design options for the EBS, known as the super-container design, the borehole design, and the sleeve design. A method was needed to help select between these alternatives that would not require the conduct of a full PA for each option. A multi-criteria decision analysis method was adopted because it allows a traceable evaluation of options against a set of agreed criteria. Using such structured methods, it is also possible to include stakeholders with a wide range of skills and experience in identifying and comparing options.

The set of criteria should be comprehensive and, to the extent possible, each criterion should be discriminatory, unambiguous and independent. In the analysis, each option is scored against the criteria and the sum of the scores then indicates the preferred option. The analysis may be enhanced by attaching weightings to the scores that account for stakeholders' values on the relative importance of the criteria.

Discussion around the presentation focused on the following points:

- **Identifying options**. The issue of how to go about identifying alternative options for assessment was discussed. Questions were asked as to how the list of options was shown to be sufficiently comprehensive and inclusive.
- **Overall views on multi-criteria approaches.** The workshop participants expressed both positive and negative views on multi-criteria decision analysis approaches. These differences in view may reflect cultural variations in approaches to decision-making within different countries and reactions to the potential for some loss of control over the process by the traditional, official decision-makers.

3.2.6 Implications of the Prototype Repository Project for Repository Design

Christer Svemar (SKB) described results from the European Commission-sponsored Prototype Repository Project (PRP) and highlighted implications for refining repository design (Appendix B). The objectives of the PRP were to:

- Demonstrate the function of deep repository components under realistic conditions and to compare results with models and assumptions.
- Develop, test, and demonstrate engineering standards and quality assurance methods.

The PRP was based on a repository concept similar to the KBS-3 concept for spent fuel disposal, and involved full scale experiments in the Äspö URL in Sweden that included boring of a deposition hole, installation of a bentonite buffer, deposition of a waste canister, and backfilling of tunnels. Electrical heaters were used within the waste canister to simulate the heating effect of spent fuel.

The project highlighted practical difficulties associated with repository operations and it was noted that these may act as constraints on disposal system design. It was also noted that often the effects of these constraints are not represented in PA models and, thus, the design process must be supported by information from engineering and other studies, as well as PA.

Examples of the practical difficulties encountered include:

1. Accurate boring of the deposition hole avoiding surface roughness, variations in diameter and curvature.
2. Having sufficiently powerful pumps to extract water flowing into the 8.5 m deep deposition holes.
3. Preventing water inflow from affecting the bentonite prior to canister deposition.
4. Handling and placement of many layers of heavy (~2 tonne) bentonite blocks to millimetre accuracy.
5. Accurate positioning of the canister.
6. Achieving sufficient compaction of the backfill.

The PRP has shown that despite the difficulties, accurate deposition hole boring is possible, that the use of larger bentonite blocks would simplify the buffer emplacement process, that engineering solutions exist for limiting the inflow of water to the deposition hole (the use of plastic liners – Figure 3.7), and that sufficient compaction of the backfill can be achieved for mixtures containing up to 30% bentonite but that the transport of the backfill mixture to its site of emplacement is an inefficient process.

Figure 3.7. A Spent Fuel Deposition Hole Lined with Plastic to Control Water Inflow
(The disc-shaped object at the base of the hole would form the bottom of the bentonite buffer)

Discussion around the presentation focused on the following points:

- **Buffer**. It was noted that swelling of the bentonite buffer will be spatially and temporally heterogeneous both between and within deposition holes as a result of the complex patterns and rates of water inflow to the deposition holes.
- **Backfill**. The implication of PRP results for the timing of repository operations was discussed. It was noted that for the KBS-3V (vertical emplacement) concept, the backfill needs to be placed in the tunnel above the deposition hole within four months of canister emplacement, in order to prevent canister movement as a result of bentonite swelling.

Plenary Discussion

The workshop session ended with a general discussion at which the following points were made:

- It was noted that although, in detail, different approaches are being followed in the various national programmes, depending largely on their state of advancement, all of the programmes have similar high-level requirements and face similar challenges. It was suggested that these high-level requirements were relatively more important than the design constraints identified during implementation.
- The need to strive for ever-better dialogue between the various groups involved in the disposal programmes (e.g. safety assessors, engineers and other stakeholders) was highlighted, and it was noted that this might help to allow better understanding of cultural differences.
- The need for integration of teams within disposal organisations was noted, as was the need for management "buy-in" and support for the proposed concept and design.
- It was noted that the need for iteration within the process leading to solutions for radioactive waste disposal was probably greater than for other construction projects.
- It was noted that it is important not to establish requirements without a well-considered and clear justification.

4. WORKING GROUP FINDINGS

The remit of each working group was defined by the Workshop Programme Committee prior to the workshop itself. In addition, a series of key questions was posed for each group to consider. The following sub-sections present the results from the four working groups and summarise key points of discussion that arose when the results were presented to the subsequent plenary session. The membership of the working groups is detailed in Appendix C.

4.1 Working Group A: Practical Approaches to Ensuring Traceability in Design Requirements Management

The primary focus of Working Group A was to consider how to address the problem of making the repository design basis traceable for the purposes of demonstrating to stakeholders that requirements have been addressed and that the disposal system has been optimised in the sense that a clear decision-making process has been followed. It was intended that the group's work would focus on practical methods and systems (e.g., software) that can be used for requirements management and that it would go beyond simple theoretical aims or statements (e.g. regarding quality assurance).

The following general observations were made:

- The group considered that a Requirements Management System (RMS) is an important part of the knowledge management system for the disposal programme.
- The group considered that a Requirements Management System is an important tool that will increase the quality and efficiency of the disposal system design process, and improve its traceability.
- The group noted that it had had only limited time to address the questions and would need further time if it were to consider the details of requirements management, but that several relevant ideas had been identified that should be discussed at the last workshop in the EBS project workshop series.

The following paragraphs summarise the working group's views on the key questions:

A1) In terms of traceability, what kind of needs should a requirements management system for a radioactive waste disposal programme fulfil?

Aims: The group noted that essential aims of a successful Requirements Management System include:

- Keeping an historical record of decisions and arguments.
- Providing a structure for the various levels of requirements and constraints.
- Ensuring comprehensiveness.

Traceability: The group considered that the establishment and use of a Requirements Management System should help to:

- Improve the demonstration of disposal system understanding.
- Organise design, research and assessment work.
- Communicate with various audiences (i.e. groups within and external to the implementing organisation) and, thus, provide increased transparency and openness.
- Record the rationale for design decisions.
- Promote credibility and build confidence.
- Prioritise requirements and constraints.
- Optimise the disposal system.

A2) What kind of properties should such a requirements management system for a radioactive waste disposal programme possess to fulfil these needs?

Structure: The group considered that a Requirements Management System should be structured in such a way that:

- Each user can immediately find the record of requirements and related decisions.
- The relationships between disposal system components can be easily identified.
- It contains, and makes readily available, a comprehensive list of requirements, assumptions, and design choices.

Capacity: The group considered that a Requirements Management System should have the capacity to:

- Record whether each requirement is fulfilled, indicating when the requirement was addressed, how it was addressed and by whom, and how its fulfilment was evaluated. If a decision is made not to fulfil a particular requirement or constraint, then the Requirements Management System should have the capacity to record the reasons for that decision.
- Ensure access to information over the long periods of interest in developing and operating a radioactive waste disposal facility.

A3) How can a requirements management system for a radioactive waste disposal programme be designed and used to trace the evolution of design requirements, regulations and decisions over long time spans?

Capability: The group considered that a Requirements Management System should have the capability to:

- Handle requirement attributes (e.g. identification code, class or type, references, QA status, rationale, authors, origin).
- Inform staff of any change in requirements (new requirements or changes to existing requirements).
- Ensure controlled access to information (e.g. various levels of access).

- Import information from various sources and media.
- Depict disposal system.

Compatibility: The group considered that a Requirements Management System should be compatible with the waste management organisation's:

- Communication strategy.
- QA and knowledge management (KM) systems (e.g. systems for change control).

Design: The group considered that a Requirements Management System should be flexible and could be designed:

- As a database structured about attributes such as the requirement type or class, origin and level of applicability (e.g. system, sub-system, individual component).
- By an integrated group of "experts" from various disciplines, led by a Requirements Management System manager.
- On the basis of clear rules and terminology, and a logical scheme for the categorisation of the requirements.
- Ensuring provision for the transfer or migration of any computer system and software to new computing facilities and platforms.
- So that it contains the current design-related justifications as well as the previous versions.

Use: The group considered that a Requirements Management System should be used:

- By trained staff.
- To generate reports.
- As a living tool throughout the developing disposal programme.

A4) Which approaches and/or tools (e.g. Research Data Management [RDM] systems, relational databases) offer the best potential to fulfil the needs of a requirements management system for a radioactive waste disposal programme?

Tools: The group recommended an approach to developing a Requirements Management System that first defines the intended purposes of the system before selecting tool(s) (e.g. software). Software systems should be regarded as providing support to project management rather than replacing the role of management in ensuring project integration and communication.

The group noted several examples of software and other tools that have potential for use in a Requirements Management System, including Internet tools, relational databases, matrices, and flow charts. The group noted the advantages of tools that can be accessed by various groups in different places (e.g. contractors, researchers, designers, managers).

The group was unable to recommend a single "best" tool because the choice of tool will depend on the context and objectives of each project.

Discussion of the group's findings at the subsequent plenary session focused on the following points:

- **Treatment of alternative designs.** It was noted that a Requirements Management System might become quite complex if it had to contain data relating to more than one current design. It was also noted that the alternative designs would probably share the same high-level requirements but that their requirements would diverge at lower, more detailed levels.
- **Resolution of conflicting requirements.** A further possible advantage of a Requirements Management System was noted; that it should help to provide the user with a holistic view of the design requirements and constraints, and that this might help in prioritising the requirements and thereby resolving apparent conflicts (see also Section 4.4, Question D3).
- **Specific examples of Requirements Management System software tools within waste management programmes.** Referring to both the keynote paper (Section 3.1) and the findings from Working Group A, a questioner asked if there was experience of applying Requirements Management System software tools within radioactive waste management programmes outside Sweden. It was noted that radioactive waste management programmes in the UK and the US have developed a number of software systems aimed at ensuring traceability of performance assessments, for facilitating disposal programme management and communications, and for managing programmes of regulatory review and stakeholder comment and response. Software tools developed as part of the US WIPP programme include PASS, a PA Support System, which was developed using the Toolbook authoring software (Crawford *et al.*, 1998), TARDIS, an Internet browser-based tool providing multi-user access to a wide range of disposal system information, which was developed using ASP software, and the RDM Initiative in which the ER-Studio software system was used to develop a master Entity-Relationship diagram for a data model of the WIPP project. Parts of this data model were established in a relational database using Microsoft Access software. Tools developed in the UK include the Environment Agency's Issues Database, which is based on the Folio documentation management software (e.g. Yearsley *et al.*, 2001).

4.2 Working Group B: Practical Approaches to Defining Design Requirements and Accounting for Uncertainty and Constraints

The primary focus of Working Group B was to consider the problem of how to establish a disposal system design, or the design of a particular component of the disposal system (for example, part of the EBS), based on the relevant requirements and constraints.

The definition of requirements and constraints is a very important task at the early stage of the disposal system design. This work is often multi-disciplinary, and is based on the selected safety strategy and on certain selected scenarios. The uncertainty associated with these scenarios also has to be accounted for.

Although not the group's primary focus, it was envisaged that the group would begin by considering the relevant terminology used within the international radioactive waste disposal community, as it was considered that it would be beneficial for the international radioactive waste disposal community to develop a common understanding of terms such as "design requirements", "design constraints", "design basis assumptions" and "functional requirements". However, based partly on the discussions of the preceding day (see "Terminology" in Section 3.1), the group decided that it would not seek to establish a set of firm definitions for these terms.

The following paragraphs summarise the working group's views on the key questions:

B1) How do we go about establishing detailed functional designs from this range of differing needs and uncertain requirements and constraints?

Design development: The group outlined a series of steps in the development of a design:

1. Define clearly who is responsible for the design requirements (e.g. the "implementing organisation").
2. Ensure that there is adequate representation of stakeholder requirements.
3. The implementing organisation should interpret the stakeholder needs and translate them into high-level requirements.
4. Establish a hierarchy of requirements following a formal process.
5. Distinguish between fundamental and derived requirements.
6. Establish the importance or priority of the requirements, for example, by assessing their impacts.
7. Ensure that the set of requirements is complete, and that, for example, the low-level detailed requirements fully satisfy the high-level requirements.
8. Document clearly the basis for the design requirements (e.g. stakeholder need, experimental data).
9. Design and design assessment through a multi-step iterative cycle.

B2) Whose responsibility is it to specify design requirements, whose responsibility is it to accept design requirements, and what are the related arguments that justify those requirements? When defining design requirements, how should possible contradictory stakeholder needs and design constraints be treated? What kind of difficulties may arise?

Responsibilities: The group considered that:

- The implementing organisation has to accept the design requirements.
- The design of the repository and the specification of detailed design requirements (e.g. of EBS components) are the responsibility of the implementing organisation.

Contradictions and difficulties: The group considered that:

- Contradictory requirements can be addressed by:
  - Following formal design processes.
  - Prioritising requirements (e.g. safety first).
  - Considering alternative designs that might resolve contradictions.
  - Undertaking sensitivity analysis to understand the impact or importance of each requirement.
  - Revisiting the basis for the requirements.
  - Consulting stakeholders about possible design changes.
- The types of difficulties that may be encountered include:
  - The identification of contradictory requirements late in the design process.
  - Translating qualitative requirements into quantitative requirements.
  - Coping with uncertainties in processes and scientific understanding.

B3) ***What are the arguments that justify the requirements? When defining design requirements how should the need to ensure that requirements are verifiable be taken into account?***

Justification: The group noted that any requirements placed on the waste management system should be justified.

- The group considered that requirements might sensibly be established for functions that are essential, but that firm requirements should not be created for functions that are just "nice to have".
- The origin of, and basis for, each requirement should be clear (e.g. stakeholder need, experimental data).
- Low-level requirements should be explicitly linked to higher-level requirement(s).
- Justification should be part of the formal process and documented.

Verifiable requirements: The group considered that when requirements are defined, consideration should be given to the means of verifying compliance.

- The group noted that the verification method will depend on the level of the requirement in the Requirements Management System hierarchy and that verification of low-level requirements supports a demonstration of compliance for the related high-level requirements.
- The group noted that the verification process may occur late in the disposal programme (e.g., during demonstration testing).

B4) ***How should uncertainties be accounted for when defining design requirements? For example, should "safety margins" or "tolerances" be established to account for uncertainties, and, if so, what approaches might be taken?***

Uncertainties: The group considered that:

- Uncertainties should be characterised where possible (e.g. the significance of quantifiable uncertainties might initially be bounded using minimum and maximum parameter values).
- The significance of the uncertainties can be further established using, for example, structured sensitivity analyses, safety assessment or PA models, and research models.
- The impact of the uncertainties should be communicated to the originator of the related requirement.
- If the impact of an uncertainty is potentially significant based on initial assessments, then it is sensible to conduct further work to reduce the uncertainty before designing the disposal system to accommodate the uncertainty.
- The link between the design and the uncertainty should be traced (e.g. the uncertainty could be stated in the justification of the requirements, and tracked through the design).
- Possible approaches to handling uncertainty include:
  - Avoid or reduce the uncertainty.
  - Robust and/or flexible design.
  - Consider alternative designs.

B5) Who initiates a change in a design requirement? How is the change managed, including possible effects on other requirements?

Change management: The group considered that:

- Change requests can come from many places, including stakeholders, safety assessments, operational safety considerations, designers, manufacturers, and researchers.
- Acceptance of change requests should be made through the implementing organisation's Change Control process.
- Best practice is to follow a formal Change Control process, which involves all of the affected groups and includes assessment of the effect of the change.

Discussion of the group's findings at the subsequent plenary session focused on the following point:

- **Prioritisation**. A question was asked as to how to prioritise between requirements and design decisions or changes that influence operational safety and those that affect post-closure safety. It was noted that this question had been addressed to Working Groups C and D (Section 4.3, Question C4, and Section 4.4, Question D2). The workshop participants had no specific answer to the question, beyond recognising that it is paramount that levels of operational and post-closure safety both have to be acceptable.

4.3 Working Group C: Practical Approaches to Developing/Evaluating/Selecting between Alternative Design Options and Refining Selected Designs

An important part of justifying any particular design (or justifying the selection of a particular disposal site) is a demonstration that potentially suitable alternatives have been considered and that the selected option represents, in some sense, "the optimal choice" or "best solution", taking into account a range of relevant factors. A range of widely differing factors may need to be considered when selecting between alternative design options, or when refining selected designs, such as operational and post-closure safety, cost, practicability, feasibility, stakeholder and societal opinions, and programmatic risk. Uncertainties will exist in all of the factors that need to be considered.

The primary focus of Working Group C, therefore, was to consider the problems of how alternatives are evaluated, how designs are refined, and how it is demonstrated that designs are sufficiently well developed for acceptance and implementation.

The following paragraphs summarise the working group's views on the key questions:

C1) What methods and criteria are currently used to evaluate alternative disposal system designs or alternative EBS design?

Methods: The group noted that multi-criteria methods are typically used to evaluate alternative design options against selected criteria. Multi-criteria methods allow the evaluation of qualitative and quantitative criteria. The following steps outline a typical multi-criteria method. All steps should be properly documented.

1. Select the core evaluation team covering all relevant areas of expertise.
   - PA staff, scientists, and engineers.
2. Develop design options.
   - The design options must comply with requirements.

3. Develop evaluation criteria and importance weighting of each criterion.
   - Typical criteria relate to high-level requirements.

4. Evaluate the options against the criteria.
   - Uncertainties and assumptions should be identified and evaluated.

5. Make and document decisions regarding the selection of an option.
   - Suggestions for further work should be included.

The group noted that potential limitations of multi-attribute methods for evaluating alternative designs include difficulties relating to:

- Uneven amounts of data on different designs and materials.
- Limitations of models used to perform quantitative evaluations.
- Ensuring completeness when developing the list of options.

Criteria: The group identified the following criteria for evaluating design options:

- Long-term safety.
- Operational safety.
- Assurance of safety.
- Engineering acceptance.
- Ease of construction, operation, and maintenance.
- Compatibility with national waste management system requirements.
- Existence of analogues.
- Cost.
- Schedule.
- Flexibility.

More detailed criteria may also be considered according to programme-specific requirements. Examples of further potentially relevant criteria include waste retrievability and repository “footprint”. The group noted that when using multi-criteria methods, care should be taken not to mix “exclusion” criteria (i.e. those that result in on/off decisions) with other criteria.

The group recommended that criteria should be:

- Clearly defined.
- Independent.
- Measurable.

C2) Are there significant differences between methods for refining detailed designs (e.g., optimising the design of a component of the disposal system) and methods for more strategic comparison of options (e.g. waste management)?

Strategic comparisons: The group noted that strategic comparison of waste management options is a high-level exercise, often conducted by government rather than the implementing organisation. In some cases, the implementing organisation provides analyses and documentation supporting the feasibility of different options for legislative or executive decision. Strategic evaluations consider a mix of stakeholder/political, safety, and technical considerations. In general, as a programme evolves, evaluations tend to become based on more quantitative technical considerations.

Design refinement: The group considered that design refinement occurs throughout the development and licensing process, and involves the evaluation of specific features or design options, such as the selection of waste package materials. These evaluations are based on quantitative technical evaluations.

C3) To what extent are stakeholders involved in the evaluation of alternative options and designs?

Stakeholders: The group considered that stakeholders include the general public, regulators, independent review boards, waste producers, and local and national government bodies, as well as the implementing organisation. Stakeholder issues and opinions are considered in the selection of designs and in their evaluation. The level of involvement depends on the importance of the stakeholder issues in the context of the particular programme. The group noted that regulators generally do not participate directly in the design process.

C4) When selecting between the various alternatives, which criteria (e.g., operational and post-closure safety, cost, practicability, feasibility, stakeholder and societal opinions, and programmatic risk) do engineers consider and which influence their decisions most strongly? How do you ensure that all selection criteria are appropriately addressed?

Key criteria: The group considered that the focus of the question solely on engineers was inappropriate. The group noted that selecting between design alternatives requires an integrated evaluation effort among experts with multiple perspectives. For example, an appropriate evaluation team might include:

- PA staff.
- Scientists and engineers with expertise in different aspects of the system.
- QA/licensing experts.
- Cost estimators.

The group did not address the remaining parts of this question.

Discussion of the group's findings at the subsequent plenary session focused on the following points:

Level of stakeholder involvement. There was considerable discussion of the level of stakeholder involvement in decision-making processes. It was noted that the level of stakeholder involvement tends to depend on the strategic importance of the decision under consideration. Stakeholders tend to be more concerned with the strategic issues than with detailed decisions, for example on EBS design. Different views were expressed from different programmes as to what level of stakeholder involvement was appropriate. These differences may reflect cultural variations in approaches to decision making within different countries and reactions to the potential for some loss of control over the process by the traditional, official decision-makers.

4.4 Working Group D: Practical Approaches to Linking "High-Level" Requirements to Detailed Design Requirements/Specifications

The primary focus of Working Group D was to consider practical approaches for dealing with difficult examples from the requirements management process. There may be different levels of design requirements derived from a range of stakeholder needs, and these design requirements and associated design constraints may need to be managed in a structured fashion so that they are fulfilled in a technically feasible design. High-level regulatory requirements, such as the potential needs for retrievability and long-term repository monitoring, are often expressed in legislation or in other statutory documents. Other high-level requirements derive from the owners of the waste.

The group first confirmed its view of what was meant by a "high-level" requirement. The group concluded that high-level requirements are those that do not depend on the site, concept or design, and which address:

- Protection of humans and the environment, and how safety is assessed (e.g. through radiation protection principles, mining safety regulations).
- Requirements specified in regulation or legislation, for example:
  - Safeguards.
  - Retrievability.
  - Monitoring.

The following paragraphs summarise the working group's views on the key questions:

D1) A significant number of high-level design requirements and a wide range of design constraints are likely to exist for any particular disposal system – how do we go about demonstrating links from these high-level requirements and constraints to detailed designs in a stepwise repository approach?

Demonstrating links: The group considered that:

- As the first step, a Safety Strategy (or safety concept) has to be developed and communicated. The Safety Strategy enables the translation of high-level requirements into system requirements, from which more detailed design requirements can be established.
- The Safety Strategy would need to satisfy all of the high-level requirements to an appropriate degree; otherwise the proposed waste management solution would not be acceptable. The group noted that the selected option also has to be technically feasible.
- Safety and performance assessment expertise is key in linking from high-level requirements and constraints to detailed designs for the EBS. The group noted the need for integration in the work of the scientists, PA specialists and engineers contributing to the design.

Stepwise process: The group noted that:

- It is common practice for the implementing organisation to make periodic statements regarding the level of understanding and the status of the design, and to identify outstanding issues and the proposed means of resolving them. This statement could be based on a multidisciplinary review of the programme. The group also noted the importance of providing a description of the process envisaged for moving from a provisional design to a firm and detailed design.
- A formal process should be used to evaluate the design against the requirements. It may be necessary to develop tools, in addition to overall system PA tools, with which to undertake this evaluation, in particular to test barrier performance and help to choose between EBS design options.
- Design choices need to be clearly linked to the requirements and the basis for design changes needs to be clearly explained.

D2) What approaches are taken to prioritising between high-level requirements at different stages of the overall repository programme?

Prioritisation principle: The group considered that the safety and environmental protection requirements are always of highest priority. The group also noted that in order to allow prioritisation in later stages of repository development, flexibility should be maintained, for example by retaining design alternatives.

Dialogue: Notwithstanding the primacy of safety considerations, the group noted that it is necessary to enter into dialogue with stakeholders in order to achieve a common understanding of the requirements and, thereby, to facilitate informed prioritisation. The group also noted that because requirements may evolve in response to events and as increasing knowledge is gained, dialogue needs to be an ongoing process and it is necessary, therefore, to keep the prioritisation under review.

D3) How do we resolve high-level requirements that at first sight act as conflicting drivers on disposal system and EBS design?

Conflicting drivers: The group noted that requirements on safeguards, retrievability and monitoring might appear to conflict with requirements for safe disposal. The group suggested that conflicting requirements have to be balanced in such a way that an acceptable overall safety case can be established. Methods for achieving this might include:

- Evaluating design alternatives.
- Weighting or prioritising requirements (see Question D2).
- Maintaining dialogue with stakeholders, explaining the safety strategy and being open about conflicting requirements.

Discussion of the group's findings at the subsequent plenary session focused on the following point:

Impossible requirements. It was noted that it is necessary to resist the establishment of requirements that would be impossible to meet. An example discussed was a hypothetical requirement derived from a strong interpretation of the precautionary principle, which would preclude waste disposal (e.g. see ILGRA, 2002).

5. WORKSHOP CONCLUSIONS

5.1 Achievement of Objectives

The workshop papers and discussions summarised in Sections 3 and 4 demonstrate clearly that the workshop was a success. Table 5.1 presents a brief analysis of how the workshop's specific objectives were met.

Table 5.1 Achievement of Workshop Objectives

Workshop Objective	Workshop Result
To state the design requirements for disposal systems and identify their basis, including the evolution of these requirements.	High-level requirements were identified and discussed and, although the workshop did not compile a comprehensive catalogue of detailed requirements, key examples were considered, as was the process of requirements' evolution.
To promote common understanding of design requirements, and of methods for linking stakeholders' needs and regulatory requirements to practical design concepts and detailed design decisions.	Methods for linking stakeholder needs and regulatory requirements to practical design concepts and detailed design decisions were discussed in detail and at length.
To promote methods for achieving and maintaining transparency and traceability in establishing and developing the design basis for the EBS, and to seek ideas on how to assess whether the requirements have been fulfilled.	Various methods and tools for promoting and maintaining transparency and traceability were identified and guiding principles for the development of such tools were documented.
To share ideas and experiences on working with challenging requirements and constraints, and in accounting for uncertainty.	This objective was achieved mainly via the papers summarised in Section 3.2.
To understand better the basis for differences in national EBS designs.	Throughout the workshop subtle differences between national programmes were identified, and the workshop discussions were important in identifying, if not in resolving, cultural differences and differences in the use of terminology.

5.2 Key Conclusions

The following principal conclusions can be drawn from the workshop:

- Requirements management systems and tools have the potential to assist in the design, construction and operation of radioactive waste disposal systems. Key advantages of requirements management systems are that they formalise the repository design process, ensure that the design takes adequate account of the various requirements and constraints on the disposal system, and help to achieve the goals of clear communication and traceable, justified decision making.

- Requirements management systems are complementary to safety and performance analysis techniques. Requirements management and performance assessment share some common inputs (e.g. site characterisation information, regulations), methods (e.g. iteration, change control), goals (e.g. transparency), and needs (quality assurance, traceability, successful integration of project teams, stakeholder dialogue – see below), but provide important and distinct outputs (e.g. detailed specifications that would allow the construction of an engineered barrier, estimates of potential dose). Thus, while the perspectives of Requirements Management System and PA are slightly different, one being principally from a design perspective – the other from a safety perspective, both could form logical parts of the overall safety case for the disposal facility.
- Active stakeholder dialogue is a key element contributing to the success of processes for selecting waste management options and developing design solutions. Ensuring clear communication between project teams and stakeholders is also of high importance.

5.3 Recommendations

The workshop noted the potential for requirements management systems to assist radioactive waste management programmes.

The workshop also noted the need to gain further experience in the application of requirements management techniques to the problem of radioactive waste management.

The workshop recommended, therefore, that the IGSC, through the EBS project consider establishing an activity that would (i) undertake the initial steps in the development of a prototype requirements management tool and (ii) develop a grid of high-level requirements common to all waste management programmes. The tools developed by this activity would feed into the last workshop of the EBS series on Confirmation and Demonstration.

It was recommended that, subsequent to the workshop, the EBS Steering Committee was best placed to define the details and scope of the activity.

6. REFERENCES

Crawford, M.B.; Wilmot, R.D.; Galson, D.A.; Swift, P.N. and Fewell, M.E. (1998) PASS: A Component of Desktop PA for the WIPP. In: Proc. Eighth Int. High Level Radioactive Waste Management Conf. (Las Vegas, 10-14 May 1998), American Nuclear Society, La Grange Park, IL and American Society of Civil Engineers, New York, NY, 1998.

ILGRA (2002): *Precautionary Principle: Policy and Application.* UK Government Inter-Departmental Liaison Group on Risk Assessment. London: The Stationary Office.

NEA (2001): Reversibility and Retrievability in Geologic Disposal of Radioactive Waste: Reflections at the International Level. Paris: OECD. ISBN: 92-64-18471-6.

NEA-EC (2003): Engineered Barrier Systems and the Safety of Deep Geological Repositories, State-of-the-art Report, EUR 19964 EN. Brussels: European Commission. Paris: OECD. ISBN 92-64-18498-8.

NEA (2003): Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case, Workshop Proceedings Oxford, United Kingdom 25-27 September 2002. Paris: OECD, ISBN 92-64-103544-6.

Yearsley, R.A.; Duerden, S.L.; Streatfield, I. and Bennett, D.G. (2001) Use of Formal Procedures in Developing Dialogue Between Operator and Regulator on Radioactive Waste Disposal. In: Proceedings of the VALues in Decisions On Risk (VALDOR) Symposium (Stockholm, 2001).

APPENDIX A

WORKSHOP AGENDA

Wednesday 27 August 2003 – PLENARY SESSION

Chairperson: Timo Äikäs, (Posiva Oy)
Rapporteur: David Bennett, (GSL)

Welcome Addresses
Sylvie Voinis, (NEA); Michel Raynal, (EC); and Timo Äikäs, (Posiva Oy)

Introduction to the EBS Project: Scope and Objectives of the Workshop
Hiroyuki Umeki, (NUMO)

Keynote Paper, "Systematic Management of Requirements: Theory and Practice"
Lena Moren, SKB

"Waste Package Requirements and Design at Yucca Mountain"
Robert MacKinnon, (US-DOE/SNL)

"Buffer and Backfill Requirements and Design for KBS-3"
Johanna Hansen, (Posiva Oy)

"Requirements and Design of French Waste Packages"
Stefan Mayer, Cécile Chapuis and Frédéric Plas, (Andra)

"Repository Seal Requirements and Design"
Nina Müller-Hoeppe, (DBE); Ralf Mauke and Jürgen Wollrath, (BfS)

"Comparing Technical Concepts for Disposal of Belgian Vitrified HLW"
Jean-Paul Boyazis and Johan Bel, (ONDRAF/NIRAS)

"The EC Prototype Repository Project: Implications of Assessments for Refining Repository Design"
Christer Svemar, (SKB)

Thursday 28 August 2003 – WORKING GROUP SESSIONS

Introduction of Working Groups Sessions
David Bennett, (GSL)

Parallel Working Groups Sessions

Friday 29 August 2003 – PLENARY SESSION

Chairperson: Alan Hooper, (UK Nirex Limited)
Rapporteur: David Bennett, (GSL)

Working Group Findings: Working Group A

Chairperson: Jean Paul Boyazis, (ONDRAF/NIRAS)
Rapporteur: Sylvie Voinis, (NEA)

Working Group Findings: Working Group B

Chairperson: Lawrence Jonhson, (Nagra)
Rapporteur: Paul P. Gierszewski, (OPG)

Working Group Findings: Working Group C

Chairperson: Stefan Mayer, (Andra)
Rapporteu: Robert Mac Kinnon, (SNL)

Working Group Findings: Working Group D

Chairperson: Hiroyuki Umeki, (NUMO)
Rapporteur: Nina. Müller-Hoeppe, (DBE)

Discussion of Recommendations for the EBS Project Forward Programme and agreement of logistical steps (e.g. for publication of workshop proceedings).

Close

APPENDIX B

PAPERS/OVERHEADS PRESENTED TO THE WORKSHOP

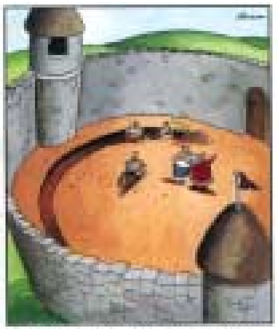
SYSTEMATIC MANAGEMENT OF REQUIREMENTS: THEORY AND PRACTICE

L. Moren
SKB, Sweden

1. Why?

- Problem understanding
- Common goal
- Common general picture

- Facilitate communication
- Avoid mistakes
- Change control
- Quality assurance



Suddenly, a heated exchange took place between the King and the moat contractor, and hence, requirements management was born.

2. Theory

What is a requirement?

- Definition (Dictionary): Something demanded or imposed as an obligation. A thing desired or needed.
- Definition (SKB): Expression describing desired function, capability, characteristic, property or quality.
- Requirements are a clear statement of objectives.
- Requirements state the initial problem and the need that is to be satisfied
- Requirements define the characteristics of the set of acceptable solutions
- Requirements also provide guidance in the selection of the most appropriate solution

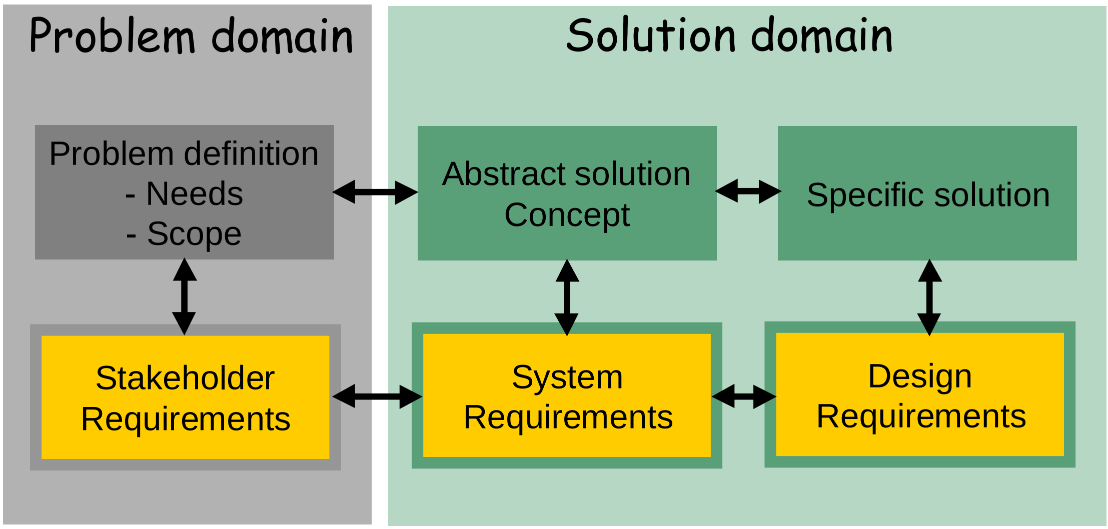
Requirement characteristics and attributes

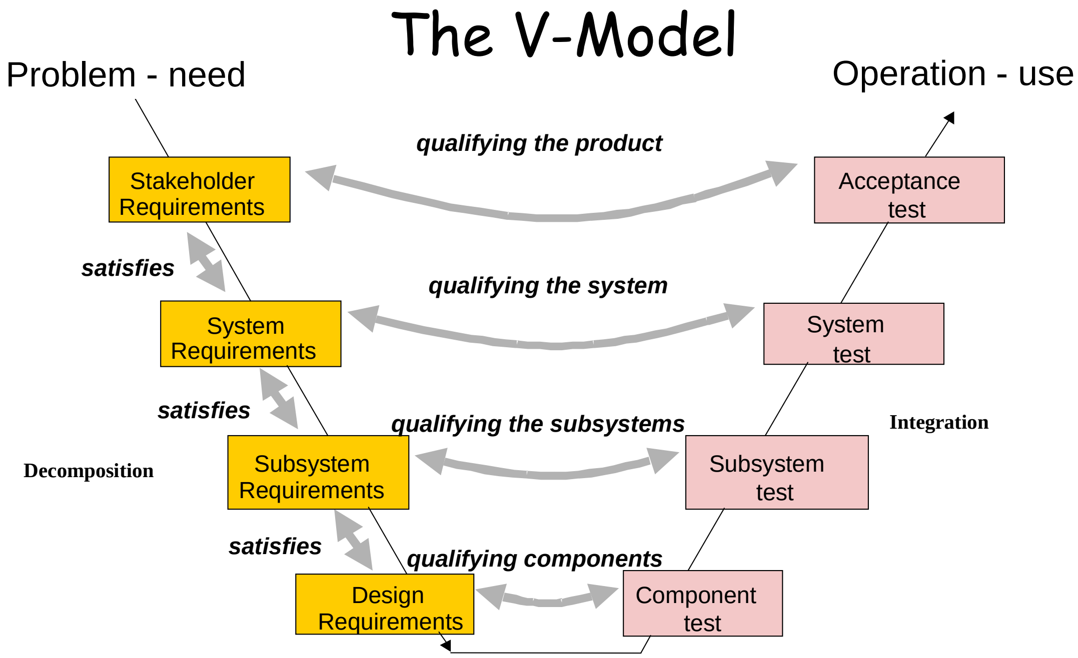
- Statement
- Identity
- Name – Source
- Class
- Type – Applicable phase – Priority
- Data
- References – Performance Measures
- Status
- Qualification

What are requirements used for?

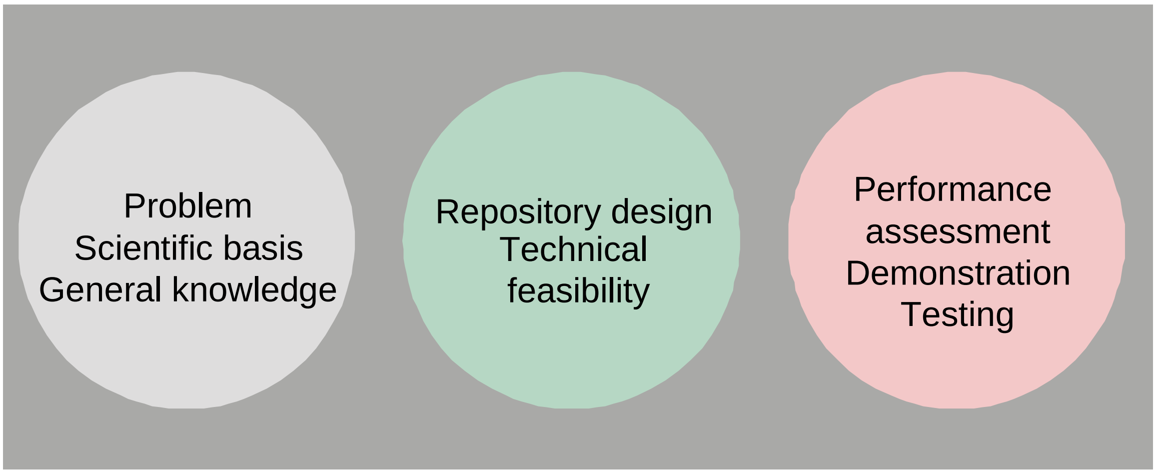
- Communication
- Definition of problem and scope
- Understanding the context
- Design
- Making the right things
- Optimisation
- Change control
- Risk management
- Quality assurance
- Testability – qualification – testing – controlling
- Traceability

Different kinds of requirements



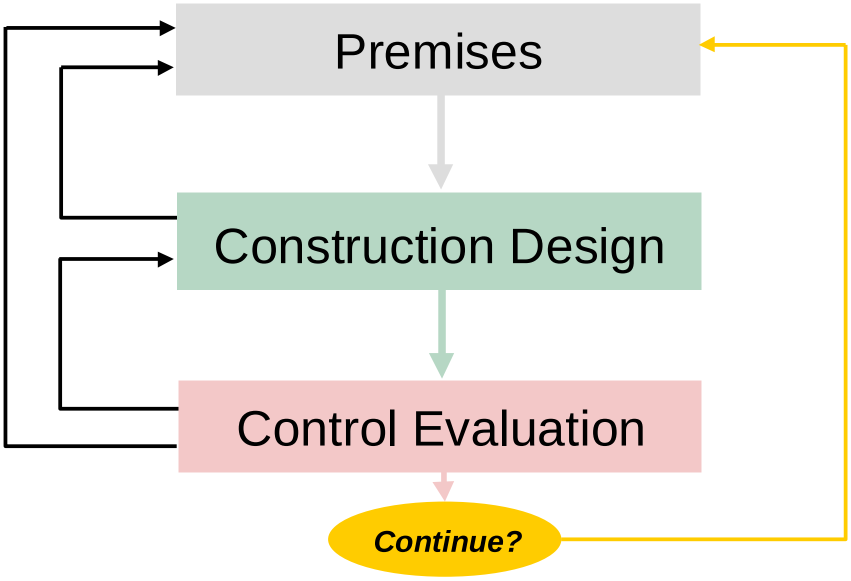


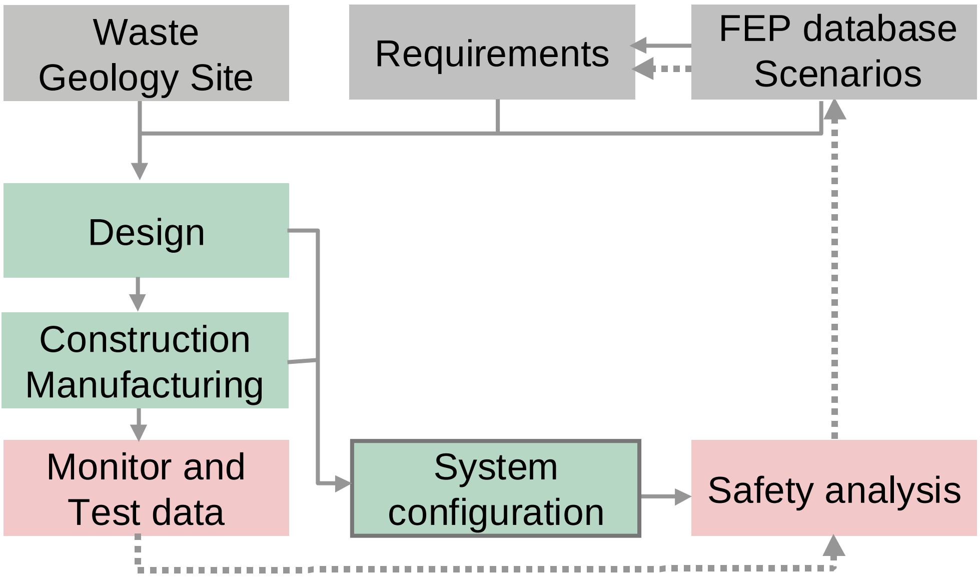
3. Practice

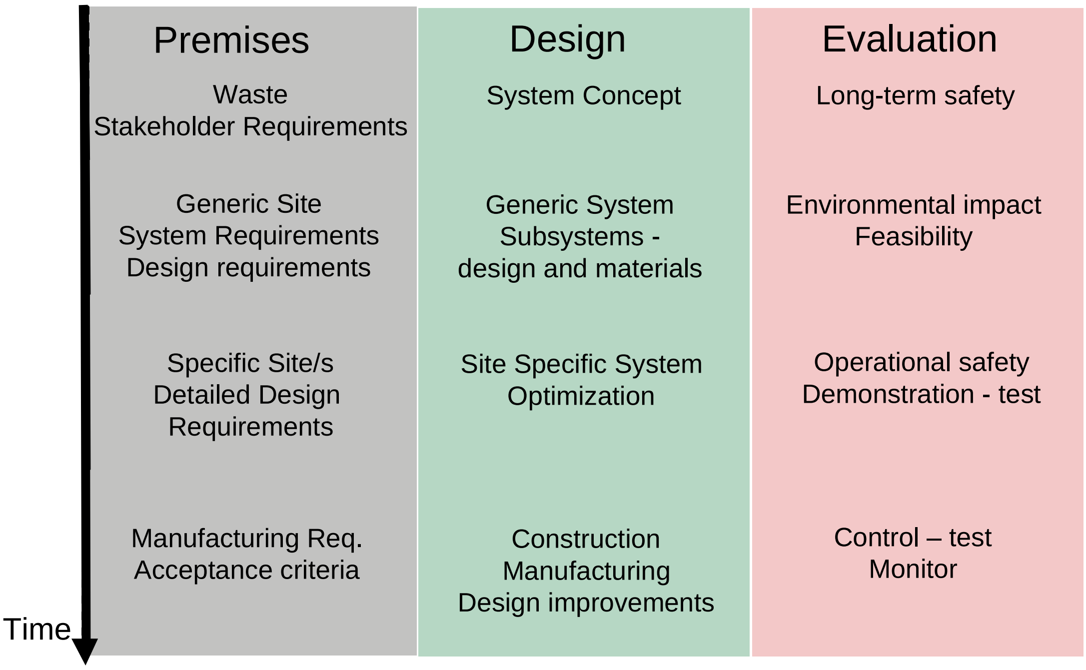


- Do we know enough?
- Can the repository be constructed?
- Is the repository safe?

4. Developments of requirements

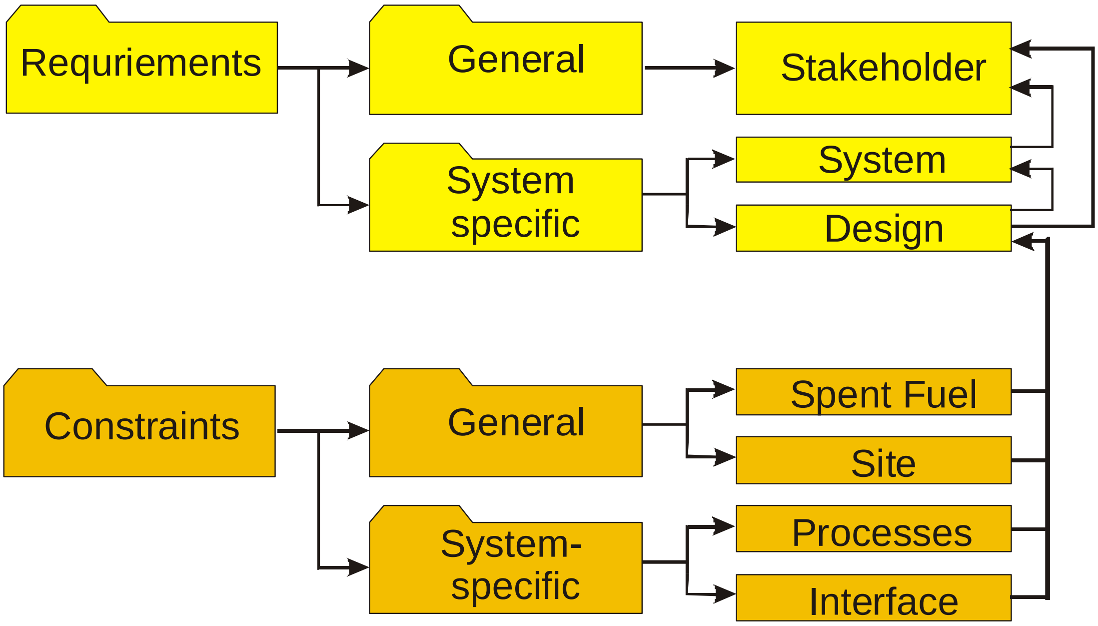






Premises	Design	Evaluation
Waste Stakeholder Requirements	System Concept	Long-term safety
Generic Site System Requirements Design requirements	Generic System Subsystems - design and materials	Environmental impact Feasibility
Specific Site/s Detailed Design Requirements	Site Specific System Optimization	Operational safety Demonstration - test
Manufacturing Req. Acceptance criteria	Construction Manufacturing Design improvements	Control – test Monitor

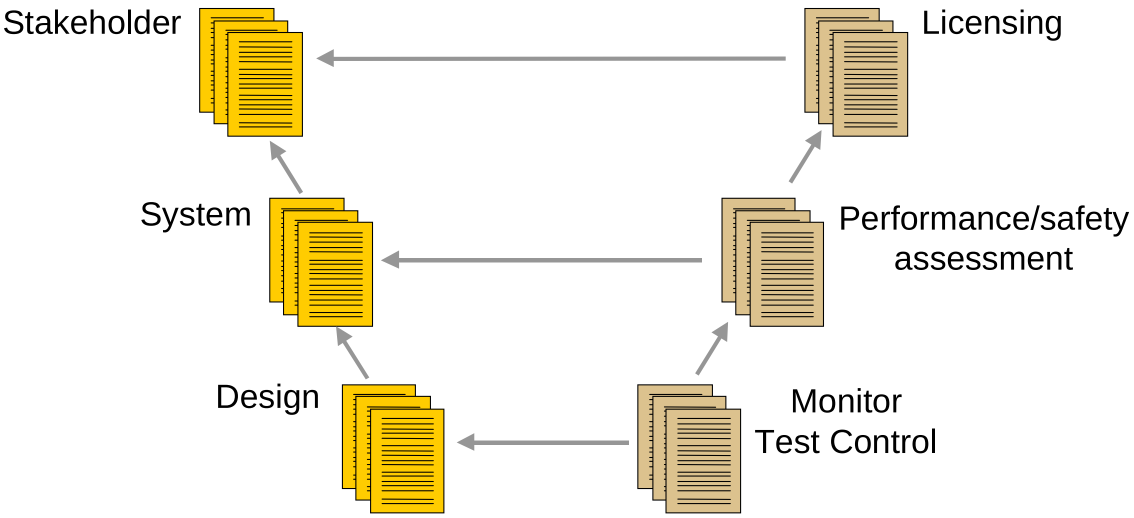
5. Organisation of requirements



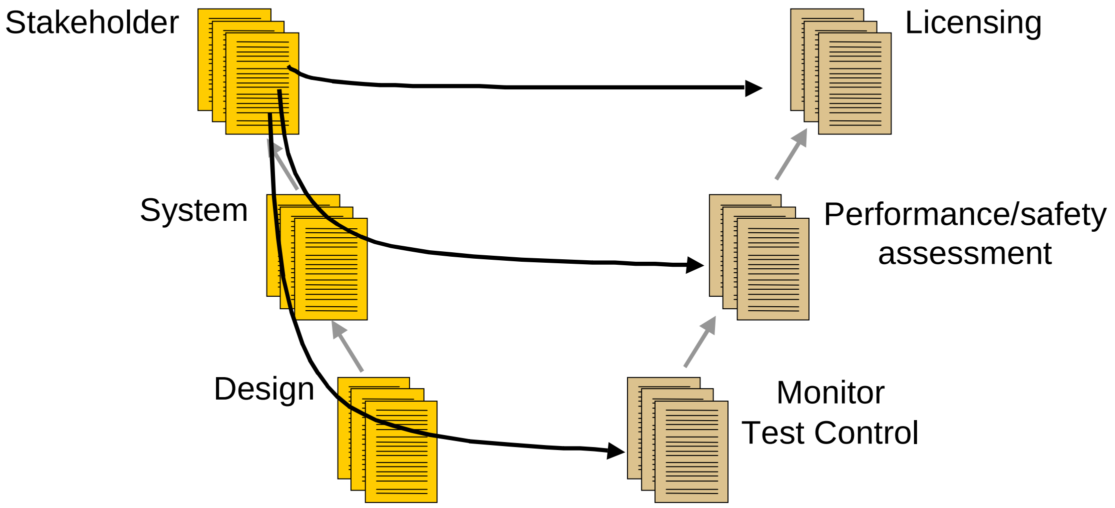
Examples:

- Stakeholder requirement: The safety shall rely on multiple barriers designed to that a failure of one barrier does not threaten overall system performance.
- System requirements KBS-3**:** The repository shall isolate the waste from man and environment. If the isolation is broken the repository shall retard the transport of radionuclides so that when the nuclides reach the biosphere they will cause no harm.
- Subsystem Requirements Canister: The canister shall enclose the spent fuel and prevent dispersion of radioactivity to the surroundings. The canister shall be watertight when deposited in the repository. The canister shall withstand corrosion processes occurring in the geological environment. The canister shall withstand occurring mechanical stresses.
- Design Requirements Canister: Mechanical stresses. The canister shall withstand mechanical stresses occurring when handled, stored, transported and deposited. The canister shall withstand the water pressure at repository depth and the swelling pressure from the buffer. The canister shall withstand stresses caused by uneven development of the swelling pressure in the buffer. The canister shall withstand stresses caused by uneven swelling pressure in a fully saturated buffer. The canister shall withstand the pressures occurring due to glaciations. The canister shall withstand mechanical stresses caused by earthquakes.

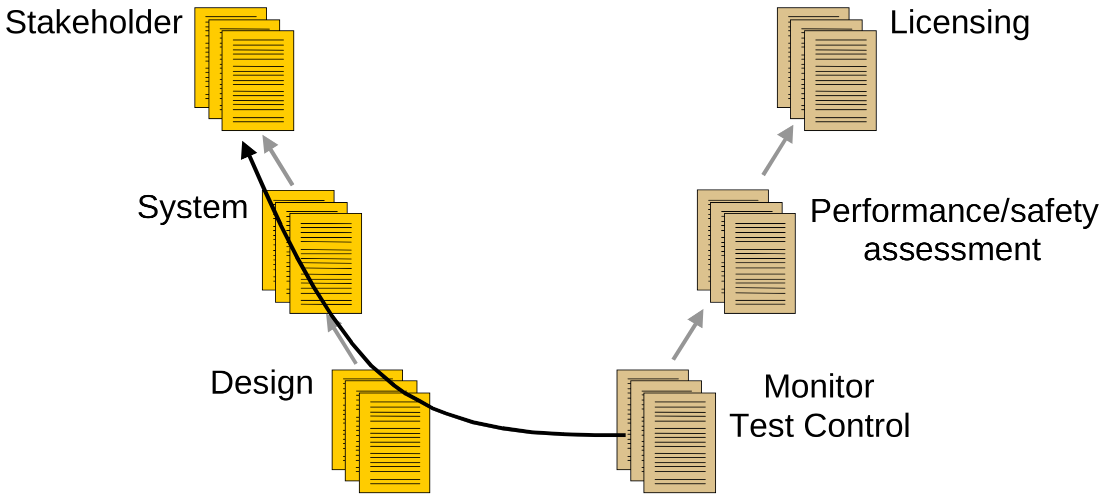
6. The V-Model



7. The Impact analysis



8. The derivation analysis



WASTE PACKAGE REQUIREMENTS AND DESIGN AT YUCCA MOUNTAIN

R. J. MacKinnon
Sandia National Laboratories, USA

1. Status of Programme

The DOE has studied Yucca Mountain for more than 20 years to characterise the site and assess the future performance of the potential repository. Yucca Mountain TSPA and scientific and engineering programs proceed iteratively:

- new data and design changes are incorporated into updated TSPA models.
- updated TSPA analyses and sensitivity studies suggest where new data and design enhancements might be valuable.

Input from NWTRB, NRC, and USGS help focus and prioritize work on scientific and engineering issues.

The DOE conducted benchmark performance assessments of the total potential repository system in 1991, 1993, 1995, 1998, 2000, and 2001. Comprehensive SR documentation submitted to the DOE Secretary in 2001 for suitability determination. On July 23, 2002 the Yucca Mountain site in Nevada was legally designated by the President of the US as a site for a proposed HLW repository. The DOE plans to submit a license application (LA) to NRC for construction in 2004. If a license is granted by NRC, construction will begin in 2008 and the first waste will be received in 2010.

2. Evolution of the design

Refining the design for the potential repository and the mode in which the design is operated has been an ongoing, iterative process involving scientists, engineers, and decision makers. The evolution of the repository design from 1987 – 1998 is described in the “Viability Assessment of a Repository at Yucca Mountain” (DOE, 1998).

The evolution of the repository design from 1998 – 2001 is described in the:

- License Application Design Selection Report (CRWMS M&O, 1999).
- Enhanced Design Alternative II (CRWMS M&O, 1999).
- Direction to Transition to Enhanced Design Alternative II (Wilkins and Heath, 1999).
- Approach to Implementing the Site Recommendation Design Baseline (Stroupe, 2000).

3. License Application Design Selection (LADS) Project

Goal of the LADS project was to develop a conceptual design for Site Recommendation (SR) and License Application (LA). Major tasks were to:

- identify design alternatives;

- specify features that might improve performance;
- evaluate alternatives and features individually;
- define enhanced alternatives (EDAs);
- evaluate final set of EDAs according to evaluation criteria;
- recommend conceptual design plus options; and
- recommend activities needed to move conceptual design to preliminary design for SR and LA.

4. Design Evolution of the EBS (VA to SR)

Spacing between emplacement drifts increased from 28 m to 81 m. Emplacement drifts were reoriented to increase drift stability. Backfill and drip shields were added to further limit the possibility of water contacting the waste packages and increase protection against rock fall. Backfill was later removed because of its potential adverse impact on spent nuclear fuel cladding.

Ground support system was changed to accommodate the removal of concrete because of concerns with the long-term impact of cement on alkalinity of the drift environment.

Regarding the waste package:

- VA design included Alloy 22 inner shell and a structurally strong, carbon-steel outer shell.
- SR and LA design utilizes 20–25 mm Alloy 22 outer shell and a structurally strong, 50 mm stainless-steel inner shell.
- Lid design has been modified to accommodate stress mitigation techniques in the closure weld area.

The Drip Shield characteristics are: corrosion-resistant 15 mm Titanium Grade 7.

Figure 1. Current Conceptual Waste Packages and Disposal Design

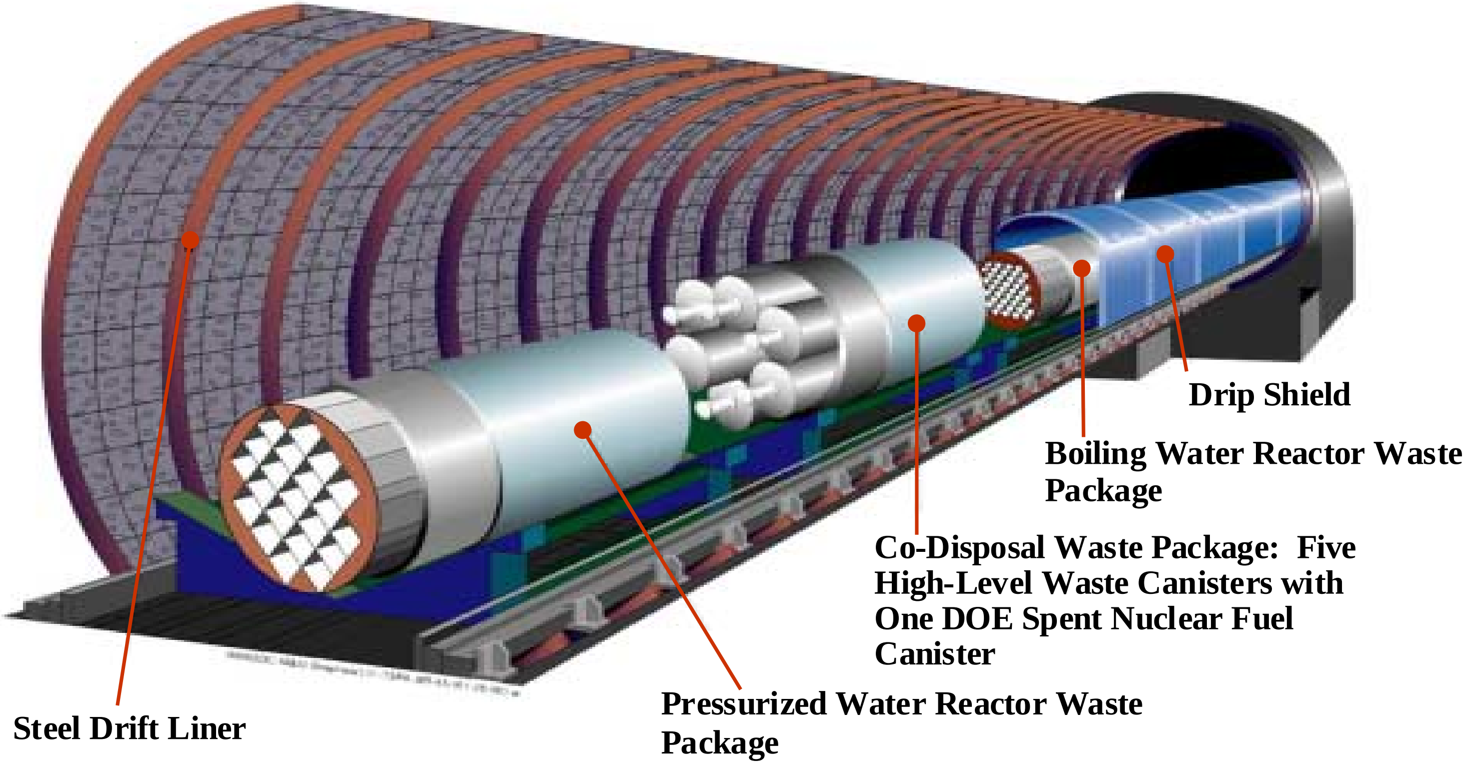
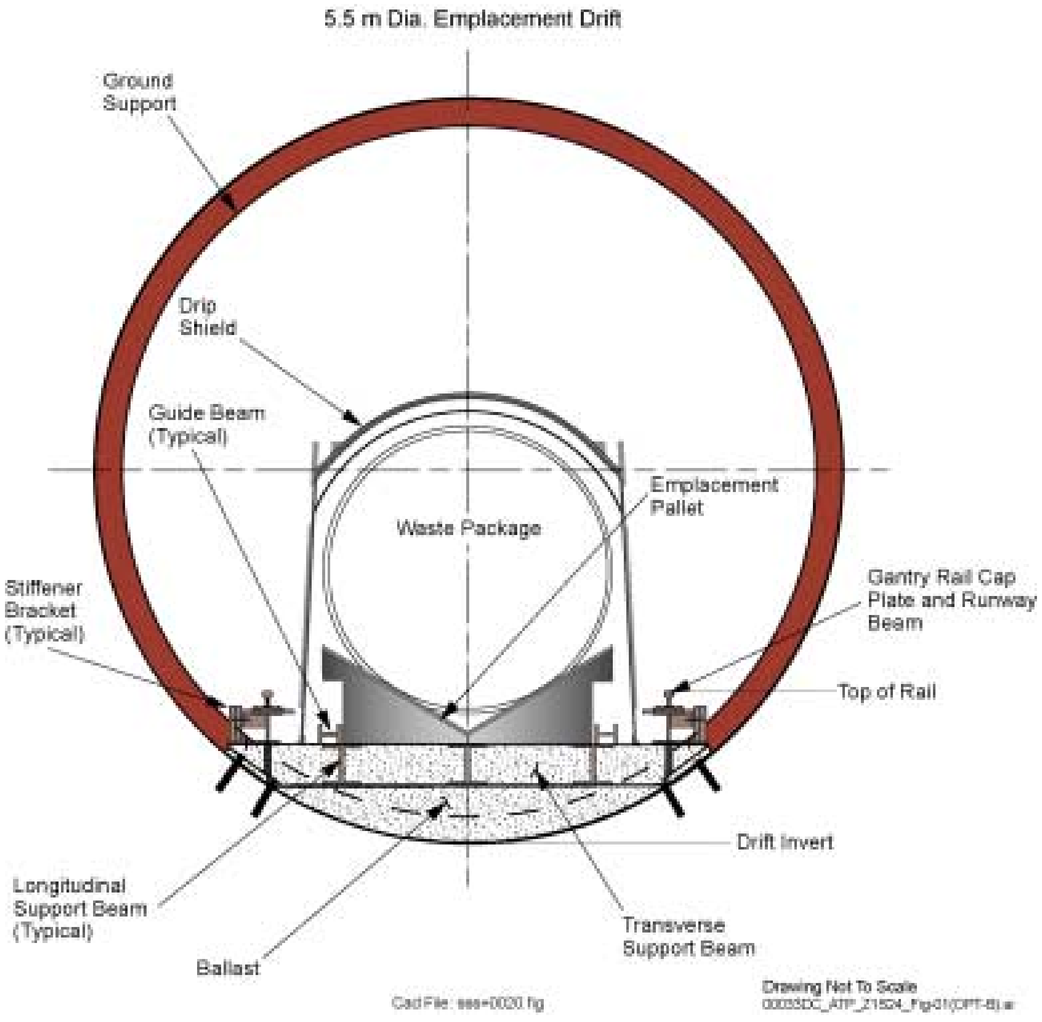


Figure 2. Cross-section Illustration of the EBS



5. Design process

Design development for the potential repository follows a structured approach that links statutory, regulatory, and design requirements.

Design requirements and process controls are influenced by the importance of each system, its structures, and its components in the overall safety strategy:

- Systems important to pre-closure safety.
- Systems important to post-closure safety.

There is an iterative process between design, pre-closure safety assessment, and post-closure safety assessment and the design and analysis work are performed in accordance with a quality assurance program.

Figure 3. Allocation of Functions, Criteria and Requirements

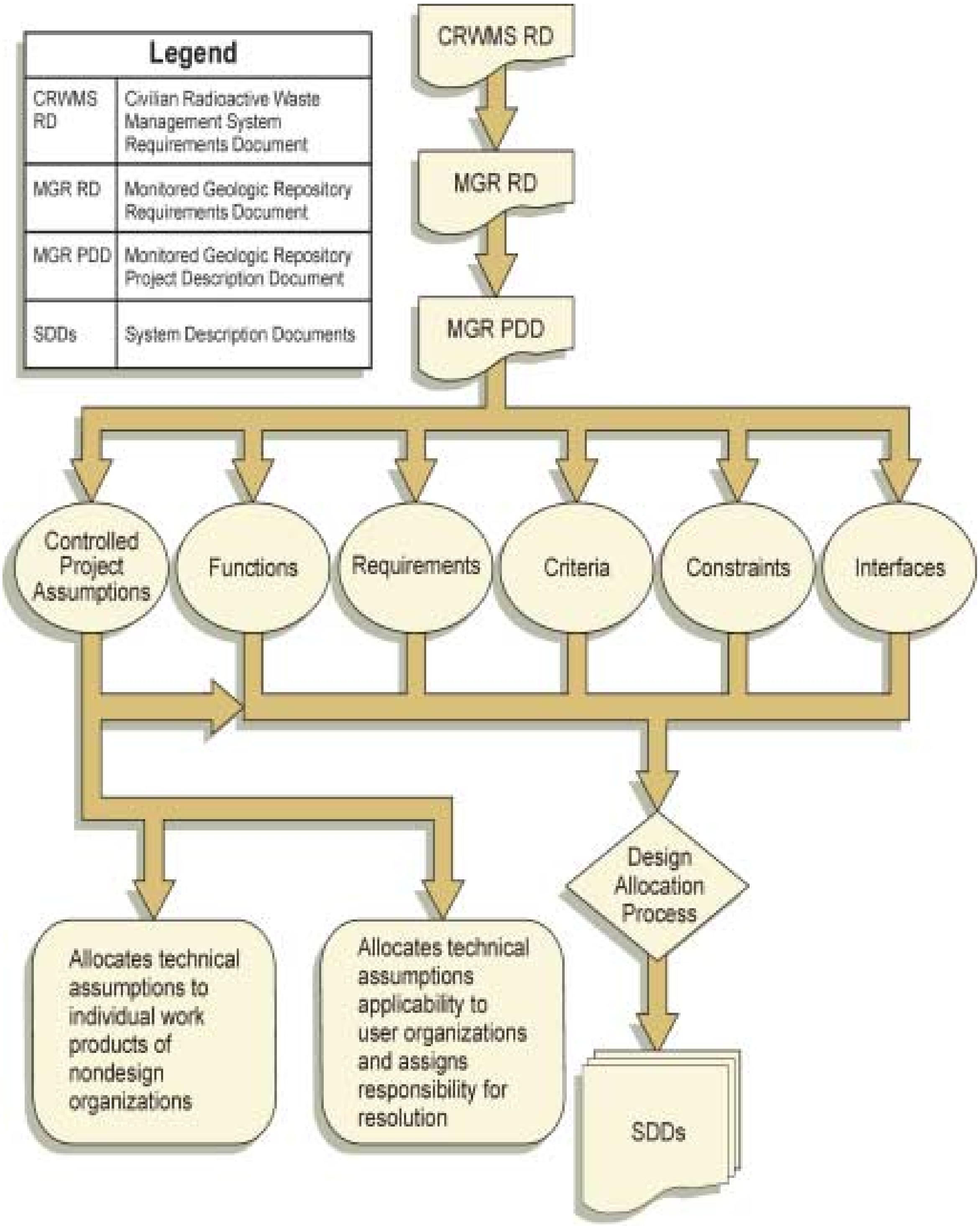


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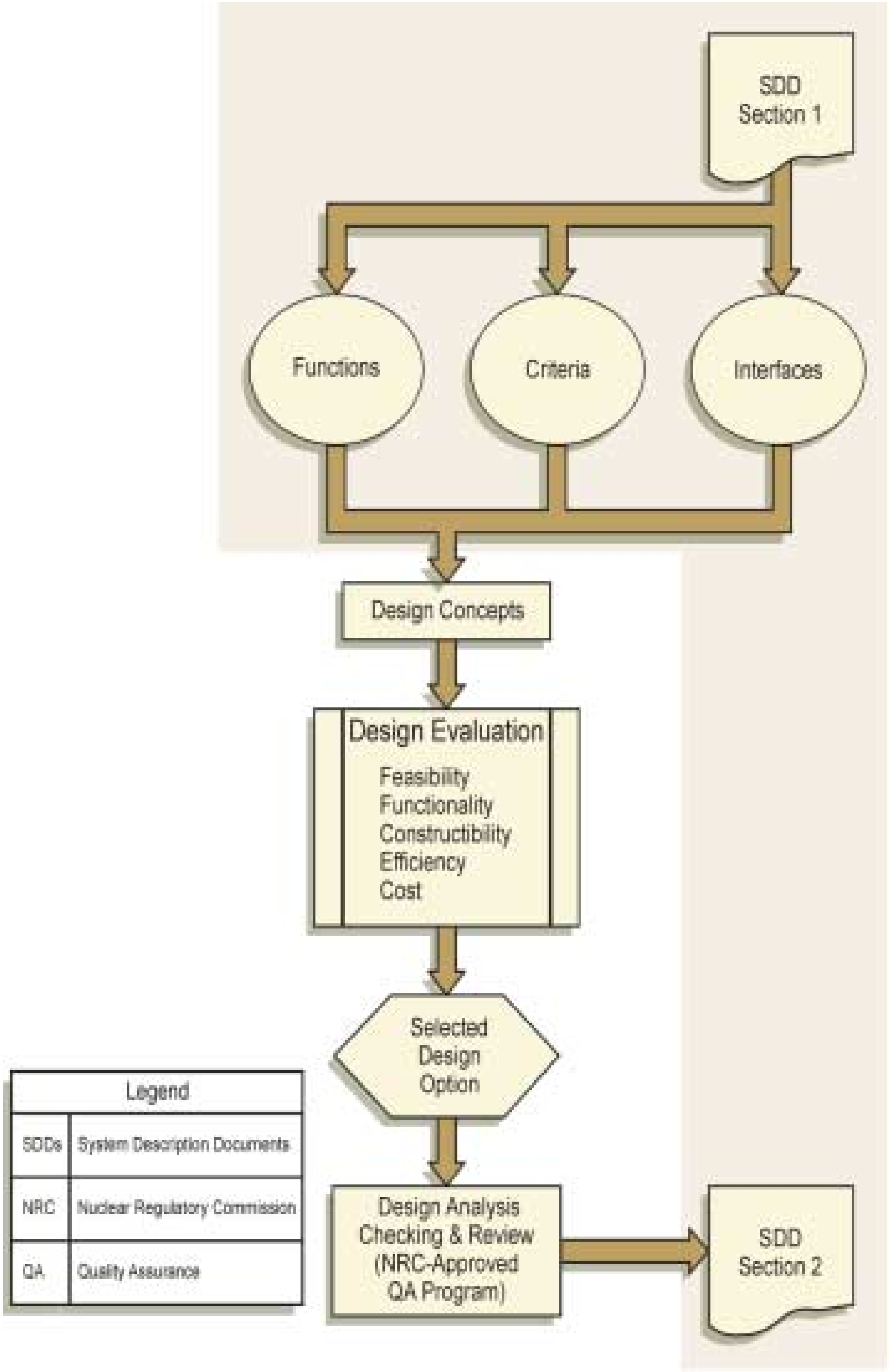
Figure 4. Design Documents Development



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6. CSNF Disposal Container System Description Document (SDD)

The document consists of:

- Summary.
- Quality Assurance.
- System Functions and Design Criteria.
  - System Functions.
  - System Design Criteria.
- Design Description.
  - System Design Summary.
  - Design Assumptions.
  - Detailed Design Description.
  - Component Description.
- Criteria Compliance.

7. Design Requirements for Waste Packages

Statutory and regulatory requirements demand:

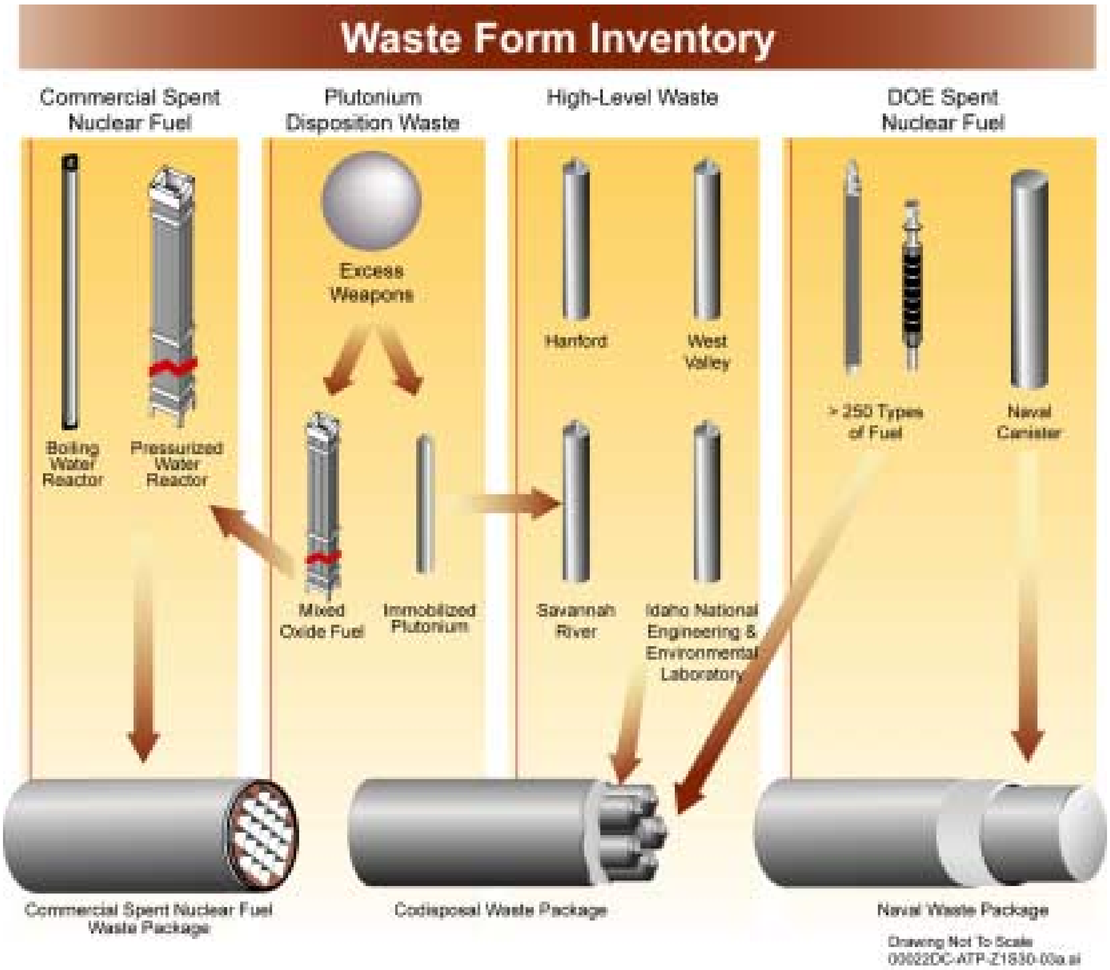
- Expected waste forms are accommodated.
- Worker and public health and safety are protected during operations and before final closure of the repository.
- Long-term system performance objectives are satisfied.

8. Waste package functions

They are:

- Restrict the transport of radionuclides.
- Provide criticality protection.
- Manage the decay heat for the potential repository.
- Provide identification (i.e. each waste package will be uniquely labeled and its contents identified).
- Enhance the safety of personnel, equipment, and the environment.
- Prevent adverse reactions involving the waste form.
- Maintain structural integrity during loading, onsite transportation, emplacement, and retrieval.
- Resist corrosion in the emplacement drift environment.
- Provide physical and chemical stability for the waste form.
- Promote heat transfer between the waste form and outside environment.
- Facilitate decontamination of waste packages' outer surface.

Figure 5. Accommodation of Expected Waste Forms



9. Pre-closure safety assurance

Waste Package must be designed to protect both worker and public health and safety after being laden with waste forms and closed. Protection must take place in the surface facility, during transport to the subsurface, and after placement but before final closure. 10CFR 63.112(b) requires analyses of the ability of the structures, systems, and components of the waste package to perform their intended safety functions during accident or event sequences.

Event sequences are determined by identifying the functions of the waste package and evaluating the effects on its performance of given events that could occur during normal handling of the WP or during a credible accident scenario.

Figure 6. Pre-closure Integrated Safety Analysis

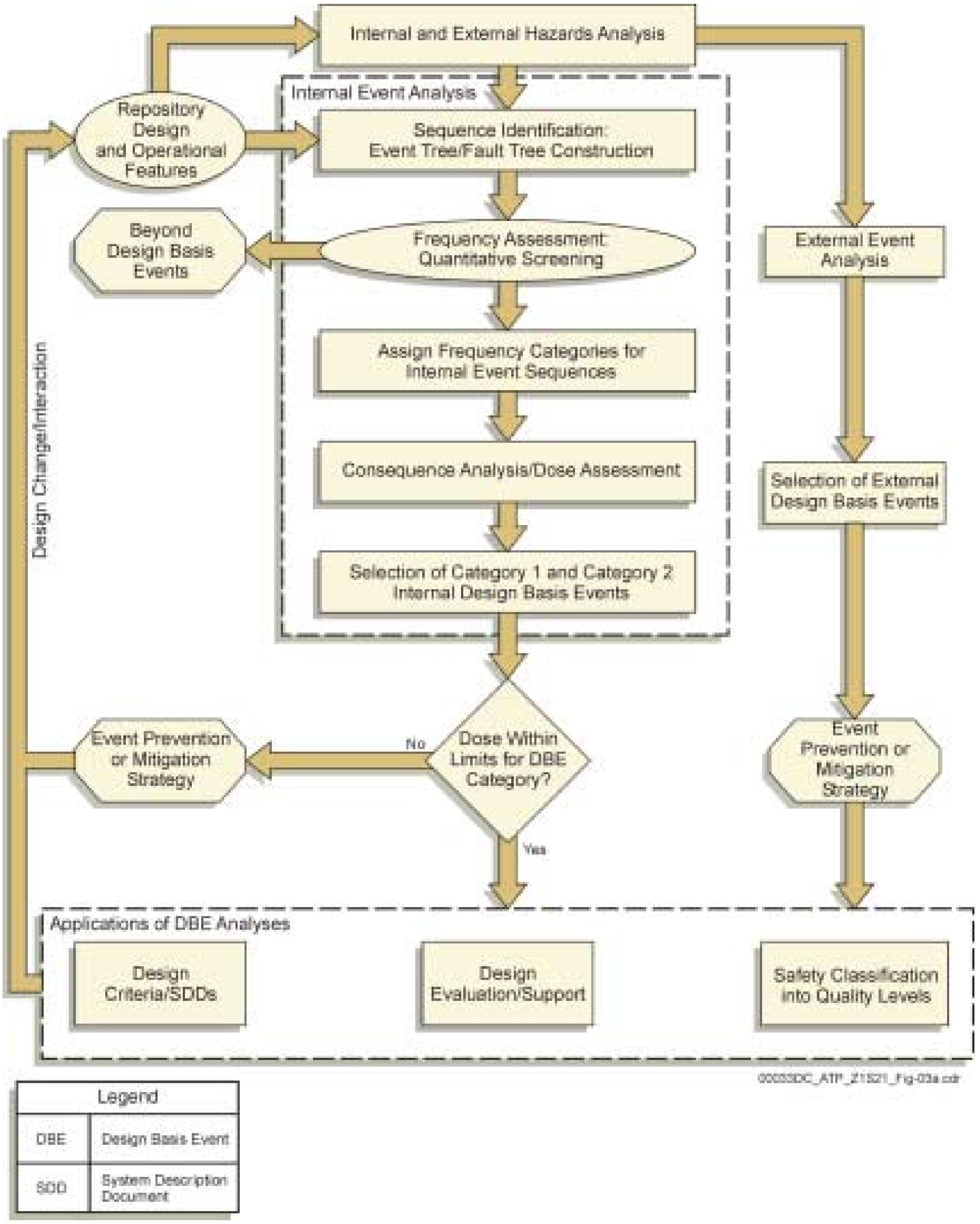


Table 1. Pre-Closure Event Sequences for Waste Package

Analysis Type	Event Group	Event	Performance Specification
Structural	Falling objects – side impact on waste package	Rock fall from the drift onto the waste package	Withstand 13 t (14 short ton)[a] rock falling 3 m (10 ft). Drop height based on a 5.5 m (18 ft) drift and a distance of 2.4 m (8 ft) between the top of the drift and the top of the waste package.
	Falling objects – end of waste package impact	Handling equipment drop onto the waste package	Withstand 2.3 t (2.5 short ton) object falling 2 m (6.6 ft). Drop height based on the distance between the handling equipment and the top of the waste package.
	Waste package vertical drops and waste package end collisions	Waste package vertical drop from the disposal container cell crane	Withstand 2 m (6.6 ft) drop. Drop height based on the maximum crane hook height; the bottom of the waste package cannot be lifted higher than 2 m (6.6 ft) above the floor.
	Waste package horizontal drops and waste package side collisions	Emplacement drift gantry drops waste package	Withstand 2.4 m (8 ft) drop
	Puncture hazards	Waste package falls onto a sharp object while being transported in a horizontal position	Withstand 2 m (6.6 ft) horizontal drop onto a steal support or 2.4 m (8 ft) horizontal drop onto a concrete pier, whichever is worse.
	Tip Over	Tip over due to vertical drop or seismic event	Withstand tip over from a vertical position onto a flat surface
	Seismic activity	Earthquake	Maintain structural integrity and prevent tip over during a design-basis earthquake
	Missile	The missile identified was a valve stem being ejected at the surface facility	Withstand impact of a valve stem weighing 0.5 kg (1.1 lb) with a 1 cm (0.39 in) diameter, inside a valve with 5 cm (2 in) of packing and under a system pressure of 2.1 MPa (305 psi), which has become a missile with a velocity of 5.7 m/s (19 ft/s)
	Transporter runaway	Failure to maintain the transporter at or below the maximum speed limit	Withstand maximum impact from a transporter runaway derailment, and impact at a speed of 63 km/hr (39 mi/hr)
	Fuel rod rupture/internal pressurization	100% fuel rod rupture and fission gas release	Withstand internal pressure of 1 MPa (146 psi)
Thermal and Structural	Thermal stresses and peak waste package temperature	Fire in disposal container cell	Survive a fire, defined as exposure of whole waste package for not less than 30 minutes to a heat flux not less that that of a thermal radiation environment of about 80ºC (1,500ºF) with an emisivity coefficient of at least 0.9. Surface absorptivity must be at least 0.8. If significant, convective heat transfer must be considered on the basis of still air at about 800ºC (1,500ºF).
Criticality	Criticality safety	Criticality scenario inside a waste package	The effective multiplication factor (k_{eff}) is less that or equal to 0.95 under assumed accident conditions, considering allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation

Note: [a]This rock size requirement was lowered to 6 t (7 short tons) since completion of the rock fall analysis is support of conceptual design.

10. Post-closure Performance Specification

10 CFR 63.113(b) requires the entire repository system to meet specific dose limits for 10 000 years. The waste package is one of many barriers relied upon to meet dose limits. DOE's objective is to design a waste package that works in concert with the natural system to meet performance standards while reducing uncertainty associated with coupled processes.

11. Material Selection

Alloy 22 was selected as the preferred material for the outer barrier.

Stainless Steel Type 316NG was selected for the structural inner layer.

The following criteria are considered for material selection:

- Mechanical performance (strength).
- Chemical performance (resistance to corrosion).
- Predictability of performance.
- Compatibility with the materials of the waste package and waste form.
- Ease of fabrication.
- Previous experience.
- Thermal performance.
- Neutronic performance (criticality and shielding).
- Cost.

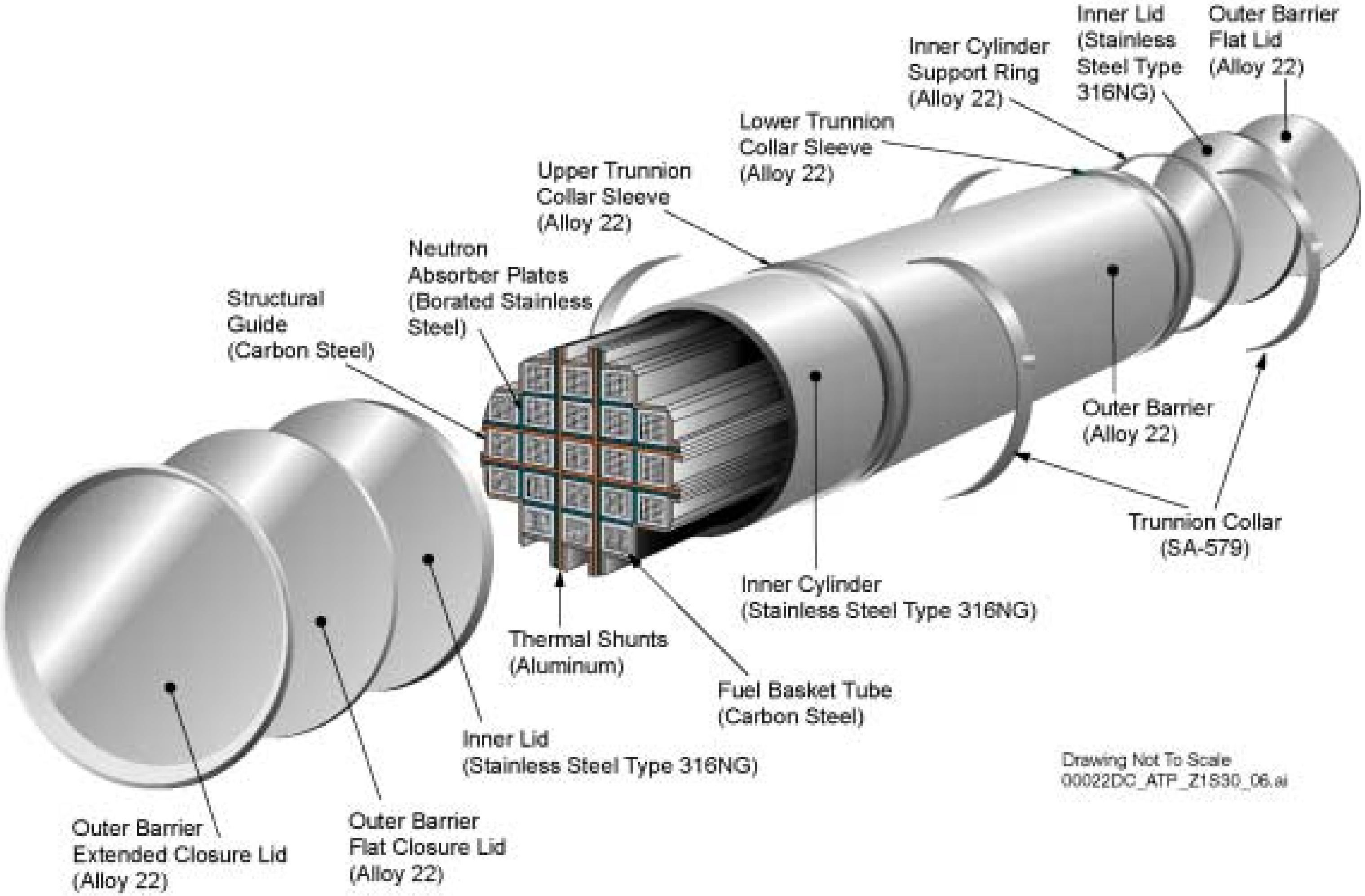
Table 2. Post-closure Failure Mechanisms (Site Recommendation)

Failure Mechanism	Drip Shield Post-Closure Assessment		Waste Package Post-Closure Assessment	
	Included in TSPA	Screened Out*	Included in TSPA	Screened Out*
General Corrosion	X		X	
Localized Corrosion		X		X
Aging and Phase Stability		X		X
Fabrication Defects		X	X	
Microbial Influenced Corrosion		X	X	
Gamma Radiolysis		X		X
Stress Corrosion Cracking		X	X	
Hydrogen Induced Cracking		X		X
Rock Fall		X		X

*Screened out based on low consequence or probability of occurence

Figure 7. Waste Package Designs with Waste Forms

Figure 8. 21-PWR Absorber Plate Waste Package Design



12. Summary

The DOE plans to submit a license application (LA) for construction in 2004. The design development follows a structured approach that links statutory, regulatory, and design requirements. The repository design process is an iterative one between design, pre-closure safety, and post-closure safety. Ten waste package designs are proposed for license application (LA).

Four designs that span the range of waste form types will be advanced as preliminary designs for submittal of LA, the remaining six will be kept at the conceptual level. The work toward LA will include pre-closure and post-closure assessments of representative waste packages.

BUFFER AND BACKFILL REQUIREMENTS AND DESIGN FOR KBS-3

J. Hansen
Posiva Oy, Finland

1. Introduction

In the Finnish disposal concept the buffer and the backfill create an important part of the engineered barrier system. The buffer consists of highly pre-compacted bentonite blocks. The main functions of the buffer are (Posiva, 2000):

Plastically isolate the canister from the rock and to protect it against minor rock displacements

Prevent advective transport between rock and canister, so that transport takes place predominantly by diffusion. The buffer thus, to some extent "decouples" the canister from the flow and transport processes in the surrounding rock and tunnels.

With respect to backfill, Posiva (2000) states that the backfill shall:

A. Prevent the tunnels for becoming major conductors of groundwater and transport pathways of radionuclides.
B. Keep the buffer and canister in place in the deposition hole.
C. Contribute to keeping the tunnels mechanically stable.
D. Shall not have any significant interactions with other barriers.

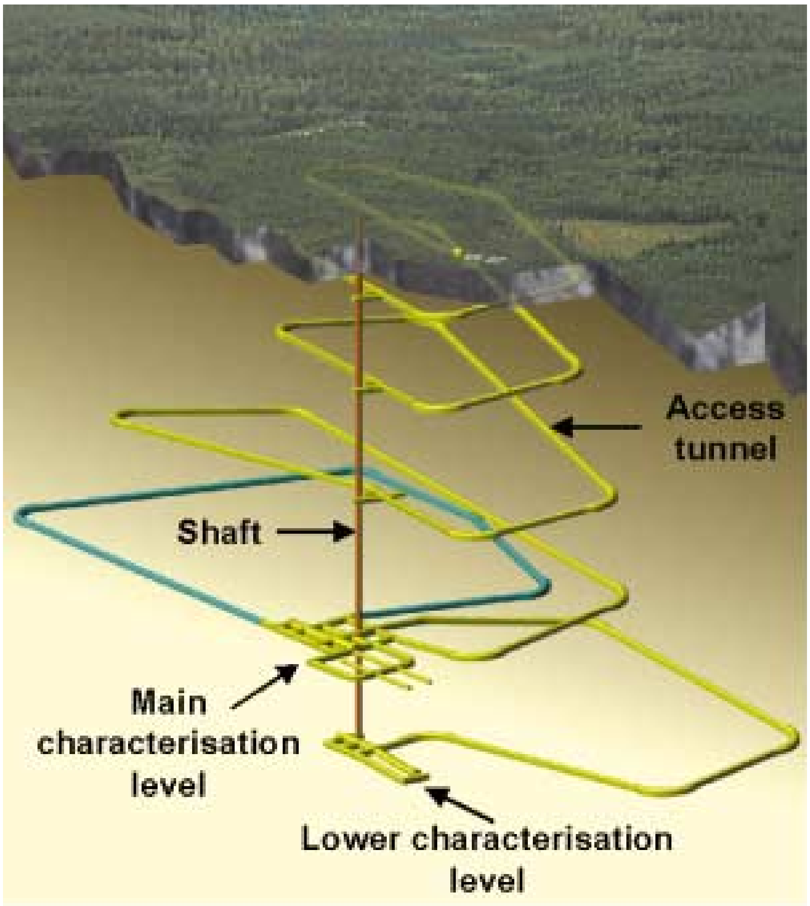
The buffer and the backfill should maintain their barrier functions at least 100 000 years. This is very conservative statement and the verification of system functioning needs discussion. The demonstration of long-term durability is not possible with direct methods, and the indirect methods do not always give reliable data either. Natural materials are preferred over man-made materials. Natural analogies can be used for compacted bentonite and the analogy data combined with other research data can be extrapolated based on different models. Backfilling mixtures and materials with low density (due to ineffective compaction etc.) may not have the required durability and resistance in different processes occurring in the repository.

2 The current situation of Posiva

The management for disposal of spent fuel in Finland is based on a stepwise approach. The long-term programme aimed at selection of a site for a deep repository was initiated in Finland in 1983. Site investigations in five different crystalline bedrock areas were based on investigations from surface in form of deep drillings with extensive sampling program. The site was selected after evaluation of results from detailed characterisation phase. The site selection programme has come to end when Olkiluoto site was selected for further investigations in 2001. The decision in principle for disposal of spent nuclear fuel was approved by Finnish parliament and a new phase aimed at implementation of the geological disposal of spent fuel has been started. In this new phase the first milestone is the application for a construction license for the disposal facility during 2010-2014. To fulfil the needs for URCF detailed design of the disposal system, an underground rock characterisation facility will be constructed at the representative depth at Olkiluoto. The excavation of this facility will start the work for underground characterisation, testing and demonstration, which is planned to be a continuous activity throughout the whole life cycle of the deep repository.

The site characterisation for the repository has been in progress for 15 years, and the possibilities to obtain new essential data by the methods used until now are limited. The strategy is to develop an underground rock characterisation facility (Figure 1.), called ONKALO, and conduct investigations and underground testing to assess the properties of the site. Construction of the ONKALO for detailed characterisation of suitable rock volumes for the repository is planned to be started in 2004. The access routes into ONKALO and other underground excavations may later be used as parts of the repository. Access to the underground facilities will be arranged via a tunnel and a shaft. The information gained will be used for the application for the construction license. The disposal facility, consisting of an encapsulation plant and a deep repository, will be built thereafter. Posiva shall be prepared to start final disposal of spent fuel in Finland in 2020. The operational phase for repository continues until disposal for Finnish spent fuel have been completed. Thereafter follows the closure and sealing the repository presumably at the end of 21st century.

Figure 1. The ONKALO consist of access tunnel, ventilation raise, main characterisation level, characterisation tunnel, demonstration tunnels and lower characterisation level (Posiva 2003)



3 Requirements from different stakeholders

The nuclear waste commission of Finnish power companies published an overall nuclear waste management program and time schedule in 1982 (Raumolin). According to this program the basis for the waste management are comprehensiveness, use of known technology, safety, well-timed concept and flexibility.

Different requirements must take into consideration when planning the design of sealing structures. The overall repository design must follow the guidelines from the regulatory body (YVL-guide 8.4).

- “Targets for the long-term performance of each barrier, shall be determined based on best available experimental knowledge and expert judgement. The performance of a barrier may diverge from the respective target value due to rare incidental deviations such as manufacturing or installation failures of engineered barriers, random variations in the characteristics of the natural barriers or erroneous determination of the characteristics. However, the performance targets for the system of barriers as a whole shall be set so that the safety requirements are met notwithstanding the deviations referred to above.
- The determination of the performance targets for the barriers shall be based on an assumption that, due to some unpredicted phenomenon, the performance of a single barrier as a whole may be significantly lower than the respective target value. The safety requirements shall be met even in such case.
- The determination of the performance of barriers shall take account of changes and events that may occur in various assessment periods. The characteristics of the host rock can be assumed to remain in their present state up to an assessment period of several thousands of years. However, the effects of predictable processes, such as land uplift and disturbances due to the excavations and the disposed waste, shall be taken into account. The performance targets for the engineered barriers shall be set so that there will be no releases of radioactive substances into the host rock during the assessment period of several thousands of years.”

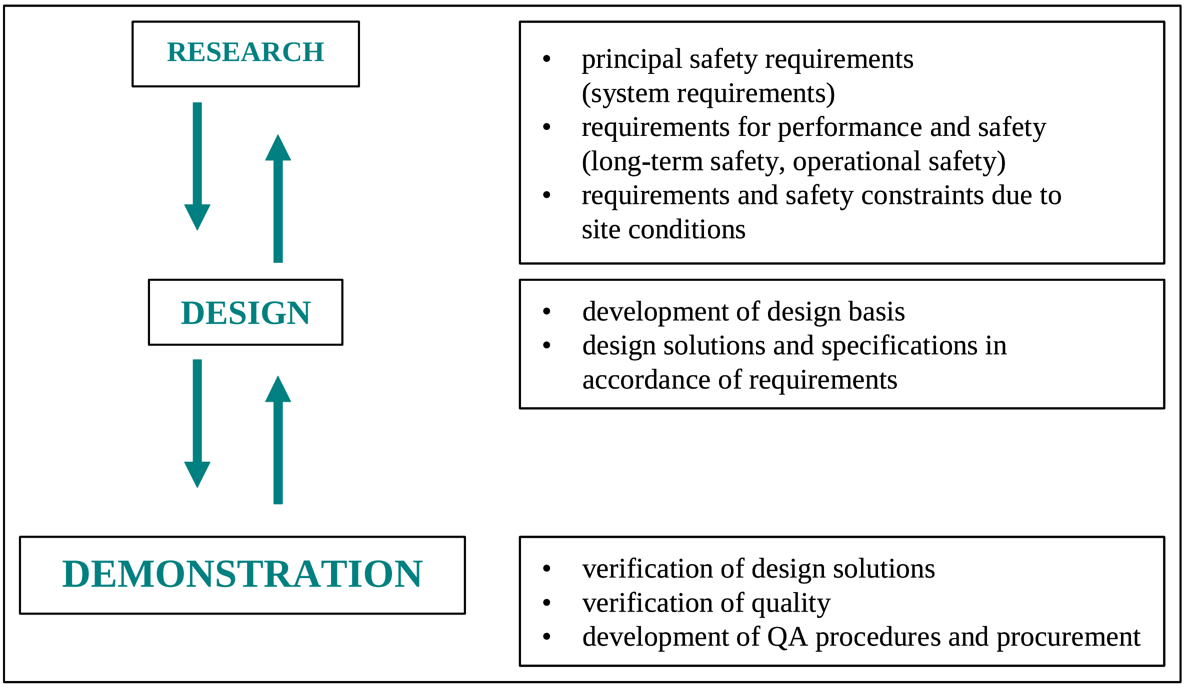
Requirements are presented in very common level and their interpretation is not always easy. The other requirements can be divided into the long-term safety requirements, and requirements set by owners, e.g. such requirements that deal with operational safety, practicability and efficiency.

During the last decades the situation has been changed. The first design solutions are based on theoretical estimations, but when the amount of knowledge and research data has increased, also the requirements have been developed. The following issues have influence on buffer and backfill design specifications: salinity, temperature, and the change of repository design.

4 Role of requirements in design process

The systematic management of requirements have been developed during the last years (Figure 2). Requirements basically integrate the work of safety and performance assessments, characterisation of geological environment and engineering. Safety requirements and assessments advise and evaluate what the system shall fulfill but they do not state in detail how and with which level of confidence the requirements shall be fulfilled.

Figure 2. **The simplified layout of RDDC-process, which gives the guidelines to Posiva's R&D-work.**



4.1 Buffer requirements

The development of buffer requirement has been long process. Experiences from various international projects (FEBEX, CROP, BENIPA, GMU, ECOCLAY I and II, LOT, PROTOTYPE REPOSITORY) have contributed the interpretation of requirements. The main functional requirement is to isolate the canister from surroundings. Practically it means that the flow around the canister must be very low. If the flow is very low, the saturation of bentonite will not occur evenly. Other important properties for buffer have been specified as follows:

- chemically and mechanically stable;
- no harmful effects on other barriers;
- sufficient swelling pressure (1-10 Mpa);
- low hydraulic conductivity;
- suitable thermal conductivity;
- suitable bearing capacity;
- suitable plasticity and self adjustment mitigate consequences of bedrock movements;
- suitable gas permeability;
- ability to act as filter against colloid;
- ability to act as a filter and limit growth of micro organisms;
- sufficient chemical buffering capacity;
- due to sorption and diffusion properties ability to limit migration of corrosion products and radionuclides.

When bentonite is tightly compacted and quality requirements are fulfilled the buffer will have very long lifetime regardless all the relevant injurious processes. The normal cement, which is typically used for sealing the leakages in crystalline bedrock, may be harmful to the durability of bentonite and that complicates normal tunnelling and underground construction operation. Several countries develop alternative sealing methods to limit inflows to the repository, which may influence the design and cost of underground facilities. But the bentonite cannot be replaced in KBS-3 concept with any other material due the all desired properties it has.

4.2 Buffer design

The design of the buffer in the KBS-3 system (vertical or horizontal) has been practically the same from the beginning. The buffer material used in the deposition holes consists of pre-compacted bentonite blocks. The blocks can be compacted by using different techniques and different types of bentonites and they can have different sizes and shapes. This design is well known and widely accepted among the scientists and stakeholders. Some small changes in design can be made without difficulties, but if alternative buffer solution is proposed it will influence the whole waste management process and systems drastically.

Designs for the bentonite buffer of deposition holes will be prepared including:

- manufacturing designs for bentonite blocks;
- dimensioning of the bentonite lining beside, below and above the canister;
- installation of the bentonite lining into the deposition hole;
- cost estimates for the bentonite buffer;
- material specifications; and
- an examination of the procurement of materials and the possibilities of manufacturing bentonite blocks in Finland (Posiva, 2000).

4.3 Backfill design and requirements

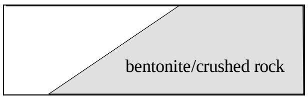
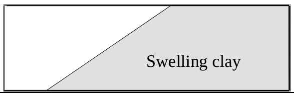
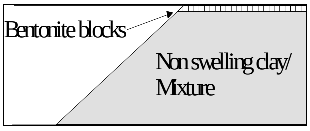
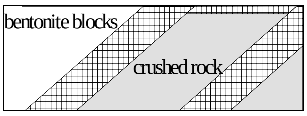
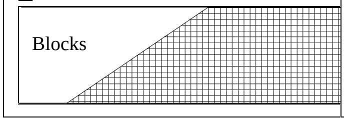
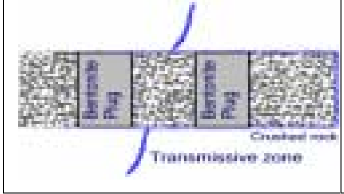
In the beginning the backfill was not a technical barrier. All design work has been based on the assumption that the final repository will be closed and sealed so that the geological conditions will return to their initial state (1992). In safety assessment reports (TILA-96 and TILA-99) the backfill are a part of the multi-barrier system.

Alternative backfilling materials and methods have been suggested because there is a risk, that the basic concept (backfilling tunnels with mixture of crushed rock 70% and bentonite 30%) wont work in high saline groundwater environment. Fore example, glacial fine-rich till has been suggested to replace the crushed rock because tills have naturally optimal grains size distribution and very low porosity leading to low hydraulic conductivity and low compressibility. Using this kind of unsorted aggregate instead of crushed rock would also enhance the density of the clay fraction within the mixture. In addition, the availability of material is relatively good in S-W Finland. Best part of the material is that till-based backfill would not be as sensitive to groundwater salinity or ion exchange processes compared to backfill comprising of bentonite and crushed rock. The natural swelling clays and pre-compacted blocks will be discussed and evaluated as possible backfilling alternatives for repository tunnels.

Also the heterogenous backfilling concept will be taken into consideration. In the “compartment” backfilling and sealing concept, the main volumes of the excavations are backfilled with crushed rock. Transport pathways along the excavations and EDZ are blocked by means of impermeable, durable plugs. A preliminary design of a plug consisting of blocks of highly compacted bentonite. The size and shape of the slots and plugs have to be adjusted to the rock quality, support from backfilling, pre-closure hydraulic conditions and state of stress to obtain a stable structure and a break in the EDZ, which is long enough to block the flow paths effectively. A layer of filter material with an optimised grain-size distribution may prevent erosion and intrusion of compacted bentonite into the crushed rock. A similar filter layer may be emplaced also on the top of the bentonite in the deposition hole. (Autio *et al.* 2001) The key issues are the required amount of plugs in deposition tunnel, emplacement technique, optimisation of grain size distribution in crushed rock, the fulfilment of requirements. The above-mentioned backfill alternatives have been considered in cooperation with SKB (Figure 3.).

The dimensions of the disposal tunnels are: maximum height 4,4 m and tunnel floor width 3,5 m. The backfill should fill the whole tunnel effectively. Tight and dense backfill mass don't however help if water-conducting features appears in connection with EDZ or the contact with roof is not tight.

Figure 3. First phase of the SKB-Posiva backfill programme consist of desk study, which compiles the basic descriptions of different backfill alternatives. (Gunnarsson *et al.* 2003)

Alternative	Potential materials	Design	Potential methods for emplacement
A 	Mixture of bentonite (MX-80 is the reference bentonite) and crushed rock (30/70)	Reference design/concept Homogeneous	In-situ compaction in inclined layers by vibrating plate. Alternative backfill methods: roller compaction, slinger-belt throwing.
B 	Friedton clay or other similar mixed-layer clay with swelling ability	Homogeneous	*In situ* compaction in inclined layers by vibrating plate. Alternative backfill methods: sheepsfoot roller, slinger-belt throwing.
C 	Mixture of fine-rich till (95%)and bentonite (5%) and bentonite blocks and/or bentonite pellets at the roof section.	Composite	Emplacement of the bulk material: *In situ* compaction in inclined layers by vibrating plate. Alternative backfill methods: roller compaction, slinger-belt throwing. Emplacement of blocks: manual or automate. Emplacement of pellets: grouting.
D 	Bentonite clay (pre-compacted blocks and pellets) and crushed rock. (The sections filled with bentonite will be placed regularly, above every disposal hole.)	Composite	Emplacement of the crushed rock: *in situ* compaction in inclined layers by vibrating plate. Alternative methods: roller compaction or slinger-belt throwing. Emplacement of the blocks: manual or automate. The gaps between the blocks and between the blocks and the roof will be grouted with bentonite pellets, if necessary.
E 	Bentonite clay, mixed-layer clay with swelling ability, non-swelling clay, mixed materials.	Homogeneous	Emplacement of blocks, manual or automate. The gaps between the blocks and between tha backfill and the walls/roof will be grouted with bentonite pellets, if necessary.
G **Compartment** 	Crushed rock and plug structures composing of bentonite clay. (The amount of plugs depends on the amount of transmissive structures intersecting the tunnel.)	Compartment	Emplacement of crushed rock: in-situ compaction in inclined layers by vibrating plate. Alternative methods: roller compaction, slinger-belt throwing. Emplacement of the plugs: manual or automate.
Concepts, where technology and materials used in backfilling of mines can be applied.	Crushed rock with suitable gradation for paste emplacement, slag (binder)	Homogeneous/ composite or compartment	Emplacement techniques: paste fill, roller compaction.

Different backfilling solutions have been proposed but all of them have some kind of disadvantages linked to e.g. the long-term safety, costs or efficiency of the process. Heterogeneous backfilling concepts could work properly at the deposition tunnels but they require complex and unpractical emplacement techniques. At this stage it is a fact that all of the proposed backfilling alternatives would need further research and development work in order to reach and verify a backfill solution that would work properly in the required conditions. How to select the right alternatives for further investigations is now the challenging question.

4.4 Design basis

The main design basis for the buffer and the backfill are derived from performance requirements set for the sealed deposition hole and for the backfilled tunnel. The design basis for the KBS-3 type system may vary between the Swedish and the Finnish repository depending the bedrock conditions and different technical solutions. One very important issue has been the identification of common design basis for future cooperation between Posiva and SKB. Different design basis could be e.g. the amount of fuel and the salinity of the groundwater (maximum value 35 g/l TDS). Some design basis should be in a more detailed level and could work as a tool for designer. An example on this kind of design basis is the hydraulic conductivity of the backfill, which should be so low, that the flow within the material would be a diffusion dominant process.

5 Conclusions

The disposal system shall provide the initial isolation and isolate the waste from biosphere. The disposal concept shall be based on multi-barriers and be able to retard the return of radionuclide. Multi-barriers consist of natural barriers like bedrock and technical barriers in Finnish disposal system are canister, buffer and backfill and seals.

The construction and emplacement methods and different materials shall be based on proven technology and shall be constructed and operated so that advantageous geological conditions will retain their good isolation properties. Even disposal is planned to be final there must be maintain the option for retrievability. The long term safety requirements should be prioritised in design of barriers, but also other demands shall be taken into account like economical feasibility and efficiency considerations.

It’s defined that requirements should give the guidelines to the work and help to design backfill and buffer solutions. There are some issues, which should be discussed to achieve the benefits of systematic management of requirements:

- Requirements and design are mixed (specify problem, not solution).
- Owners of requirements are not recognised (or they escape their responsibility).
- Unverifiable requirements are presented (indirect verification i.e. canister corrosion).
- Missing requirements.
- Ambiguous and unclear requirements.
- Contradictory requirements.
- Traceability of decisions to requirements.

6. References

Autio, J., Hautojärvi, A., Salo, J-P., Vieno, T. 2001 Backfilling Concepts For A Spent Fuel Repository At Olkiluoto, Paper in 6th international workshop on design and construction of final repositories “backfilling in radioactive waste disposal”

Gunarsson, D., Börgesson, L., Hansen, J., Keto, P., Tolppanen, P., 2003. Backfilling concepts for KBS-3. Posiva Working report xx-2003. (In progress)

POSIVA 2000. Disposal of spent fuel in Olkiluoto bedrock. Programme for research, development and technical design for the pre-construction phase. Posiva Oy, Helsinki. POSIVA 2000-14.

POSIVA 2003. ONKALO Underground Characterisation and Research Programme (UCRP) POSIVA 2003-03 (in print) 142 s.

Raumolin, H., 1982. Programs and schedules for TVO's nuclear waste management. Report YJT-82-55. 24 p. (In Finnish)

STUK 2001. Long-term safety of disposal of spent nuclear fuel, Regulatory guide on nuclear safety. YVL 8.4. 2001

Teollisuuden Voima Oy, 1985. Final disposal of spent nuclear fuel in Finnish bedrock. Report YJT-85-30. 168 p. (In Finnish)

Vieno, T., Nordman, H., 1999. Safety Assessment of Spent Fuel Disposal in Hästholmen, Kivetty, Olkiluoto And Romuvaara – Tila-99. POSIVA Report 99-07, 253 p.

Vieno, T., Nordman, H., 1996. Interim report on Safety Assessment of Spent Fuel Disposal – Tila-96 POSIVA Report 96-17, 176 p.

MANAGING DESIGN REQUIREMENTS OF FRENCH WASTE DISPOSAL PACKAGES

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Introduction

Identifying design requirements and constraints of a repository system is an iterative process. It is seeded by an initial analysis and interpretation of varying stakeholder needs and requirements, and evolves with the improved understanding of site specific characteristics, increasingly detailed design concepts, experimental and modeling results pertaining to engineered barrier and near field evolution, and intermediate results of safety analyses.

Requirements and constraints applicable to waste disposal package (noted WDP) are derived from system wide functional analysis and design specifications, from the interface between WDPs and other engineered repository components, and from the scientific understanding of WDP behaviour in its environment. This paper describes the procedure followed by Andra to identify design requirements and constraints, in general, considerations pertaining to French WDPs, in particular, and presents the status of current WDP design concepts.

WDPs include a primary Waste Package (noted WP, as designed and manufactured by the waste producer), and possibly an over-pack.

A fundamental design constraint of the French research program on geological disposal is given by the substantial variety of primary WPs. These are grouped in three broad categories, containing transuranic waste (intermediate level or B-type waste, noted ILW), vitrified waste (high level or C-type waste, noted HLW) and spent fuel (noted SF). Each category contains a variety of waste types, packaged in primary containers of different material and dimensions. Note that it has not yet been decided whether or not spent fuel will be disposed of. Various scenarios are being studied, some of which include the disposal of SF.

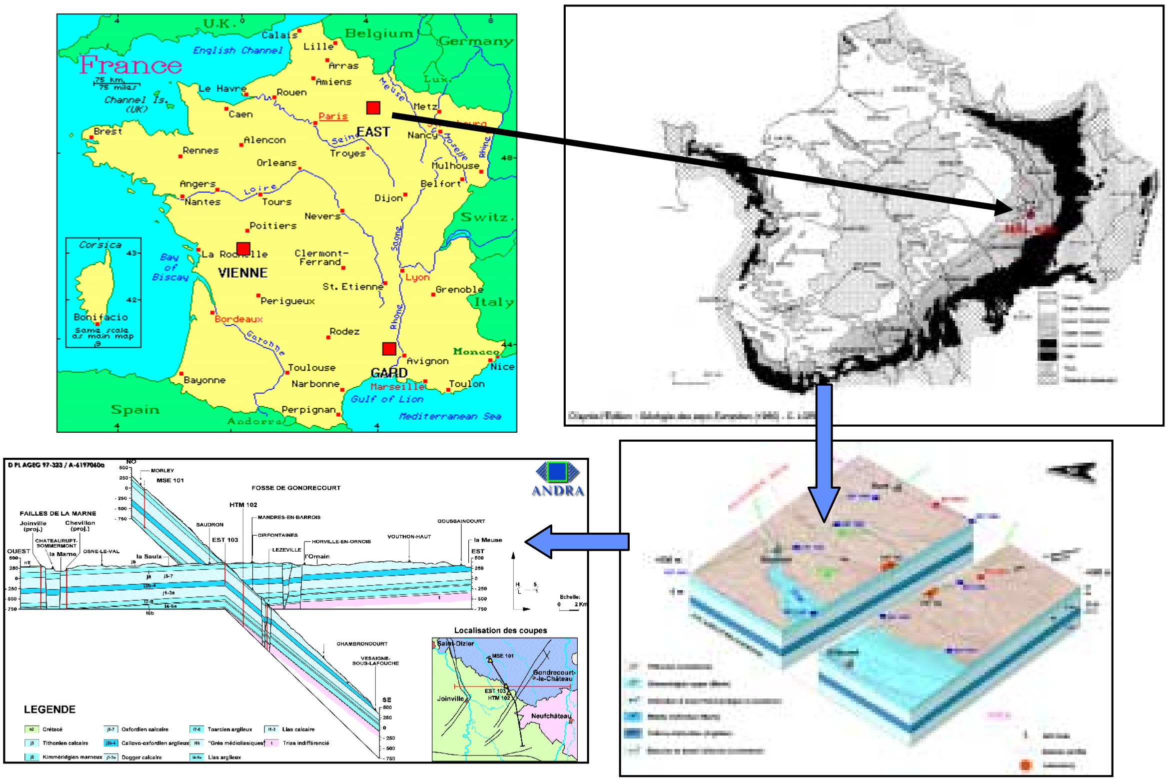
Status of disposal program

The French law of 1991 on managing HLW, ILW, and SF requested that feasibility studies be performed on three possible options: Separation and transmutation, deep geologic disposal, and long term storage. Results of each feasibility study are due by the end of 2005, with an evaluation and decisions pertaining to future work expected in 2006. In preparation of its 2005 feasibility report on deep geologic disposal, Andra presented a first report on the overall approach and methodology in 2001 (Andra, 2001a).

The disposal program is thus currently performing a feasibility study, to analyze if the safety objectives as described in applicable rules and regulations can be met, in the context of a reversible waste management approach. The program is in a conceptual, preliminary design phase, and current design options are selected with an emphasis placed on their simplicity and robustness. These options are not optimized on technical and economical points of view.

The feasibility study addresses all aspects of a repository life time (site characterization, construction, operation and monitoring, and post closure). A site is being investigated in the French "Meuse/Haute Marne" region (Andra, 2001b). It is located in the Eastern part of France, and the intended host rock of the repository is the Callovo-Oxfordien clay layer, as shown in Figure 1. The site has been geologically stable for 10^8 years, and benefits from the absence of significant seismic activity and of major faults. The clay host rock has favourable radionuclide transport properties in a reducing environment, in which transport is expected to be driven by diffusion due to low permeability.

Figure 1. Callovo-Oxfordien Clay layer at the Meuse/Haute Marne site



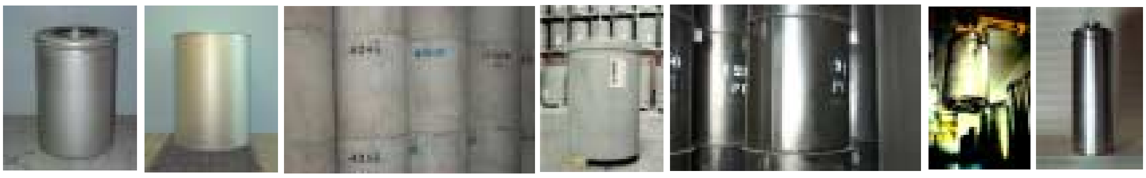
An important input to the feasibility studies pertaining to French waste disposal is the inventory and description of existing and anticipated waste. This task has been completed and is summarized in the "*Modèle d'Inventaire de Dimensionnement (MID)*" (Andra, 2002). It reflects the variety of existing and potential high and intermediate level waste sources, as well as potential spent fuel. To facilitate future analyses and to support the feasibility studies, this waste inventory is grouped into three main categories for Spent Fuel (including five sub-categories of potential spent fuel), five main categories for Vitrified Waste, noted HLW, (including 11 sub-categories), and eight main categories for Intermediate Level Waste (including 46 sub-categories).

The average properties in each category are specified, as pertaining for example to:

- Thermal power generation over time.
- Radiological description.
- Chemical properties.
- Mechanical properties.
- Geometrical description.
- …

The design of disposal over-packs takes into account the diversity of existing primary WPs and waste forms. The design of the disposal facilities and over-pack (see section 5) for HLW benefits from the use of a standardized primary vitrified waste package. The design of a disposal package for spent fuel (see section 6) is directly related to well defined fuel assemblies. ILW, however, comes in a variety of primary WPs, as illustrated in Figure 2. The design of a corresponding over-pack (see section 7) therefore allows for sufficient flexibility to emplace the existing variety of primary package geometries and weight. In order to provide confidence in WDP design concepts, a number of limited demonstration projects are planned with ILW and Spent Fuel.

Figure 2. Diversity of the inventory of the French ILW primary packages



The design requirements for the overall disposal system, as well as specifically for the WDPs, are well established at this stage. They are based on an iterative approach to design, functional analysis, scientific modeling ability, and lessons learnt from safety studies. They are assembled into a set of specifications of functional and technical requirements, which summarise the current status of requirements. This “current” status may evolve in response to the external status of the program, for example as related to decisions of national waste management solutions. They are also very likely to evolve in response to the internal status of the program, to the scientific understanding and modeling capabilities, future design evolutions, or to lessons learnt from future safety and performance assessments.

The design that is being developed for the feasibility study is not necessarily optimized with respect to all technological and economical considerations. It should, however, allow to demonstrate feasibility of the concept in all important aspects. To this end, some high-level design requirements are that the repository concept and design should be simple and robust. In addition, one of the overall design requirements is that the repository architecture be modular, to provide for a flexible waste management, to be able to receive a broad variety of waste types and of Spent Fuel, and in response to safety constraints related to human intrusion. Disposal cells are positioned in horizontal tunnels. In order to benefit from diffusive transport times through clay, these are situated in the center of the host rock layer. Repository architecture and disposal cells are designed to respect, among other things, the overall temperature requirement not to exceed 100°C in the buffer and host rock. This is required to manage current understanding and modeling capability of transport. To manage current uncertainty pertaining to argillite mechanical behavior (related to the extent and impact of an EDZ), two design options are considered for HLW: a horizontal disposal tunnel without or with a surrounding, swelling clay based buffer.

High-level Requirements

Post-closure: Long term safety

Post-operational safety functions of a potential repository are developed consistently with the Basic Safety Rule issued by the French Safety Authority (Rule RFS III.2.f). They address fundamental objectives of repository safety, design concepts related to safety, and the ability to demonstrate safety. Fundamental objectives of the long-term safety strategy include the functional requirements of human and environmental protection from spreading of radionuclides. The strategy relies upon the properties of the chosen repository site, the embedding of the repository in the site, the design of engineered barriers and the quality of their construction.

The rule provides for an iterative approach between knowledge acquisition, design evolution and safety analysis. Among other things, the evolution of the repository must be modeled over the first 10 000 years within a well defined range of uncertainties, as part of a multiple barrier concept. At greater time scales, increasing levels of uncertainty should be dealt with by providing reasonable, conservative estimates. The emphasis is shifted on demonstrating the performance of the geosphere, in combination with EBS tunnel and shaft seals. Improved understanding allows for a gradual development and refinement of specific requirements, increasing detail of design considerations, and improved model representation.

The main functional constraints related to long term safety are:

- Limit and retard transfer of radionuclides.
- Restrict groundwater flow.
- Preserve favourable WP properties.
- Preserve favourable isolation properties of the geo-sphere.
- Respond to human intrusion.
- Respond to internal and external geo-dynamic evolution.
- Take into account potential other hazards.
- Remain sub-critical.

Design specific regulation defined in the rule addresses, among other things, WDPs. Vitrified waste packages should prevent radionuclide release while short- and medium-lived waste products dominate the overall activity, and while environmental (thermal) conditions are susceptible to alter the waste matrix. They should limit any release at greater time scales. ILW packages should limit possible releases in response to potential alternative scenarios, such as including a short-circuit of the geological barrier. The evolution of WDP properties should be understood and modeled over a time frame comparable to the decrease of short- and medium-lived fission products.

These high-level requirements translate into a number of specific design requirements for WDPs. For example, resistance of vitrified WDPs to corrosion and pressure must be guaranteed during the thermal phase, because waste form dissolution rates are not sufficiently well known at elevated temperatures. Similarly, spent fuel must be contained in WDPs until environmental conditions (temperature) allow to demonstrate solubility and sorption properties in the buffer and the near field host rock of the disposal.

Pre-closure: Operational safety

In addition to long term safety requirements, the repository must fulfill a set of functions specific to the operational/observational (pre-closure) phase. The protection of workers and the public (incl. visitors) from nuclear hazards should be ensured during normal and accidental situations. The prevention of radioactive exposure is considered during transfer, emplacement, and until permanent closure of the disposal tunnel. Dissemination of radioactive material is included as a design constraint under normal operating conditions, for example as pertaining to control and filtering of potentially contaminated ventilation air flow. It is also considered as a design constraint related to accidental WP drop, either during tunnel transfer or during transfer from the surface. The design of WDPs and their emplacement in disposal cells should ensure that a sub-critical design configuration is maintained at all times and in all circumstances (including an accidental drop).

The protection of man against non radioactive hazards is similar to that of other mining operations. It includes constraints of safety related to potential fire, hydrogen or other gas related hazards, geo-technical hazards, and handling/traffic/other accidents within the facilities. Fire protection constraints require, among other things, that the design includes alternative escape routes. This requirement needs to be considered in combination with the long term safety requirement of opposing water flow: any additional tunnel must be closed in a manner that overall safety requirements are respected as well. Hydrogen or gas related hazards have their origin in a number of ILW categories generating hydrogen, as well as in hydrolysis and corrosion by-products. ILW disposal tunnels are ventilated to prevent any gas accumulation. HLW and potential SF disposal tunnels are closed upon emplacement of the WDPs. If a return access, for example to retrieve WDPs is required, care should be taken to manage any potentially accumulated and sealed in gases.

The protection of the environment during the operational phase pertains, for example, to the safe management of construction and operation related excavation material. Excavation of a large access and disposal tunnel system may generate unusually large volumes of such excavation material. The option of surface storage at the site may have a substantial impact on the landscape. In addition, potential leaching of groundwater and oxidation of the excavated clay may present an environmental safety constraint to be considered.

Other pre-closure requirements

The principal function of the repository before closure is to receive waste (as inventoried) in the studied clay formation. Associated are the high-level requirements that the disposal facility be able to receive, transfer, and emplace all primary WPs. These functions are to be accomplished while respecting all safety constraints, in the context of a reversible management of the facilities and the WPs.

A number of considerations motivate the requirement of a reversible repository management. These are a consequence of a precaution principle, controlling the evolution of repository management by a stepwise reduction of the level of reversibility, commensurate with parallel, progressive confidence building. Current limits of scientific knowledge impose a level of modesty in imposing long term decisions. It is instead decided to offer a freedom of choice to future generations as pertaining to waste management, and therefore to maintain an open and flexible approach during the operational/observational phase. This approach also maintains the option to address and correct potential errors.

Reversibility translates into a number of technical requirements that need to be considered together with operational and long term safety requirements. To allow for the advocated flexibility, the disposal process is designed to follow a stepwise approach. No a priori time frames are attached to each step: Within reasonable technological constraints as pertaining, for example, to operational safety, the decision on proceeding to the next step is taken when available information is considered to be adequate. It is therefore necessary to include observation of repository evolution in the design, to support confidence building and disposal process management.

Management and Documentation of Requirements

High-level requirements are at the origin of a list of technical requirements applicable to the sub-systems (for example, ILW emplacement facilities, ILW disposal packages…) of a repository. Technical requirements allow to guide the design of the sub-systems. There is no systematic procedure to relate these levels of requirements. Rather, the technical requirements are progressively defined by an iterative process between design, modeling and safety analysis, along with increased knowledge from ongoing site investigations and experimental results as obtained for example in underground research laboratories.

Studies pertaining to deep geologic repositories can only rely on limited, if any related past experience. They benefit, however, from the experience gained in an important number of more or less parallel studies conducted within the framework of varying national programs. Experience building is an essential component in understanding and specifying design requirements. A number of such requirements are clearly understood while design solutions are attempted. In addition, each design includes an extensive interaction between sub-systems, choice of materials, etc., and requirements pertaining to such interactions can only be established interactively with the proposed solutions. Lessons learnt from safety assessments are analyzed and lead to considerations of additional requirements, or may lead to a new balance of performance related requirements imposed on various sub-systems. Finally, limits of scientific understanding restrict the acceptable sub-system environment conditions to a domain for which models are applicable. For example, dissolution rates of glass are more uncertain (high) at higher temperatures. Unless future developments in scientific understanding reduce this uncertainty, it may be necessary to require any dissolution to take place at lower temperatures.

This iterative process is supported by a Functional Analysis (Andra, 2003a). The analysis is a method allowing to determine all functions that a system or its sub-systems should fulfill. This tool helps to ensure that the analysis is conducted in a comprehensive manner, following a systematic procedure to minimize the risk of any remaining gaps in the complete list of requirements. It can therefore be considered as a tool to manage requirements and constraints. It does not, however, substitute for the aforementioned iterative design process. Nor can the method replace the input based on experience, knowledge and creativity.

It is also supported by a process analysis (Andra, 2003b), in which processes governing the evolution of sub-systems or of the repository as a whole is analyzed at various stages of their evolution. This analysis allows for a preliminary determination of what processes govern sub-system evolution, and to identify related uncertainties. Feedback guides design requirements pertaining to the restriction or enhancement of such processes. For example, if re-saturation of a swelling clay based buffer is an advantageous process evolution, design requirements are directed not to oppose such a re-saturation. Conversely, if oxidation in a closed tunnel conflicts with other requirements, a detailed design requirements may be to reduce, as possible, the exchange of air.

Finally, detailed design requirements are identified and evolve as a result of safety analysis. The influence of process uncertainties are analyzed and the results justify any modifications in design requirements.

Integration of information and considerations is an ongoing process. The definition as well as evolution of all requirements is an interactive process which includes contributions from engineering, scientific modeling and safety. To manage the requirements, a specification was established at the current stage of knowledge and development (Andra, 2003c), and was declined as specific to the whole potential repository, its disposal facilities (ILW, HLW, SF), disposal packages, and other sub-systems.

Design of disposal packages for High-level vitrified waste

The need for and technical requirements imposed on the HLW WDP were derived from high level requirements and constrained by the current level of scientific understanding.

The waste form (glass matrix) contributes to waste containment and is an important component of the barrier system. Due to its low dissolution kinetics, controlled by the low solubility of silica in water as well as by the surrounding physicochemical conditions (i.e. water flow, solute transport and retention), the glass matrix strongly limits the release of radionuclides over a very long period. At higher temperatures, however, this dissolution rate increases by one or several orders of magnitude. In addition, the speciation of dissolved radionuclides is not well understand at temperatures exceeding 80°C, and their sorptive properties are unknown above the range of 50 – 60 °C. It was therefore required that no water contact the waste form while temperatures are in this higher range. Given the proposed repository architecture and waste canister density, this requirement applies for on the order of one millennia.

Current estimates of resaturation rates of a waste disposal cell suggest that liquid water will be in contact of the waste package during this period. Under the effect of high levels of radioactivity, the water would undergo radiolysis, and cause a high oxidizing potential on the surface of the waste package. If the primary waste package, made of stainless steel, were to be disposed of directly, the risk of breaching by corrosion after a few decades cannot be excluded. This would result in an early release of radionuclides, accelerated by the still "high" temperature.

To protect the waste form, the choice was therefore made to supplement the primary stainless steel container by an over-pack (Figure 3) that is water tight during the thermal period (defined for this purpose to last on the order of 1 000 years).

Carbon steel and a strong thickness were retained for the over-pack. This material also responds to the requirements of simplicity, in particular as related to its construction and welding, and of robustness, as related to the ability of describing and modeling the corrosion processes. The technical requirements include a corrosion thickness which takes into account the influence of an initially high radiolytic oxidizing potential (reducing conditions will be restored after complete resaturation of the waste disposal cell).

The life time of a water tight WDP is sufficient to avoid any risk of radioactive dissemination in the disposal cells during the pre-closure phase, which facilitates operation near these cells and contributes to requirements related to the reversible repository management (including a potential WDP retrieval).

Figure 3. (a) Primary COGEMA La Hague vitrified waste
(b) Scheme of the vitrified waste disposal package with the over-pack

(a) (b)

Design of Disposal Packages for Spent Fuel potentially disposed

The reasons leading to the requirement of a steel overpack for the SF disposal are similar to those discussed for the HLW. Temperature requirements imposed at the WDP surface limit the values at less than 100°C, which restricts the maximum number of fuel assemblies to four UOX or one MOX per WDP, respectively. Because of the slower thermal decrease of fuels due to the presence of actinides, the required life time of a water tight steel container is on the order of ten thousand years. It should be noted that this life time limits a high radiolytic oxidative dissolution of fuels.

Other requirements and constraints taken into account in the design of the container are:

- An acceptable weight (and dimensions) for WDP transfer, emplacement, potential recovery, with regard to industrial practice (100 to 110 metric-ton maximum considered, including recoverable shielding).
- The prevention of criticality.
- A mechanical strength compatible with the applied load *in situ*.

A demonstration programme of this container is carried out jointly by Andra, the CEA (*Commissariat à l'Énergie Atomique*) and Edf (*Électricité de France).*

Design of Disposal Packages for Intermediate Long Live Waste

The requirement for an ILW overpack (Figure 4) was established primarily to reduce unit flow rates during emplacement operations, by grouping several WPs into a single WDP, and to allow for the use of standardized operations and equipment (in response to the variety of primary WP dimensions and materials).

In response to the high level requirements of long term safety and reversibility, a parallelepiped geometry of the WDPs was chosen. This simplifies the management (emplacement and potential retrieval) of the disposal cells and thus contributes to reversibility. The long term safety requirement to be met is that remaining void space be a volume fraction small enough to prevent any long term damage to the host rock (after loss of structural strength and recompression of void spaces). The shape allows to optimise the use of available volume in the disposal tunnels by minimizing the gaps between disposal packages and thus by keeping the void volume small.

To ensure structural stability and avoid internal overpressures, WDPs containing hydrogen producing waste must be breathing by suitable devices. Any safety requirements related to preventing potential radioactive gas dissemination need to be met by additional safeguards, such as the use of adequate transfer and disposal cell sealing equipment. All other WDPs are designed to seal in gas during pre-closure in order to limit the radioactive dissemination in the installations and to protect against potential radioactive gas releases (tritium, krypton 85, carbon-14...).

Surrounding equipment and the disposal facilities may need to be designed in conjunction with the WDPs to contribute to additional safety requirements. For example, studies are undertaken pertaining to the consequences of a WDP drop or of its exposure to fire. These studies will make it possible to distribute the performances of protection against radiation and safety between disposal packages and installations. Some of the ILW WDPs contain a relatively greater amount of long lived fission or activation products (for example ^{94}Nb, ^{93}Zr, ^{135}Cs), and additional requirements may be identified as pertaining to improved waste containment.

Figure 4. (a) COGEMA compacted hulls and ends caps packages
(b) Scheme of a ILW Disposal Package type under study

(a) (b)

Summary

An iterative procedure to identify and manage design requirements is described in the context of French WDPs. It leads from high-level requirements to component and detailed technical requirements, that are ultimately reflected in the WDP design. Current design proposals, while prone to further evolution, are given within the context of a feasibility assessment of deep geologic disposal of ILW, HLW and SF. Technical requirements and constraints take into account all high level requirements and include the constraints imposed by current limits of technical and scientific knowledge.

Among the high-level requirements considered are operational safety, long term safety, robustness, and the operational flexibility given by a reversible waste management approach. Important design constraints are imposed by the substantial variety of primary WPs and waste forms, by the chosen site and by its hydrogeological, geochemical and geomechanical properties.

Additional, lower level requirements are identified within the context of the repository architecture (thermal load…) and of its main sub-systems (disposal cell design…). These lead to specific low level requirements (preventing water to contact the waste form during the thermal period…), that are translated into technical requirements (WDP integrity taking into account expected corrosion rates and mechanical loads during the thermal period).

The development and management of requirements, as well as their traceability from stakeholder needs to technical requirements, rely on (i) and analytical tool, the functional analysis of the repository and its components (Andra, 2003a), (ii) a database of requirements and their justification (Andra, 2003c), (iii) a process analysis (Andra, 2003b), allowing to derive technical requirements (resistance to pressure…) from the constraints imposed on and/or by system and sub-system evolution (host rock deformation…), (iv) an iterative engineering design process, with subsequent analysis of technical requirements related to the interaction between sub-systems (disposal cell…) and components (WDPs…), and (v) repeated safety analysis, allowing to verify that safety objectives (as derived from stakeholder needs) are met.

References

[1] Andra (2001a) *Dossier 2001 Argile*.

[2] Andra (2001b) Référentiel Géologique. Andra report A.RP.ADS.99.005.

[3] Andra (2002) Projet HAVL Argile – Modèle d'inventaire de dimensionnement (MID). Andra report C.NT.AHVL.02.105.

[4] Andra (2003a) Projet HAVL Argile – Analyse Fonctionnelle Externe. Andra report C.RP.AHVL.00.140.

[5] Andra (2003b) Projet HAVL Argile – Analyse Phénoménologique des Situations de Stockage (APSS). Andra report C.NT.ASIT.03.077.

[6] Andra (2003c) Projet HAVL Argile – Spécification technique de besoin, Exigences applicables à l'ensemble du concept de stockage. Andra report C.SP.AHVL.02.132.

COMPARING TECHNICAL CONCEPTS FOR DISPOSAL OF BELGIAN VITRIFIED HLW

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1. Introduction

The choice of a suitable repository design for different categories of radioactive waste is an important element in the decisional process that will eventually lead to the waste disposal in geological ground layers during the next decades.

Most countries are in the process of elaborating different technical solutions for their EBS [1]. Considering possible design alternatives offers more flexibility to cope with remaining uncertainties and allows optimizing some elements of the EBS in the future. However, it is not feasible to continue carrying out detailed studies for a large number of alternative design options. At different stages in the decisional process, choices, even preliminary ones, have to be made. Although the impact of different stakeholders (regulator, waste agencies, waste producers, research centers, …) in making these design choices can differ from one country to another, the choices should be based on sound, objective, clear and unambiguous justification grounds. Moreover, the arguments should be carefully reported and easy to understand by the decision makers.

ONDRAF/NIRAS recently elaborated three alternative designs for the disposal of vitrified HLW. These three designs are briefly described in the next section. A first series of technological studies pointed out that the three options are feasible. It would however be unreasonable to continue R&D work on all three alternatives in parallel. It is therefore planned to make a preliminary choice of a reference design for the vitrified HLW in 2003. This selection will depend on the way the alternative design options can be evaluated against a number of criteria, mainly derived from general repository design requirements. The technique of multi-criteria analysis (MCA) will be applied as a tool for making the optimum selection, considering all selection criteria and considering different strategic approaches. This paper describes the used methodology. The decision on the actual selection will be made by the end of 2003.

2. The three alternative designs

2.1 Introduction

The Safety and Feasibility Report SAFIR 2 [1], published in 2002, describes the reference design used by ONDRAF/NIRAS in the period 1990-2000. During the redaction of the SAFIR 2 report as well as the preparation of the in situ demonstration project PRACLAY[2], it became clear that the choice of some elements of the EBS was not sufficiently elaborated and that a revision of this reference design would be necessary. A multidisciplinary working group (GTA) consisting of people

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[1] EBS = Engineered Barrier System.

[2] PRACLAY = PReliminary demonstration test for CLAY disposal of highly radiaoctive waste.

from different fields of expertise (technology, phenomenology, performance assessment) was created and this group worked out three alternative designs. These three designs are briefly explained in the next sections.

2.2 The Supercontainer design

The basic aims of this design are:

- To construct the different engineered barriers around the waste as much as possible in above ground conditions, thus facilitating the implementation of a QA/QC Program.
- To enhance operational safety by separating nuclear and mining operations.

The *Supercontainer* design provides radiological protection by means of a radiological shielding which permanently surrounds the waste canisters (see Figures 1 and 2). This is the so-called buffer. The design foresees in the use of an overpack containing two canisters (see Figure 3). For reasons of maximizing the long-term stability of the borosilicate glass matrix in which the waste has been immobilized, crushed glass can be inserted in the space between the canisters and their overpack. For mechanical rigidity, and in order to provide a casting form in the case of a cementitious material, the whole is packed in a metal barrel. Final closure of the *Supercontainer* is performed by welding the cover part to it.

Figure 1. Composition of Supercontainer (axial cross-section)

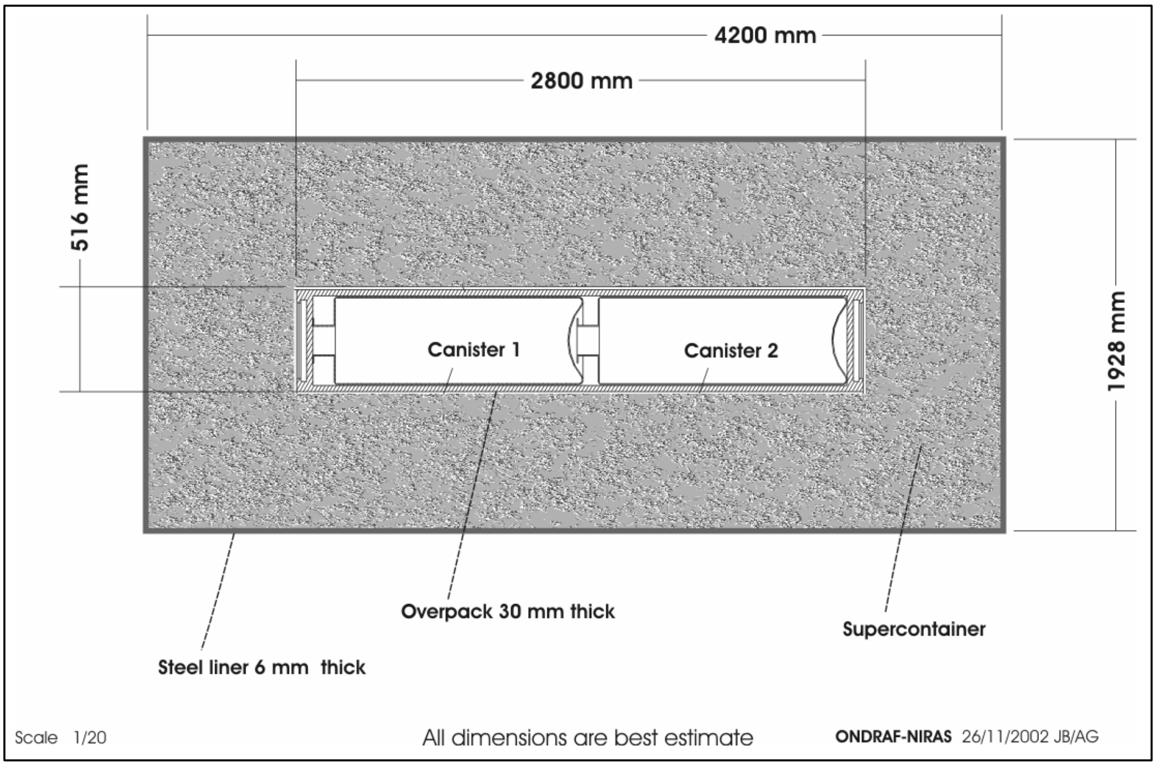
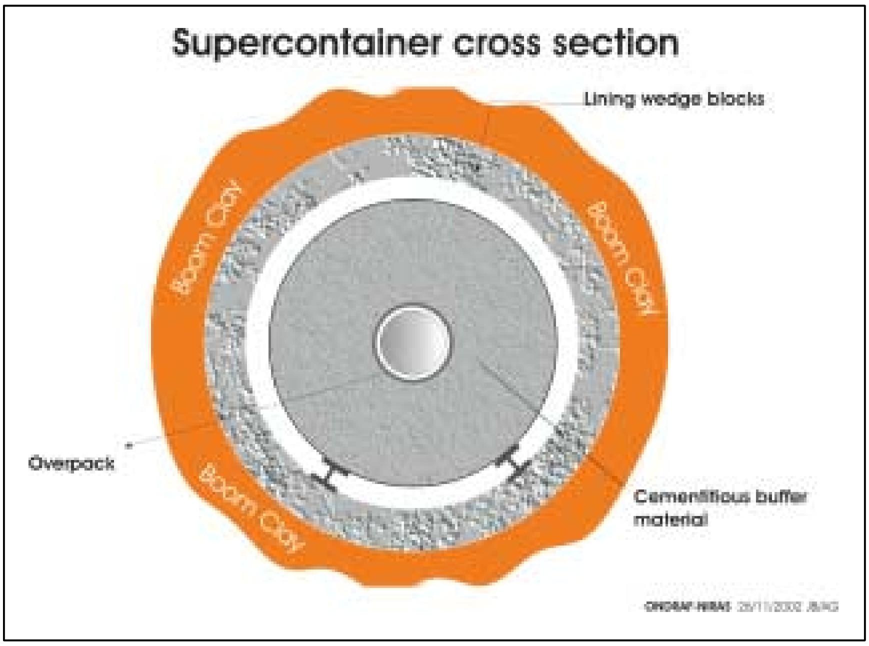
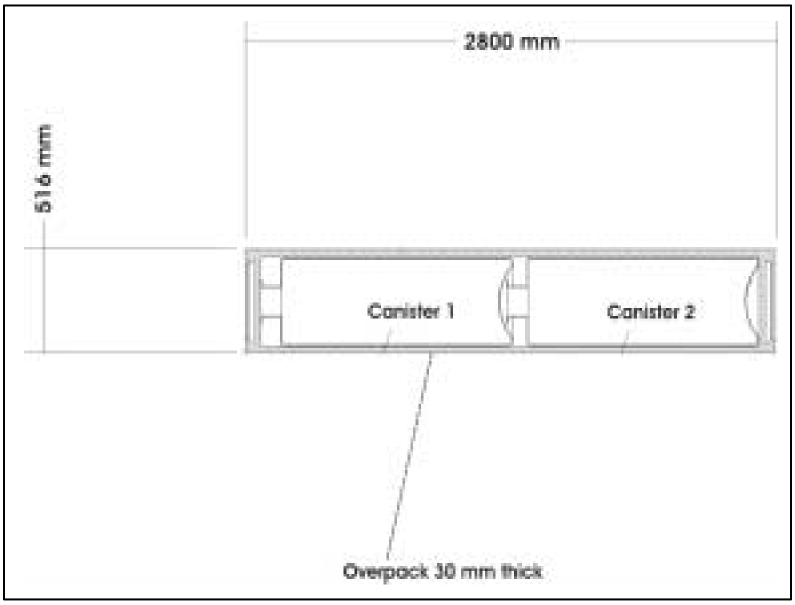


Figure 2. Composition of Supercontainer (radial cross-section)



The choice of the material for the buffer has not yet been made. Nevertheless, some of the main requirements of the material have already been determined. Most importantly, the material should be chemically compatible with the nearest components (i.e. overpack and clay). Further, it should remain stable under high temperature conditions (up to 100°C), have about the same expansion coefficient as the surrounding metal barrel, have a sufficient thermal conductivity, and preferably have a density between 3 000 and 4 000 kg/m^3 (for radiological shielding).

Figure 3. Overpack for two canisters of vitrified waste



Disposal galleries

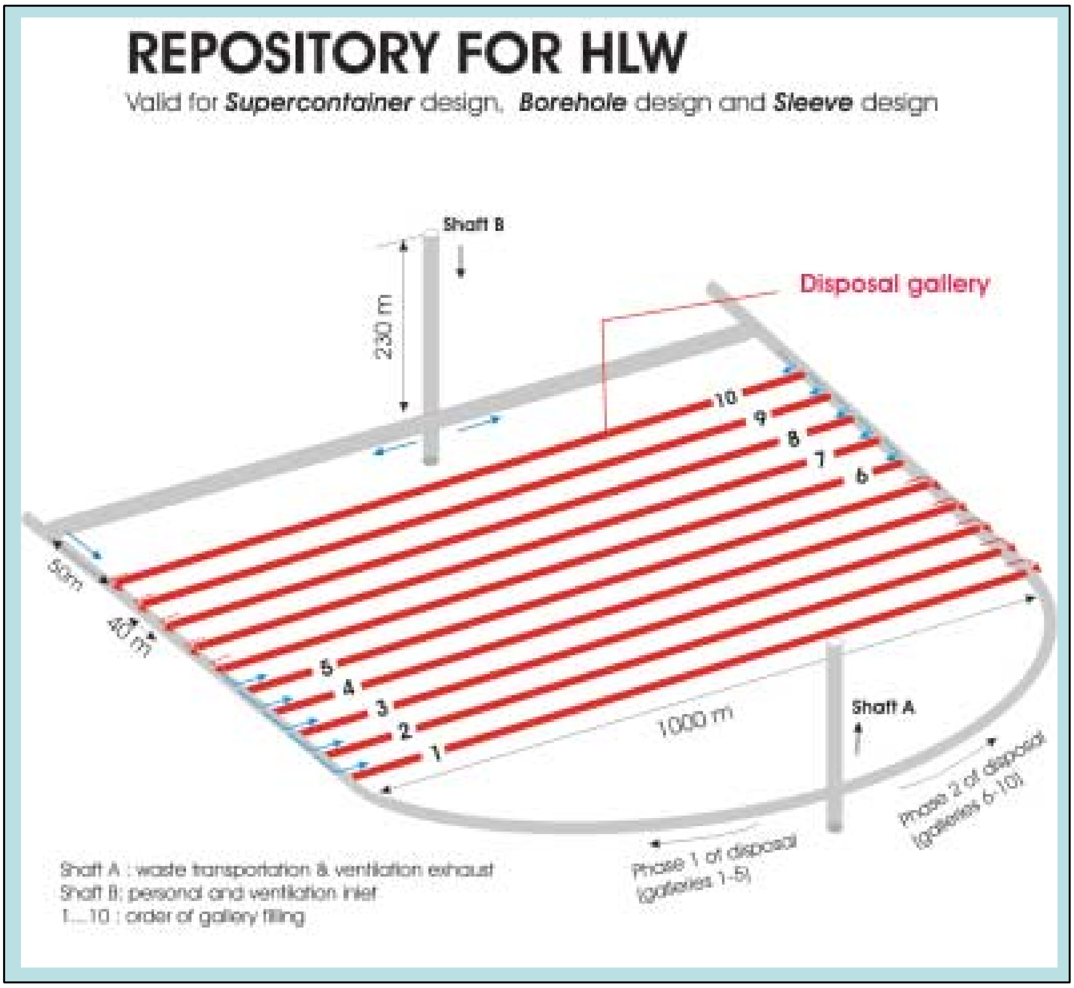
For the *Supercontainer* design, the disposal gallery lining is composed of concrete vault stones (see Figure 2). The vault stones will probably be of the “wedge blocs” type, which were used as gallery lining elements for the connection gallery in the HADES URL, constructed in 2002. These wedge blocs are prefabricated, non-reinforced concrete ring elements which are placed against the excavated gallery wall with special mechanical equipment. Key wedge blocs, inserted with a certain pressure as a last step, provide the necessary expansion force to keep the ring elements in place.

The diameter of the disposal galleries is 2.5 m. Sufficient space between the outer radius of the *Supercontainer* and the concrete walls should be provided, thus allowing an easy movement of the *Supercontainer* through the length of the disposal gallery.

No decision has yet been made on the means by which the *Supercontainer* will travel through the transportation gallery and disposal gallery. Possibilities are movement on rail, movement on an air cushion or a combination of both.

Figure 4 shows the general layout of the envisaged system of galleries.

Figure 4. Repository lay-out: valid for 3 designs



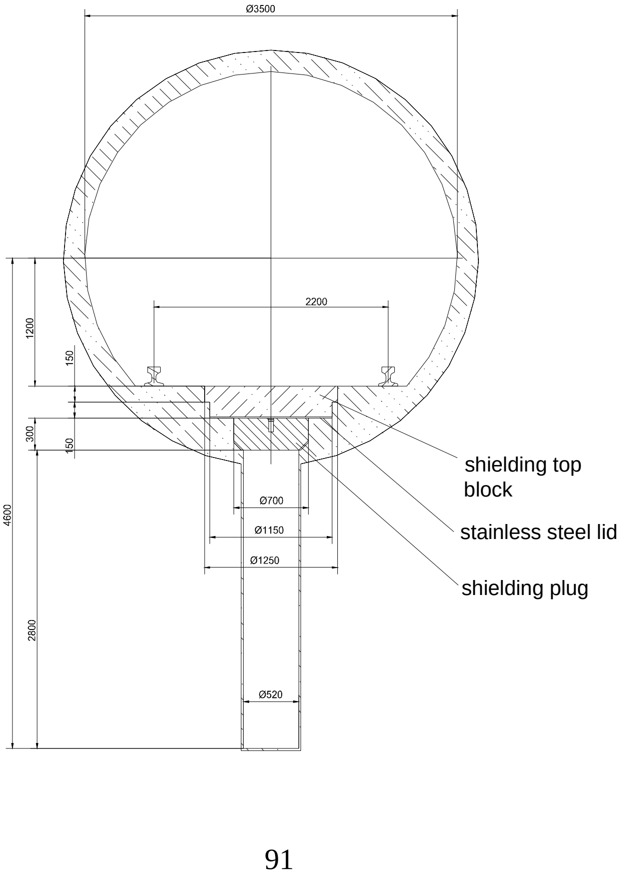
Once a disposal gallery has received all its *Supercontainers*, the space between the concrete wall and the *Supercontainers* may eventually be filled with backfilling material. No decision has yet been made on this subject.

2.2 The Borehole design

A second alternative is the *Borehole* design. Next to providing radiological protection, the main aim of this design is to keep the system of engineered barriers around the waste packages as simple as possible. This is justified by the consideration that the Boom Clay layer is the main component in the disposal system from a radiological safety point of view. One engineered barrier is however needed from a safety point of view, namely the overpack around the waste canister. The Borehole design is inspired by the KBS-3 design used in Sweden and Finland for the disposal of spent fuel in granite formations.

In the Borehole design, the waste packages are transported through the main and disposal galleries to the place where they will be deposited. The disposition of the waste occurs in holes drilled perpendicular to the centerline of the disposal gallery and only long enough to fit one package of waste. These are the so-called boreholes. After drilling, the boreholes are immediately equipped with a stainless steel liner, thick enough to withstand the forces exerted by the surrounding clay. The distance between the centerlines of the different boreholes of one disposal gallery has preliminary been set at 5 m, with the aim of limiting the maximum near field temperature to 100°C. Figure 5 gives the design layout for a vertical borehole. Like the *Supercontainer* design, the *Borehole* design foresees in a waste package containing two canisters (see Figure 3).

Figure 5. Borehole design



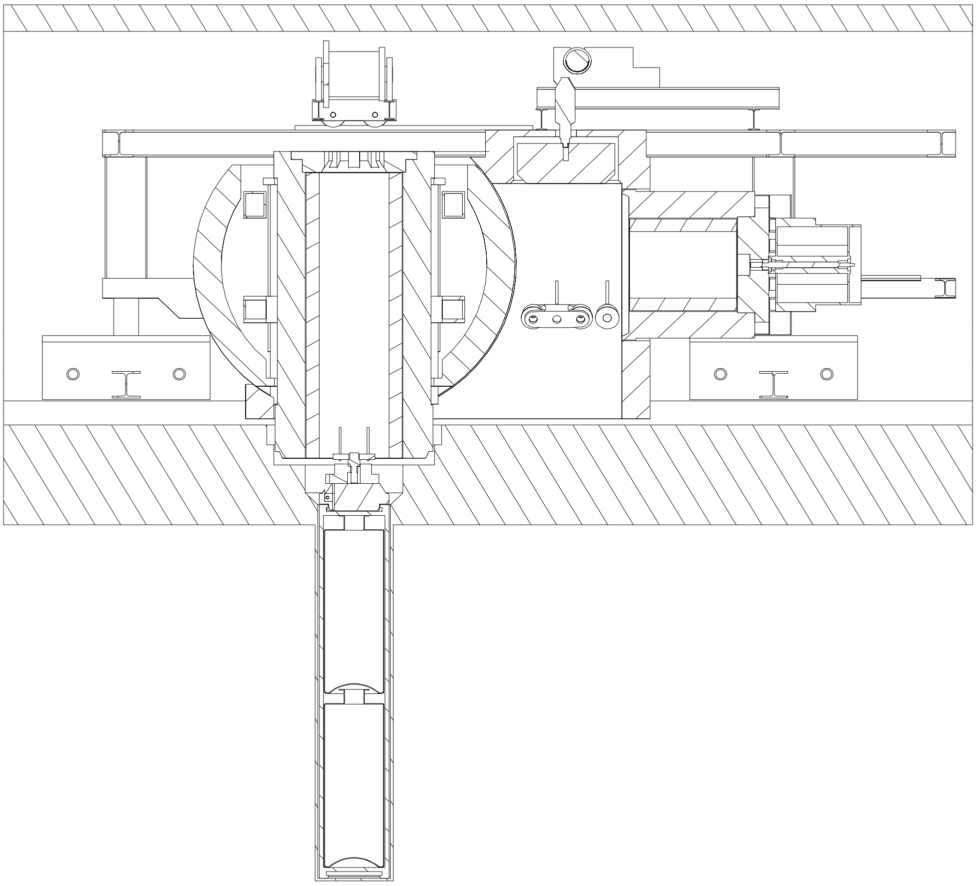
The disposal gallery lining is composed of concrete elements. At the bottom is a circular opening, which gives way to the borehole. The actual room for disposition of the waste overpack is the above mentioned metal liner fit into the borehole and fixed to the concrete bottom of the disposal gallery. The inner diameter of this liner is somewhat larger than the outer diameter of the overpack. After the waste has been disposed, the borehole is closed off with a plug of radiological shielding material. On top of this plug then comes a lid in stainless steel, followed by a concrete block which is even with the floor of the disposal gallery.

An alternative configuration exists in the construction of two horizontal boreholes instead of one vertical borehole. The horizontal boreholes are located at equidistant intervals and in an alternating left/right sequence with respect to the disposal gallery.

The overpack will be placed into the borehole by a specially designed machine, which will incorporate a radiological shielding, to allow underground workers to perform repair works in case of breakdown when loaded with an overpack.

Figure 6 gives a general idea of the how this machine would work.

Figure 6. Deposition machine



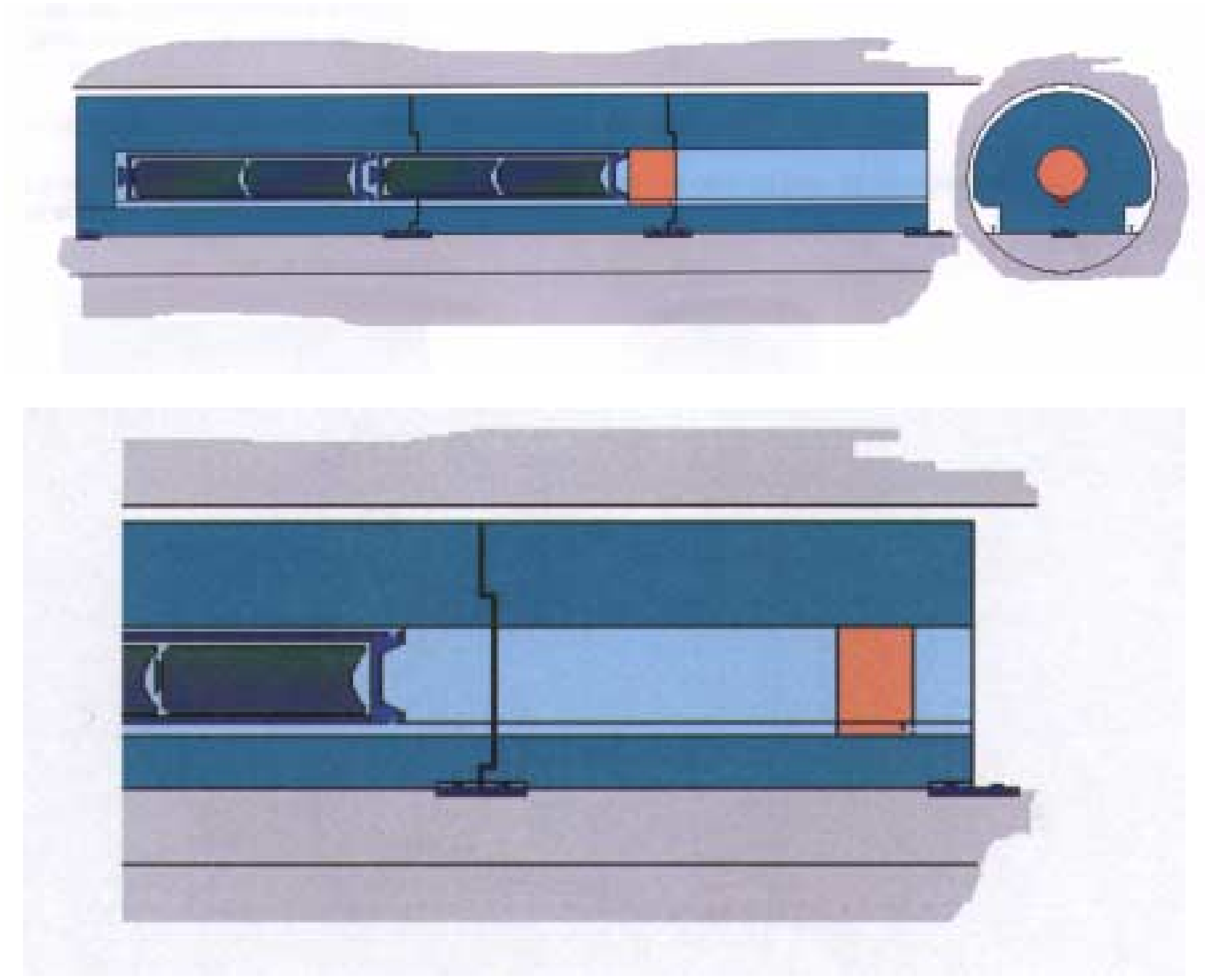
No decision has yet been made on the means by which the overpack will travel through the transportation gallery and be handed over to the disposal machine in the disposal gallery. Possibilities are movement on rail, movement on an air cushion or a combination of both.

2.3 The Sleeve design

A third alternative design is the *Sleeve* design. Next to providing radiological protection, the main aim of this design is to minimize the perturbation of the host rock.

In the Sleeve design, the waste packages are disposed within concrete sleeves lying in the disposal gallery. Each concrete sleeve contains one package of waste. This concrete sleeve is installed in the disposal gallery just before the waste package is inserted. Each new concrete sleeve is aligned against its predecessor by means of a key stone. A shielding plug closes off the already disposed waste in the gallery and thus provides radiological protection. The plug is removed before the arrival of each new waste package, and put back in place after the waste package is inserted. Figure 7 depicts the basic principle of the *Sleeve* design and the shielding plug.

Figure 7. Sleeve design



Like with the *Supercontainer* and Borehole designs, the Sleeve design foresees a waste package containing two canisters (see Figure 3). Eventually, if the overpack with two canisters would prove to be impractical, the number of canisters can be reduced to one.

The design layout of the galleries is the same as for the *Supercontainer* and the Borehole designs (see Figure 4).

3. Multi-criteria analysis

The selection among the three above described design options will be made based on the way the alternative design options comply with a number of criteria set forth by the GTA working group. An important basis for these criteria are the general repository design requirements, summarized in SAFIR 2 [1] and further elaborated for design purposes in the GTA interim progress report [2].

The selection is not only a matter of best compliance with the design requirements, but is also a matter of strategy, i.e. preference for specific qualities. The selection of the optimum design is therefore not obvious. A solution to this kind of decision-making problems can be provided by applying the technique of multi-criteria analysis.

A multi-criteria analysis is based on the evaluation of the alternative options against a set of clearly-defined criteria. It can be done according to the following steps:

1. Definition of the different options.
2. Establishment of a list of criteria that are:
   - Comprehensive i.e. encompass all significant aspects of the problem.
   - Discriminatory it does not make sense to use criteria with which all options comply in the same way.
   - Focus on a specific aspect and be unambiguously defined.
   - (Preferably) without interdependence or overlaps; the existence of strong links between criteria may falsify the weighting factors attributed to the criteria since then the same parameter is accounted for more than once. The analyst should verify the existence of these links and decide how to take account of them.
   - Attribute weighting factors to the different criteria, according to a possible strategy. Several different strategies may be considered.
3. Attribute scores against each criterion for each option. A score is made on a scale which may be verbal or numeral. This score is then converted to another value by means of a linear or non-linear function. This is called “mapping”.
4. Multiplication of the mapped values by the specific weighting factors.
5. The best option (according to a certain strategy) is the one with the highest sum of the mapped and weighted (according to a certain strategy) scores. This sum is called the total benefit of an option.

4. Definition of criteria and weighting

4.1 Repository requirements

In [1], a comprehensive set of requirements for a geological repository has been defined. For ease of reference, the Table 1 provides a summary of these requirements.

Table 1: Schematic overview of SAFIR 2 General Requirements

Requirement name	Explanation
Long-term radiological safety	The safety functions (C = *Physical containment, R = Delay and spread releases, D = Dilution and dispersion, L = Limited access*).
Robustness	A measure of the independence of the true functioning of the repository.
Operational safety	Safety for workers and members of the public during the phases of construction and operation of the repository.
Nuclear safeguards	Subcriticality and non-proliferation.
Environmental protection	The repository may not: • give rise to the release of (non-radioactive) toxic chemicals to the biosphere, • cause excessive temperature increase in the surrounding aquifers used for drinking water.
Flexibility	The design must allow for easy adaptation (incl. reversibility) of the organisation of the construction and operation of the repository in case of new types of waste or post-conditioning methods.
Feasibility	• Technical feasibility : – prefer the use of proven technology, – maximize imposition of a QA/QC programme to all aspects of the construction and operation of the repository • Financial feasibility is relative to the acceptability to political authorities and sponsors of the total cost (money).
Retrievability	The ability to safely withdraw waste from the repository, during the time period from the filling of the disposal gallery until the filling of the main gallery. Before that period, this requirement is part of the flexibility requirement. After that period, retrievability is assumed to be not applicable.
Boom Clay requirements	• The characteristics of the host rock may be perturbed as little as possible. The disturbance can be caused by: – excessive heat injection by the waste, – build-up of gas from EBS corrosion, – chemicals out of the EBS (alkaline plume) – roughness of excavation techniques The repository should exhibit maximum adherence to the Boom clay layer median plane, with minimal extension in the vertical direction.
Quality control in R&D	Is relative to the way in which R&D is performed (includes aspects such as Knowledge Management and Peer Review). Since all designs are investigated according to the same quality standards, this requirement is not discriminatory and thus not applicable to our task.

4.2 Comprehensiveness

In order to be comprehensive, the selection criteria should be established based on the above repository requirements. However, these requirements cannot be directly used in the multi-criteria analysis because they are not formulated in a suitable way. The formulation of a criterion should focus on a single specific aspect and should be described in an unambiguous manner. Moreover, the formulation should be such that there are little or no overlaps or direct correlations with any other criteria, because this could falsify the weighting factors attributed to the criteria.

A precise description of each proposed criterion, together with its units of expression is provided by Table 2. Preferably, the evaluation of an option with respect to a certain criterion is made in real world units, since this is the most objective way. If verbal evaluation needs to be made, then this is done on a 1 to 5 scale as follows:

- if quality-related (e.g. "facility"): poor – fair – medium – good – excellent
- if "extent", or "size": very small – small – medium – large – very large

It is important to mention that requirements that have to be fulfilled in any case cannot give rise to a criterion. A good example is the requirement that the steel overpack around the waste canisters should confine the radionuclides during the full thermal period. This requirement is a "must", so a design not complying with this requirement is eliminated even before carrying out a multi-criterion analysis. However, if the overpack fulfills the confinement function much longer then strictly required, then this can be considered as a reserve ("nice to have") and this safety "reserve" can be used as a criterion (see criterion # 1 in table 2).

Table 2: Identification and description of the selected criteria

#	Criterion name	Definition	Units of expression	Most relevant lifetime phase
1	C reserve C = containment	Estimated time period that the C-function of the overpack will remain beyond the minimum requirement of 500 years for ZAGALC	resulting duration of function (5 ranges)	design (performance)
2	R1 reserve R1 = difficulty of leaching	Estimated time period that the R1 function of the glass matrix will remain effective beyond the minimum requirement of 10 000 years.	resulting duration of function (5 ranges)	design (performance)
3	R2 performance by the EBS R2 = diffusion and retention	The ability of the EBS to delay and spread the release of radionuclides.	poor…excellent	design (performance)
4	Gas generation	The maximum release rate of corrosion product gases (essentially H_2) within the EBS, which could perturb the host rock characteristics	corresponding overpack corrosion rate (µm / year)	design (performance disturbance)
5	Chemical compatibility (with host rock)	The chemical compatibility of the EBS (essentially the buffer material) with the host rock, to not perturb the host rock characteristics	poor…excellent	design (performance disturbance)

#	Criterion name	Definition	Units of expression	Most relevant lifetime phase
6	EDZ	The expected thickness of the Excavation Disturbed Zone (geomechanical zone of plastic deformation) surrounding a disposal gallery.	m	design (performance disturbance)
7	Loss of clay layer (thickness)	The longest vertical distance, within any disposal gallery cross-section, from the gallery centerline to the highest point of the excavated contour.	m	design (performance disturbance)
8	Repository size	The spatial magnitude of the repository layout when projected to the ground surface	circumference of layout (km)	siting
9	Proven technology	The extent to which techniques are applied that have proven their effectiveness in the industry.	small…large	licensing (tech. feasibility)
10	QA/QC implementation (facility)	The easiness with which QA/QC procedures can be implemented. This is essentially linked with the extent to which operations can be performed above ground.	poor…excellent	licensing (tech. feasibility)
11	(natural and/or archeological) analogues	The level of confidence in a repository design provided by the existing natural and/or archeological analogues.	poor…excellent	licensing (assessment)
12	EBS characterization (facility)	The level of understanding of the features, events and processes of the EBS.	poor…excellent	licensing (assessment)
13	Flexibility	The flexibility of the organization of the repository construction and/or operation in case of new types of waste or post-conditioning methods.	poor…excellent	construction
14	(repository) construction cost	The estimated cost to construct the post-conditioning building and the waste repository.	10^6 EUR-2003	construction
15	Handling complexity	The level of complexity of the handling operations needed to transport the waste package from the post-conditioning building to its location of disposition.	poor…excellent	operation
16	Deposition rate	The rate at which waste packages are emplaced at their location of disposition in the repository (minimum 4 canister per 8 h working day)	# canisters per day	operation
17	(repository) operation cost	The estimated cost to emplace all waste packages at their location of disposition in the repository and to fill all disposal galleries.	10^6 EUR-2003	operation

#	Criterion name	Definition	Units of expression	Most relevant lifetime phase
18	Backfilling (facility)	The facility with which the backfilling material can be put into place in the disposal galleries.	poor…excellent	post-operation
19	Retrievability	The ability to safely withdraw waste packages from a backfilled disposal gallery, with the main gallery still free.	poor…excellent	post-operation

4.3 Weighting factors

After defining the different criteria to be used in de MCA, a suitable weighting and scores should be attributed to each criterion.

The scores should be attributed by experts for the given criterion. For instance, the score for the criterion "reserve on containment function" should be given by an expert in long-term corrosion behavior of the steel overpack, whereas "handling complexity" is a criterion more likely to be evaluated by a mechanical engineer.

The weighting, attributed to each criterion can differ from one person to another and reflects to some extent the specific strategy followed by that person.

These weighting factors can be attributed according to the following principle:

- criterion is considered to be of top importance: give weight between 100 and 85;
- criterion is considered to be of importance: give weight between 65 and 35;
- criterion is considered to be of minor importance: give weight between 15 and 0.

ONDRAF/NIRAS asked the working group GTA, representing people from different fields (technology, performance assessment, phenomenology) to attribute their weighting for each criterion. This GTA weighting reflects the opinion of a wide group of different experts and can be considered as very relevant.

4.4 Strategies

Three different strategies will be considered:

1. **Engineer's point of view** (emphasis on practical implementation)
   The engineer will highly appreciate aspects that facilitate practical implementation (flexibility, use of proven technology, backfill facility) and augment reliability (QA/QC, handling simplicity). At the same time, the engineer will want to maximize the performance of the repository design (high engineered robustness, small host rock perturbation), but at an affordable price (cost). Applied to criteria mentioned in the table 2, criteria n° 9, 10, 13, 15 and 18 will be highly quoted by this approach.
2. **Safety analyst's point of view** (emphasis on scientific demonstration of safety to the authorities)
   The safety analyst will highly appreciate aspects that will facilitate demonstration of safety to the authorities (EBS modeling, use of proven technology, QA/QC). At the same time, the safety analyst will want to maximize the performance of the repository design (high engineered robustness, small host rock perturbation), provided it is not excessively expensive (cost). For a Safety Case, the availability of natural and/or archeological

analogues will be valued. Applied to criteria mentioned in the table 2, criteria n° 1 to 7 and 9 to 12 will be highly quoted by this approach.

3. **Political authority or sponsor's point of view** (emphasis on confidence-building of safety with the public and financial aspects)
   The fact that costs can be kept low is an aspect that will be highly appreciated by the political authorities. The political authorities will also be highly appreciative of aspects that facilitate demonstration to the public that the repository is safe (analogues, proven technology) and that there is a possibility for a way back (retrievability). Both the political authorities and the sponsors will want to avoid technical problems during the operating phase (QA/QC, low handling complexity) and keep the duration of the operating phase as short as possible (depends on deposition rate). Applied to criteria mentioned in the table 2, criteria n° 9, 10, 11, 14, 15, 16, 17 and 19 will be highly quoted by this approach.

5. Conclusions

ONDRAF/NIRAS recently developed three alternative designs for a repository for vitrified HLW. In order to be able to choose among these different design options, firstly a thorough analysis of the repository requirements and functions was carried out. These requirements gave consequently rise to the identification of a number of different selection criteria.

A multi-criteria analysis technique will be used to help finding the optimum design according to a certain strategy, based on a set of weightings for the selected criteria.

By using this technique, the different components and functional requirements of the EBS have to be carefully identified. The MCA methodology also contributes to the justification of the choices and to the traceability of the different stages in the decisional process.

Finally, it should be underlined that this multi-criteria analysis is only a tool to help tracing and making decisions on a sound and objective basis but it should be used with care because some relevant aspects, which might be quite difficult to assess, are possibly not taken into account.

References

[1] NIROND 2001-05 E, "Technical overview of the SAFIR 2 report", December 2001

[2] NIROND 2003-01, "EBS architecture for disposal of cat. Band C waste in Boom Clay", dated February 2003.

REPOSITORY SEAL REQUIREMENTS AND DESIGN

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1. Introduction

As a result of history Germany owns two repositories, Konrad and Morsleben, in deep geological formations licensed for LILW and one exploration mine, Gorleben, for investigating the site's suitability to erect a repository for HLW/SNF and heat generating ILW. Due to political decisions, exploration at Gorleben is interrupted presently and no waste emplacement takes place in any of the LILW repositories. The Morsleben repository for LILW now is under licensing for closure.

To assess long-term safety of the repositories different safety strategies were applied linking site independent high level requirements to site specific conditions, constraints, and boundary conditions due to the type and amount of waste to be disposed of. Using the closure of the Morsleben repository as an example different safety strategies are shown leading to different technical closure concepts and multi-barrier systems. Evaluating these different closure concepts on a conceptual level qualitative criteria may be applied first, followed by performing a provisional safety assessment being quantitative approaches for deriving a first set of safety related quantitative requirements concerning the multi-barrier system and assuring that high level requirements are fulfilled. On this basis engineered barrier design is drafted and a set of criteria for evaluating their first design qualitatively is given. When assessing single barriers quantitatively to show their compliance with the derived requirements reliably, increasing knowledge in verifying the multi-barrier system as well as single barriers leads to changes of derived requirements and modifications of technical solutions regarding the engineered barriers. Within the repository project derived requirements are documented as well as design decisions. To guarantee traceability of requirement evolution and design decisions quality assurance measures are applied. However, today they solely allow traceability, active management is not possible. Finally, a brief description is given of how engineers, scientists and safety assessors having worked together up to now and their role within the projects at different project stages. A systematic approach to integrate information from engineers, scientists and safety assessors has not been applied until now. Integrating information within a repository project is a question of applying quality assurance from the start of the project.

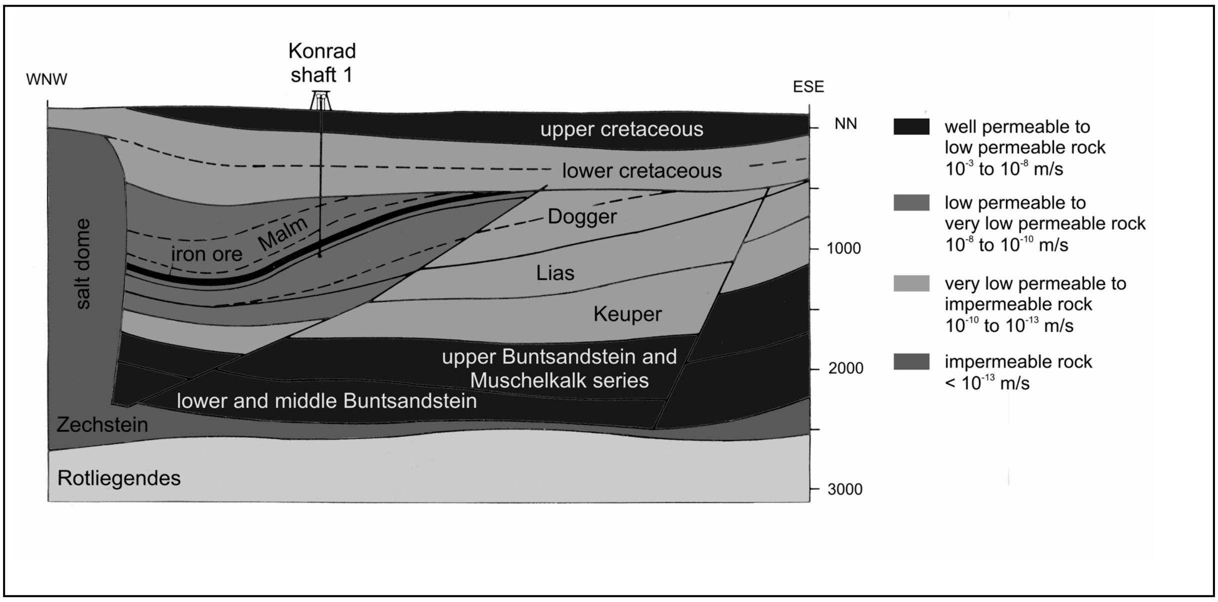
2. Disposal programme status

In Germany final disposal of all kinds of radioactive waste is provided in deep geological formations [1]. Near surface disposal facilities are not regarded in the final disposal programme. Due to German reunification in 1990 the disposal programmes of the former GDR and former West Germany were combined. Therefore, the disposal programme status in Germany is complicated and heterogeneous. Additionally, the Atomic Energy Act [2] was modified recently influencing the German disposal programme status and progress. Politically it was decided to look for alternative disposal sites suited for the disposal of all kinds of radioactive waste in one repository. To improve understanding of the present disposal programme status a brief historical overview is given next.

When starting civil use of nuclear energy in West Germany it was intended to create a so-called closed fuel cycle. i.e. to burn enriched fuel in PWR and LWR reactors and to use the fast breeder reactor for fuel production. Spent fuel was planned to be reprocessed until the fuel was burnt completely. Thus, the first disposal programme for HLW was focussed exclusively on reprocessing waste.

In 1975 in West Germany it was decided to investigate the Konrad mine for its suitability to serve as a final repository for LLW and ILW with negligible heat generation [3]. At that time the Konrad mine was an iron ore mine which was planned to be closed in 1976. This mine showed very dry mining conditions due to a large clay layer above the potential host rock formation which consists of Korallenoolith (Figure 1). Further investigations showed very slow groundwater movement at the planned repository depth. Groundwater ages were determined to several million years and a long-term safety analysis showed that an earliest possible release of contaminated water to the biosphere must not be considered before 300 000 years [3]. In 2002 the Konrad repository was licensed after an approval procedure lasting 20 years. Presently, three communities and one individual brought an action against the license and now the legality of the license is proved by court. To license a final repository in West Germany the performance of a plan-approval procedure is stipulated. In the context of the plan-approval procedure measures for repository closure must already be described, e.g. the shaft seals in the case of the Konrad repository. Because the focus of this paper is on engineered barriers in salt formations and because the main safety relevant engineered barrier are the shaft seals the EBS system of the Konrad repository it will not be viewed at in detail further on.

Figure 1. Local geology of the Konrad repository



To dispose of HLW/SNF and heat generating ILW it was decided to excavate a new mine in a virgin salt formation far from existing mining cavities. In West Germany salt formations in northern

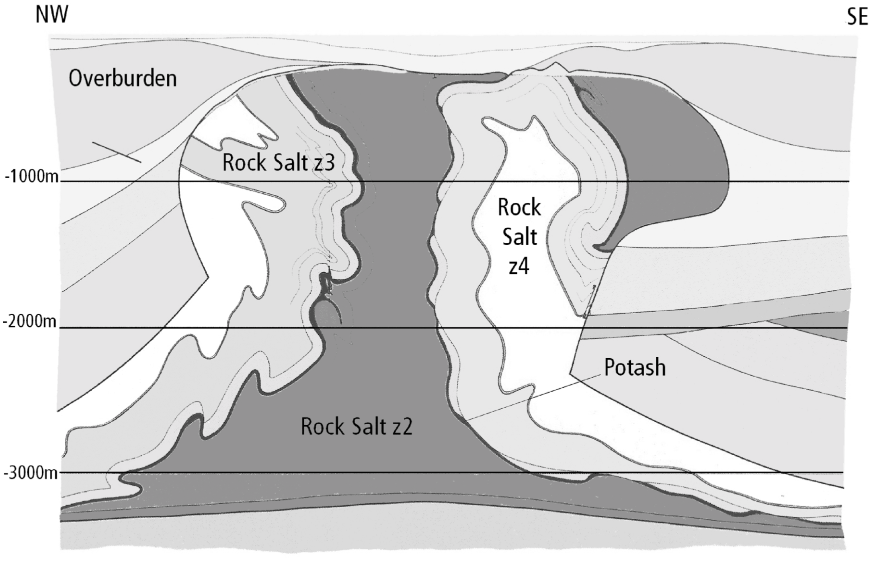
Germany were regarded being suited to emplace heat generating HLW and ILW due to several favourable properties fulfilling stipulated siting criteria:

- Absence of water within a geological time period shown by the existence of salt.
- Tightness of undisturbed salt host rock against salt solutions (permeability to gas < 10^{-21} m^2 disconnected pore space).
- Creep behaviour closing cavities and voids induced by mining activities and healing capacity eliminating fractures with increasing time.
- High thermal conductivity.
- Simple mining conditions and large experience in salt mining.
- Abundance of salt in northern Germany.
- Existence of stable geological conditions in northern Germany with negligible seismic activities.

By the way, in Germany the disposal of high (chemical-)toxic waste is restricted by the regulatory framework to deep salt structures because of their tightness and the absence of water [4].

In 1977 the Gorleben site was selected among four sites as a possible candidate site for an HLW repository. Geologically, the Gorleben salt formation is classified as a salt dome. In 1979 exploration of the Gorleben salt dome started using surface seismic investigation methods and drilling exploration boreholes. In 1986, with the shaft sinking process, it was started to explore the salt dome from underground. In 2000 the first exploration segment was nearly finished, when exploration was interrupted due to a political decision [5]. Since October 2000 there has been no further exploration activity in the Gorleben salt dome. An overview of the present status of exploration of the Gorleben salt dome is given in Figure 2. Because it has not yet been decided whether it will become a repository in future, the exploration activities were licensed according to the Federal Mining Act and related ordinances [6,7]. An official approval of a plan according to the Atomic Energy Act will be necessary for licensing the mine as a disposal facility for radioactive waste.

Figure 2. Local geology of the Gorleben site (present state of exploration)



Another decision of the past is of relevance today. It was decided to distinguish strictly between research activities and the site selection of a future repository. Thus, research activities in the context of HLW disposal were performed in the Asse research mine, which is located in a former salt and potash mine close to the village of Remlingen. The Asse research mine served as URL from 1967 until 2002, when the underground activities of the BAMBUS large scale heater test [8] were terminated. Now it is not permitted to start new research projects in the Asse research mine, because it becomes backfilled due to increasing stability problems in some parts of the mine caused by former mining activities.

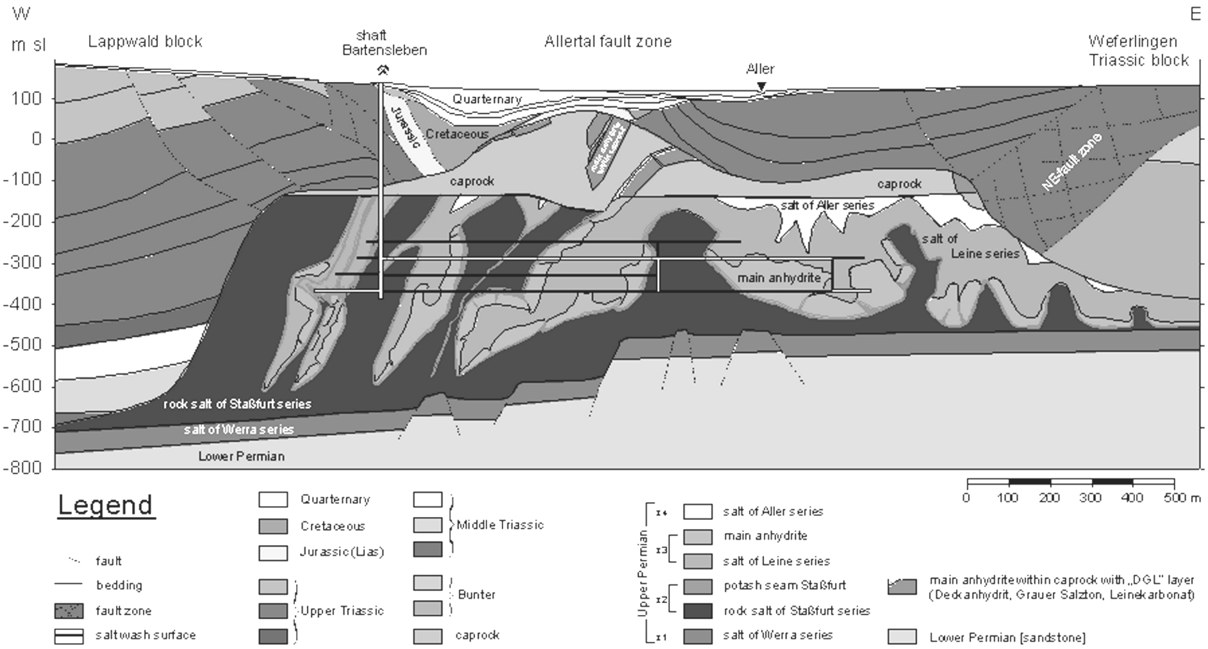
In the former GDR disposal of HLW was not taken into account because fresh fuel for nuclear power plants was received from the former Soviet Union on a leasing basis and spent fuel was taken back for reprocessing. However, it should be kept in mind that spent fuel from the former GDR plants is now available in German interim storage facilities. This fuel could not be sent to Russia anymore after the former Soviet Union had dissolved.

Due to the situation in the past, only LLW and ILW were regarded in the disposal programme of the GDR. Among 10 sites the former rock salt and potash mine Bartensleben was selected to serve as an LILW repository in 1970. Located close to the village of Morsleben the facility was named "Morsleben Repository for Radioactive Waste (ERAM)". A first operation license for five years was granted in 1981 from the former GDR following a phase of design, construction and commissioning of the repository between 1972 and 1978. After having demonstrated successfully the disposal technologies applied waste emplacement started in 1978. A further permanent operation license, issued in 1986, allowed disposal for unlimited time. However, the license of the Morsleben repository did not include the license for repository closure. After German reunification in 1990 the Morsleben repository became a federal repository in Germany and BfS took on the responsibility for repository operation supported by DBE as main contractor. According to the Atomic Energy Act a license application for repository closure had to be prepared by BfS.

In this deep geologic repository different categories of LLW and ILW as well as sealed radiation sources were routinely disposed of until 1998. The Administrative Court competent for the site ruled on September 25 of that year to stop waste disposal in the new chambers of the so-called eastern field as a temporary measure to protect the rights of one opponent to site operation who had filed suit until her complaint had been resolved by the court. BfS then ordered the suspension of all other disposal operations until a final court ruling reassured the site license status. The last waste disposal operation was carried out on September 28, 1998. The new Federal Government resulting from the federal elections held in October 1998 later decided never to reassume waste disposal. BfS issued a corresponding statement on April 12, 2001. The site will be completely decommissioned and closed down.

Presently, the closure of the Morsleben repository is being planned. An overview to the geological situation of the Morsleben repository is given in Figure 3.

Figure 3: Local geology of the ERAM



3. The relationship between requirements and the safety strategy adopted

In Germany final disposal of radioactive waste in deep geologic repositories requires the use of a multi-barrier system to protect human health and the environment against injuries from radionuclide release [1]. The multi-barrier system consists of natural (geologic) and engineered barriers. Retrieveability of radioactive waste is not provided.

Basic site independent requirements the safety strategy must comply with are given by the legal framework. They are given in the following:

To license a repository for radioactive waste in Germany radiological safety has to be shown in the operational period as well as in the post closure period. The yardstick to rate radiological safety is given by the Radiation Protection Ordinance [9]. An individual dose rate of 0.3 mSv/a must not be exceeded. Not complying with the ICRP recommendation to use a dose upper bound in the case of a normal repository evolution and a risk upper bound in the case of a disturbed repository evolution [10] no risk upper bound is fixed in Germany. The dose rate must at no time be exceeded unlimitedly [11].

Additionally, conventional safety goals defined by the Water Protection Act [12] and the Federal Mining Act [6] must be regarded. They are of the same importance for licensing as the radiological safety goal.

It can be summarised that requirements directly related to the protection of human health [9] and the environment [6], [12] must generally be fulfilled, independent of the repository site selected and the amount and type of waste to be disposed of. According to our definitions these requirements are high level safety requirements. They may be modified in future due to increasing knowledge, however, fundamental changes may be excluded.

3.1 Safety strategies for long-term radiological safety issues

Safety strategies are linking site independent high level requirements to host rock/site specific conditions, constraints, and boundary conditions due to the type and amount of waste. Creating a waste and host rock/site specific safety strategy different options are available, e.g. long-term fixation or encapsulation of radionuclides, significant retardation of radionuclide mobilisation and release, dilution of radionuclides. These options are combined to the finally selected safety strategy. For example, safety strategies applied to the three different German sites are given in the following:

Konrad repository:

- Waste inventory of low radiotoxicity (LILW) with negligible heat generation, site specific conditions according to Figure 1.
- Safety strategy applied: Dilution and retardation of radionuclides in depth, very slow or even stagnant groundwater movement from repository depth to biosphere, dilution in overburden.
- Current status of safety assessment: Long-term safety assessment was performed for licensing.
- Engineered barrier(s) of importance: Detailed, quantitative requirements arose due to the long-term tightness of the shaft seals.

HLW repository in rock salt, e.g. Gorleben:

- Heat generating waste of high radiotoxicity, provisional site specific conditions according to Figure 2.
- Safety strategy aimed at: negligible radionuclide release in case of normal repository evolution, retardation of radionuclide mobilisation and release and dilution of radionuclide concentration in case of disturbed repository evolution.
- Current status of safety assessment: Site specific long-term safety assessment not yet available, site independent long-term safety assessments regarding several generic disposal concepts in a salt host formation performed /13/, no further research at present.
- Engineered barriers(s) of main importance identified up to now: Qualitative requirement to shaft seals and drift seals, their tightness should be comparable to that of the host rock in the long-term.

Morsleben repository (ERAM):

- Waste inventory of low radiotoxitciy with negligible heat generation, site specific conditions according to Figure 3.
- Safety strategy applied: Significant retardation of radionuclide release caused by a sequence of natural and engineered barriers, dilution of radionuclide concentration inside the mine as well as in the overburden.
- Current status of safety assessment: Long-term safety assessment performed, engineered barrier design developed for licensing repository closure.
- (Engineered) barriers of importance: Detailed, quantitative requirements due to long-term tightness of the shaft seals as well as of the drift seals are available, natural barrier must be protected against breaking up and stability failure by engineering measures.

Different safety strategies may lead to different technical concepts and related multi-barrier systems in the conceptual stage. For example different technical concepts discussed for the Morsleben repository closure are described in the following.

3.2 Example: Technical concepts regarded for the Morsleben repository closure

Due to different safety strategies, different technical concepts for decommissioning the Morsleben repository (encapsulation concept, pore reservoir concept and concept of extensive backfilling) were discussed. In parallel extensive site investigations were performed and evaluated leading finally to a multi-barrier system that is related to a technical concept and its underlying safety strategy. Relevant site specific constraints influencing the safety strategy respectively the closure concept are due to the large void volume of the former mine, very low brine inflow of about 10 m^3/a at two locations inside the mine, one location being very close to the main anhydrite (which tends to brittle failure and may act as future pathway because it is connected to the water bearing overburden, presently the brine originates from an internal brine reservoir), a low permeable cap rock, and disposal areas whose natural salt barrier long-term integrity can be shown after having been stabilised by backfill.

3.2.1 Encapsulation concept

The concept of encapsulation aims at enclosing the disposal rooms by seals erected in their immediate vicinity. From high level requirements a permeability of k < 10-19 m2 (tightness to liquids and gas) was derived the drift seals had to fulfil. Spherical drift seals consisting of highly compacted bentonites [14] were planned. To guarantee the required tightness in the excavation disturbed zone (EDZ) as well the seals should be saturated with salt solution to achieve fast bentonite swelling to tightening and stabilising the EDZ. This concept was cancelled due to site specific constraints, high risks of realisation and difficulty to show technical feasibility. A reliable methodical structural safety proof for bentonite seals in a salt environment was not available. Neither was it possible to dispel doubts on long-term stability of bentonites under aquatic salt conditions. It is important to notice that in a salt environment material behaviour of highly compacted bentonites particularly regarding swelling behaviour was not describable sufficiently to establish a reliable structural proof of safety.

3.2.2 Pore reservoir concept

The pore reservoir concept required backfilling pre-selected drifts with materials showing a high pore volume. Radionuclide-contaminated brines should be stored temporarily within the pore space to delay radionuclide transport into the geosphere [15]. To achieve a relevant delay a large number of additional drifts was planned to be built to direct the radionuclide flux in the mine. This concept was given up due to site specific constraints, high risks regarding realisation and difficulty to prove technical feasibility, too – e.g. to realise this concept it would have been necessary to create some huge siphon structures (consisting of special shaped mine openings in rock salt) to equalise the hydraulic pressure in the mine and to separate brines with different densities. It was not possible to demonstrate reliably the required 1 000 to 10 000 years lifetime of this structure.

3.2.3 Concept of extensive backfilling and its underlying safety strategy

The extensive backfill concept [16] requires backfilling of large cavities with inexpensive salt concrete (e.g. mixture M2, Table 1) stabilising the host rock on the short term and improve the integrity of the natural salt barrier. By limiting leaching processes of potash seams due to reduction of void volume the natural geological barrier will be conserved in the long term. Additionally, the disposal areas are separated from the residual mine by drift seals, and shaft seals are designed to act in parallel with the host rock barrier [17].

After having developed a technical concept taking into account site specific conditions and constraints as well as waste specific boundary conditions the underlying safety strategy becomes more detailed:

- Delay of solution inflow into the mine openings by protecting the existing host rock barrier and the low permeable cap rock [11] against breaking up caused by stability failure → delay of radionuclide mobilisation.
- Delay of solution inflow into the disposal areas by drift seals acting as a hydraulic resistance → delay of RN transport out of the disposal area.
- Delay of RN contaminated brine by drift seals acting as hydraulic resistance → delay of radionuclide mobilisation and transport into the residual mine.
- Dilution of contaminated brine in the residual mine → reduction of radionuclide concentration.
- Hydraulic resistance of the salt barrier and shaft seals → delay of radionuclide transport.
- Flow resistance of overburden and sorption in overburden → delay of radionuclide release into the biosphere.
- Dilution in overburden → reduction of radionuclide concentration.
- Radiation exposure to biosphere → reduced radiotoxicity due to long travel time.

This technical concept and the underlying safety strategy have led to a multi-barrier system consisting of two independent barrier systems acting in sequence, i.e. drift seals, and natural geological barriers supported by shaft seals.

Remark: The concept of extensive backfilling also complies with conventional safety goals according to the Water Protection Act and the Federal Mining Act. Additionally, occupational heath is guaranteed [18], [19].

4. Evaluating design alternatives

4.1 Evaluating alternatives of a multi-barrier system in the conceptual stage

In Germany a set of safety principles for nuclear power plants [20] is available, some of the safety principles can theoretically be transferred to a multi-barrier system of a final repository. They are:

- Experienced design and standardisation.
- Redundancy.
- Diversity.
- Spatial separation.
- Fail safe.
- Simple structure.
- Quality assurance in planning and construction phase.
- Evaluation of experience during operation.

Evaluating the different technical concepts planned for the sealing of the Morsleben repository qualitatively by the safety principles, engineering practice as well as safety assessments shows that the extensive backfill concept and its multi-barrier system complies best with the safety principles. It fulfils a large number of them, although the repository was erected in a former salt and potash mine which was excavated under the aspect to extract salt economically. At first the natural cap rock and host rock barriers act as hydraulic resistance in parallel with the shaft seals against brine inflow. Than the void volume of the residual mine serves as a large brine reservoir slowing down brine pressure built up to drift seals, which again act as a hydraulic resistance delaying brine inflow into the disposal areas. After radionuclide mobilisation drift seals serve again as a hydraulic resistance retarding outflow of contaminated brine into the brine reservoir of the residual mine, where the radionuclide contaminated brine is diluted. Next, the contaminated brine has to pass the shaft seals or the host rock and cap rock barriers. In the overburden hydraulic resistance, sorption and dilution are taken into account. Thus, the multi-barrier system of the concept of extensive backfilling complies with the safety principles redundancy, diversity and spatial separation. Additionally, experience in rating rock salt barriers is available due to a long history of salt mining [7] as well as the knowledge how to construct seals in salt mines [21], [33].

The multi-barrier system structure is simple. Applying standards however is not possible as no standards are available. Obviously, quality assurance measures in the planning and realisation phase are applied and experience from watching the natural rock salt barrier during repository operation and comparing it with experience gained from other salt mines is evaluated. Finally, due to creep and healing processes the natural rock salt barrier will improve with time after having backfilled large mine openings for stabilisation.

4.2 Evaluating alternatives of a single engineered barrier in the conceptual stage

To evaluate a single engineered barrier within a multi-barrier system more detailed safety principles may be applied, which were transferred from reactor safety components [22] to an engineered barrier in 1994. These principles can be grouped and classified as follows:

- Design and layout.
- Calculation (i.e. structural safety proof).
- Construction material.
- Construction.
- Quality assurance and tests.

When evaluating a structure by these safety principles they may be verified independently from each other, but only a structure complying with a combination of safety principles will show a high level of reliability.

4.2.1 Safety principles due to design and layout

The structure should have a simple functionality or mode of operation (**functional-compatible structure**) so that favourable conditions for operational loads exist. Incorrect loads must not arise. Deformations should be limited and the number of joints (including working joints) should be minimised.

The structure should be **load-compatible** i.e. stress peaks should be avoided and in case of discontinuities a reasonable stress state should be achieved. Parts of an engineered barrier subjected to localised forces should be designed favourably, too.

The construction should be **site-compatible** i.e. the site specific conditions have to be regarded. When preparing the location for drift seal construction harmful impacts to the host rock should be avoided as far as possible.

The structure should be **material-compatible** taking into account the aspects of stability, permeability, deformability, temperature and corrosion resistance. The materials should be produced routinely (in terms of minimising flaws during the production) and the verifiability of reliable material properties must be granted. Materials should be used in their favourite form of manufacture. The number of different materials used should be minimised. The feasibility of repair actions also should be taken into account.

To exclude imperfections due to the construction process the structure should be easy to construct **(construction-compatible),** i.e. due to the specific application the material should be used being as simple to handle as possible and simple installation conditions should be applied.

Details of the structure have to be described carefully.

The verifiability of the structure **(verification-compatible)** should be assured by non-destructive testing.

4.2.2 Safety principles due to calculation

The layout of the complete system and its components has to be performed using the most unfavourable loading conditions.

Site specific loads and demands from transport and erection must taken into consideration.

Admissible stresses should be limited conservatively.

The influence of failure of structure components (also linked to failure assumptions) has to be investigated.

4.2.3 Safety principles due to construction material

High-quality materials with defined properties should be used. Extensive experience should be available using the material for the specific application. If there is not sufficient experience available for a specific material it has to be avoided.

If special materials can not be avoided not having sufficient experience, their properties must harmonise with the required properties (e.g. corrosion resistance).

Special materials have to be examined and qualified taking into account their form of manufacture.

4.2.4 Safety principles due to construction

Only high-qualified manufacturers are to be appointed (personal, production equipment, test institutions, quality assurance).

For each step of erection pre-certificated documents must be available concerning manufacturing, construction, design and layout. A quality assurance procedure must be defined taking into account the construction process. A scheme of test sequences must be developed for each step of erection.

During the erection solely optimised technologies should be used and proper conditions have to be granted.

The control of the erection process has to be carried out systematically using written guidelines. The erection as well as the implementation of tests has to be documented, so that existing faults can be identified.

Manufacture requirements are to be appointed in detail.

4.2.5 Safety principles due to quality assurance and testing

Only components have to be used which are pre-certificated by manufacturers, appreciated authorities or other experts.

Testing of materials has to be performed using optimised test technologies in particular taking into account the form of manufacture of the material.

Regarding the sequence of erection construction has to be supervised on an appropriate level by the appreciated authority or other appointed experts. Arbitrary random tests and supervising are possible at any time. In case of detecting errors the spot-checks have to be increased. As final test after the construction phase the proper function (e.g. test of tightness) has to be tested.

All three test types (preliminary, material and supervision/control) have to be documented.

These rough safety principles may serve as a basis for design decisions in principle to chose the first design variant among others. If they are considered a reasonable technical solution will automatically turn out because these principles lead to simple structures which are feasible to construct, simple to prove and relatively cheap. Additionally, relying on accepted standards facilitates the licensing procedure. If one basic solution is available, it may be optimised. However, to our experience, the number of options is limited.

5. Evolution of design requirements

Being a basic engineered barrier within a multi-barrier system a drift seal in a salt host rock formation is selected to serve as an example for requirements evolution. First an overview of the history of drift seal design is given.

5.1 Example: History of drift seal design in a salt host rock formation

In Germany drift seal design efforts under the aspect of separating radioactive waste (HLW/SNF) from the biosphere systematically started in the late 70ties and 80ties [8], [23] based on site independent generic disposal concepts with rock salt serving as host rock formation.

At that time it was required to keep the disposal concept sufficiently flexible to be able to adopt it to site specific geological structures later on. Disposal of HLW from reprocessing packed in canisters was planned in deep vertical boreholes [24] of about 300 m depth which were arranged in emplacement fields of about 300 m in length and width. When starting the discussion on direct disposal of spent fuel in POLLUX containers [25] drift emplacement was also regarded, using emplacement fields of identical dimensions. After waste emplacement mining openings were planned to be backfilled by crushed salt, whose compaction and healing capacity was assumed to guarantee the long-term safety of the repository. After having been filled with waste completely high quality drift seals were planned to separate the repository mine in operation from respective emplacement fields. The safety goal was due to occupational health because brine intrusion from undetected brine pockets as well as from water bearing rock neighbouring the salt dome could not be excluded. Drift seal function was required instantaneously after having abandoned a single emplacement field. In the post-closure phase no function was assigned to the drift seals.

In this first approach function of drifts seals was required for 25 years regarding exclusively the operational phase [26]. Some times later the required lifetime for drift seals was extended to the post-operational phase. A first set of functions of the seals (dams) was listed [27]:

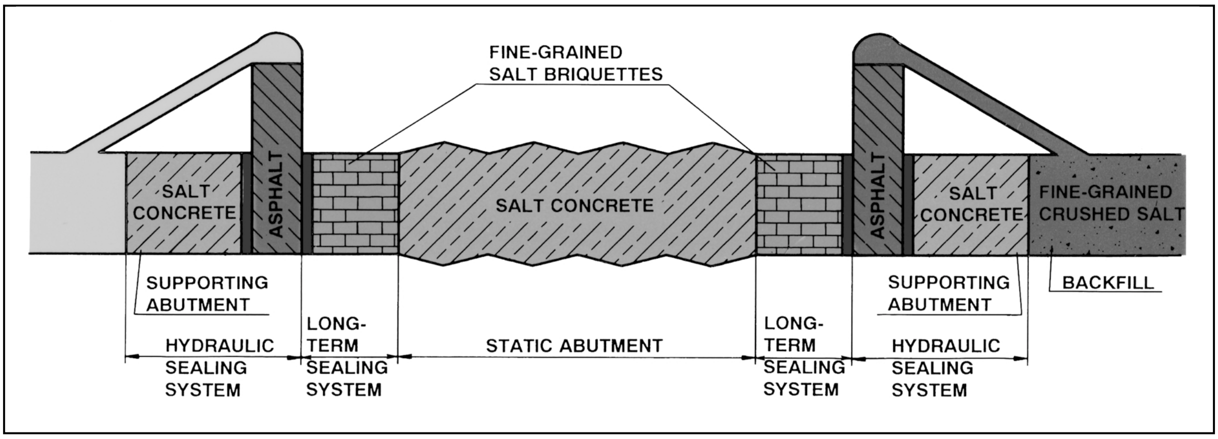
1. In the operational phase:
    - Limitation of brine inflow into the mine openings in operation.
    - Limitation of inflow of solutions from the salt formation into backfilled and abandoned areas of the mine.
    - Limitation of hydrogen generation due to radiolysis.
    - Limitation of natural gas inflow.
2. In the post operational phase:
    - Limitation of water or brine inflow from the main anhydrite layers.
    - Limitation of inflow of solutions from the salt formations (brine pockets).
    - Limitation of hydrogen generation due to radiolysis.
    - Limitation of natural gas inflow.

Thus, the seal (dam) had to fulfil the following requirements derived from functions in the operational and post-operational phase:

- Stability against rock pressure.
- Stability against liquid and gas pressure.
- Loading capability from both sides of the dam.
- Impermeability to pressurised liquid and gas during the operational phase.
- At the beginning of the post-operational phase the dam permeability against liquids should not exceed 2·10-16 m2.
- Resistance of seal construction materials against corrosive salt solutions.
- Thermal stability of construction materials.

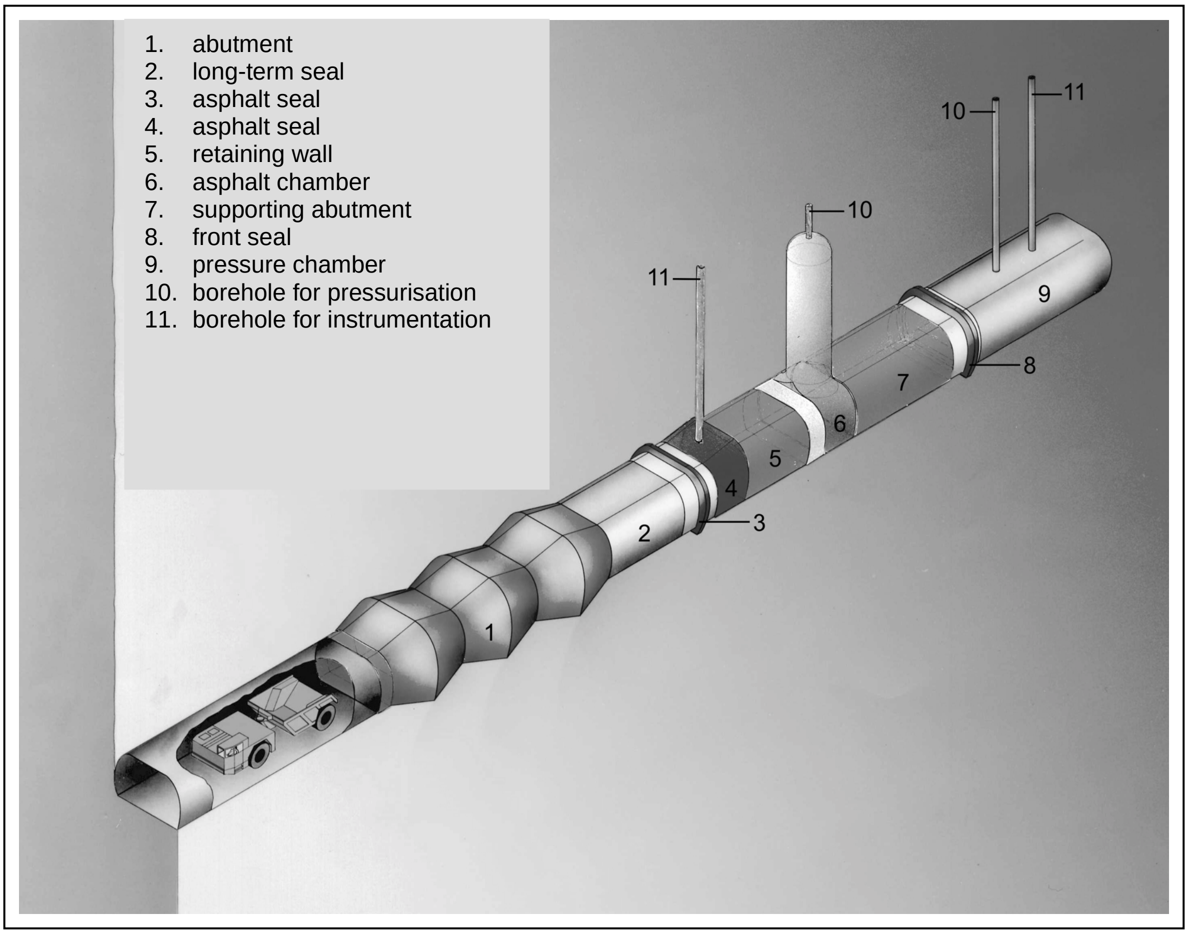
The seal design arising from these requirements is given in Figure 4. It consists of a multiple prism shaped abutment placed between two symmetrical sealing systems. The abutment is loaded by rock and fluid pressure. The sealing systems cover the sealing function of the dam and protect the abutment against corrosive brines or gases. The sealing systems have several functions. The hydraulic sealing system is designed to become effective early after construction of the seal. The long-term seal has to sustain liquid or gas pressure occurring in the post operational phase. The hydraulic seal (originating from seals of gas reservoirs) is built of asphalt, whereas the long-term seal consists of slack salt briquettes. The material provided to construct the abutment was salt concrete.

Figure 4: Draft design of drift seals in 1988



Under contract of the Federal Ministry of Research and Technology (BMFT, today: BMBF – Federal Ministry of Education, Science, Research and Technology) the construction of a prototype seal (one half of the seal, Figure 5) began in the Asse research mine in 1990 to demonstrate its function practically in situ after a period of material investigation in laboratory and medium scale tests.

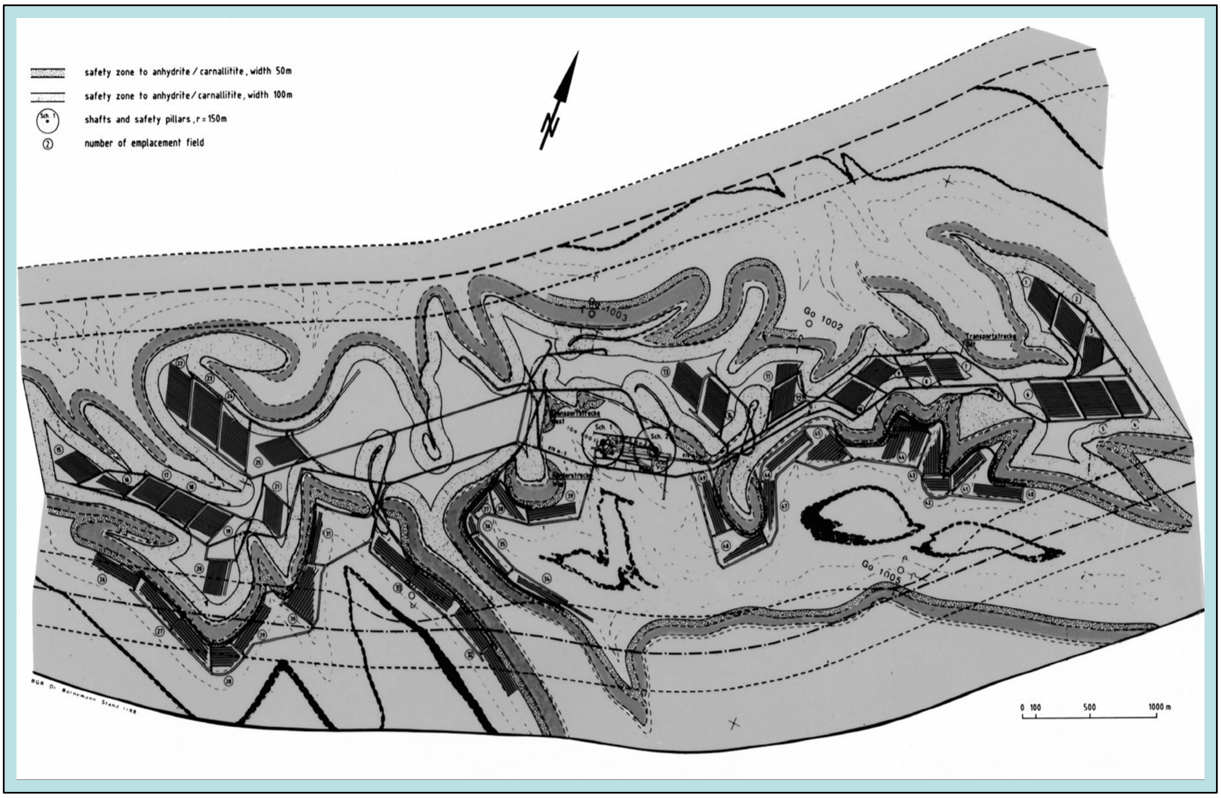
Figure 5: Design of prototype in 1990



At that point of time the required lifetime of the drift seal was fixed to 500-1 000 years [28] due to increasing knowledge that in situ crushed salt compaction proceeds slower than forecasted on basis of laboratory experiments [8], [29]. Induced by convergence crushed salt compaction might be a long lasting process as the convergence rate depends on local properties of the salt structure, which may vary significantly. Thus, crushed salt compaction is affected with significant uncertainties [8].

Progress in exploring the Gorleben site and adopting the generic disposal concept [32] to the so-called Gorleben working model (Figure 6) the question of selecting the optimal seal position arose, because there is sufficient rock salt available that safety margins (spatial distances) were not exceeded and water intrusion from the overburden or water bearing rock neighbouring the salt dome could be excluded [7]. In parallel exploration methods were improved to detecting brine pockets inside the salt formation. It was intended to improve electromagnetic radar techniques (EMR) further on assuming that in future sufficient knowledge will be available to detect and manage large brine pockets inside the salt formation. Therefore, the shafts became the only potential pathways. In the operational phase the shafts are protected by a watertight lining system [30]. This discussion was not yet finished, when exploration and research concerning the Gorleben site was interrupted. Evidently, the shaft seals will be the most important engineered barriers in the case of a salt host rock comparable to Gorleben in the early post-operational phase [31] because zero release is aimed at in the case of normal repository evolution according to the safety strategy adopted.

Figure 6: Gorleben working model



With German reunification in 1990 financial conditions for national research projects changed because projects in the former GDR had also to be supported. At that time responsibility for funding the Asse prototype seal project, which was not yet finished, was transferred to the BfS. However, funding by BfS was only possible due to the constraint that the results of the project could be used in a future plan-approval procedure for a potential Gorleben repository. In 1993 not enough scientific knowledge had accumulated to transfer relevant data from one rock salt site to the other and a concept to prove structural safety in the context of a plan-approval procedure was not developed. Attempts to develop a structural safety proof concept in the short-term failed due to the complicated structure of the seal. Thus, the Asse prototype seal project was stopped.

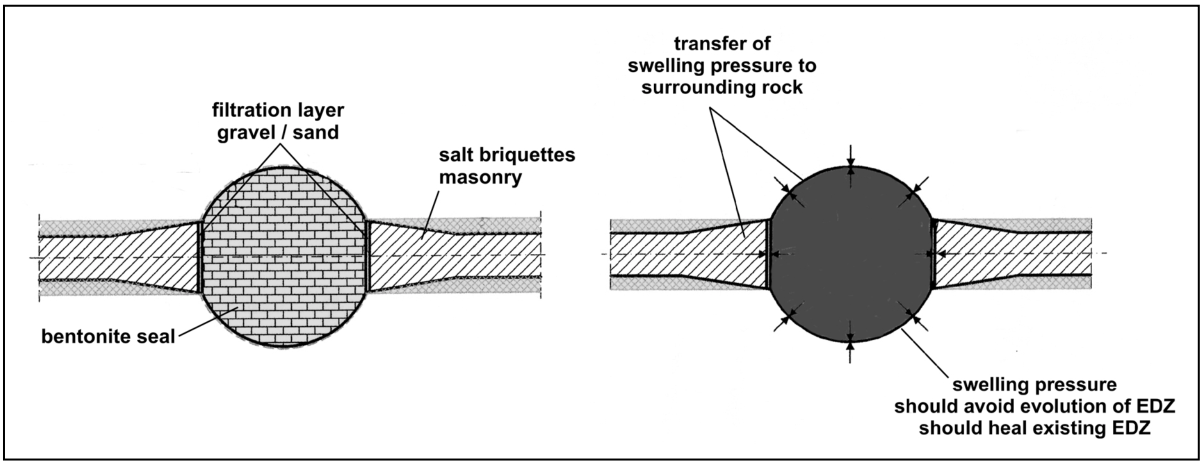
When the Morsleben repository became a German federal repository a license application for its closure had to be prepared [2]. As a first approach three backfilling and sealing concepts were developed, two of them based mainly on engineered barriers in drifts (see Chapter 3.2).

Regarding the encapsulation concept the following requirement on the drift seals was developed from the long-term safety assessment:

- Gas and watertight encapsulation, i.e. permeability $k < 10^{-19}$ m^2.

The seal design arising from this requirement is given in Figure 7, when using highly compacted bentonite as sealing material. Due to the swelling properties the optimal shape (sphere) of the sealing system was figured out keeping the structure simple. The sealing material's position was planned to be fixed by abutments made of salt briquettes respectively salt concrete. A filtration layer placed between abutment and sealing material was planned to improve the saturation process of the bentonite. As a reliable mathematical description of bentonite material behaviour when becoming saturated by brine with high ionic strength was not available short-term, a reliable structural proof of safety could not be performed.

Figure 7: Draft of drift seal design in 1998



Regarding the extensive backfilling concept due to site specific constraints the following, more detailed requirements arose from the long-term safety assessment:

- Initial permeability $k < 10^{-18}$ m^2.
- Lifetime of seals 5 000-30 000 years.
- Compatibility of drift seal material with the main backfill material, i.e. salt concrete.

The following site specific constraints have to be taken into account:

- Limited length of sealing structure due to site specific geology.
- Difficult and limited access.
- Low convergence rates.

Due to the boundary conditions and requirements mentioned above the suitability of salt concrete was investigated to serving as construction material for the drift seals. Parameters from laboratory tests are given in Table 1 describing hydraulic and mechanical properties.

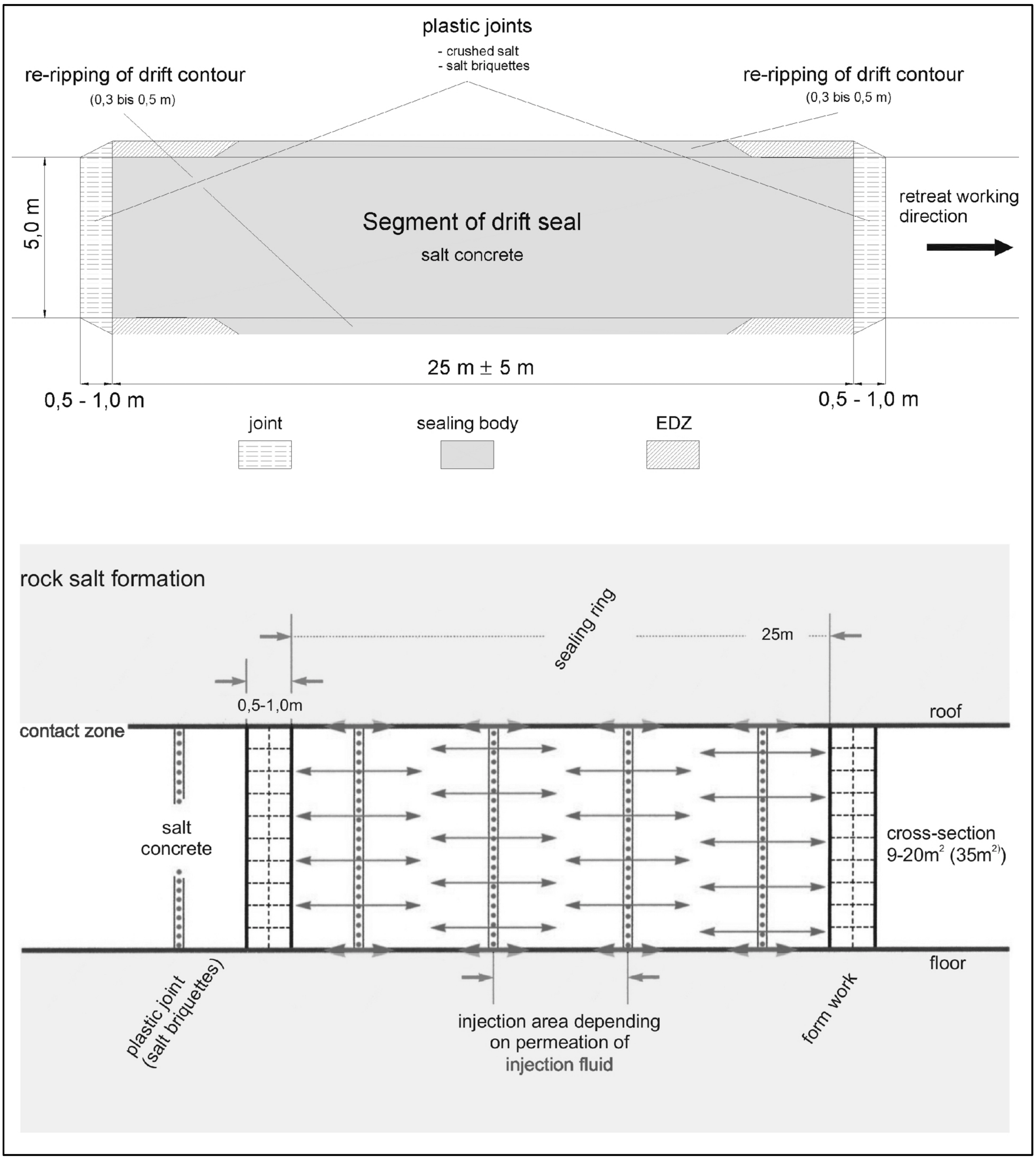
Table 1: Mechanical and hydraulic properties of salt concrete M2

Material properties	Range
Density [kg/m^3]	1,966 – 1,997
Uniaxial compression strength [MPa]	21.2 – 39.7
Uniaxial tensile strength [MPa]	2.04 – 3.03
Young´s modulus [MPa]	11,700 – 23,900
Permeability to gas [m^2] (dried 20°C/65% rel. humidity)	$5.4 \cdot 10^{-18} – 5.3 \cdot 10^{-21}$
Permeability to brine [m^2]	$< 3 \cdot 10^{-23} – 6 \cdot 10^{-24}$
Threshold pressure [MPa] (brine saturated)	> 7

Salt concrete shows a permeability sufficiently low and due to its mechanical properties a drift seal made of salt concrete is able to serve as a seal as well as abutment. Thus, maximum length of hydraulic resistance is achieved which is restricted by the local geology. Corrosion investigations combined with calculations showed that the required lifetime is guaranteed. The compatibility with the main backfill material is naturally given because of the same ingredients. A salt concrete plug is the most simple structure when taking difficult and limited access into account.

Because the length of some drift seals is short grouting of the contact zone is foreseen. From a literature investigation it turned out, that in rock salt seals of short length became tight within a short period of time solely after having been injected [21]. As the convergence rates are very low in Morsleben, creep induced high pressure can not be assumed tightening the contact and the excavation disturbed zone short-term. Thus, technical measures will be applied, i.e. injection. The present state of drift seal design is given in Figure 8.

Figure 8: Draft drift seal design in 2002



For the plan-approval procedure, technical feasibility and safety of drift seals have to be shown. For the use of salt concrete civil engineering [34] and geotechnical regulations [35] of the European Standard and some German regulations on concrete structures against substances polluting the environment [36] can be applied. Except for the long-lifetime these regulations can be applied to the seals and the safety proof can be performed according to these regulations. That makes the licensing process more simple and methodical, because the difficulty to establish a structural proof that is generally acknowledged and should not be underestimated.

When performing a structural proof of tightness German regulations require to evaluating hydraulic conductivity of contact zones using measured data from comparable structures. A comparable structure is an uncompleted seal in the former Asse research mine. The salt concrete abutment (supporting abutment, Figure 5) was completed in 1992. Now it is used to gain actual measured data for rating the contact zone. Additionally, the quality of the salt concrete structure achieved in situ is investigated. Today sufficient knowledge is available to transfer the site specific conditions of the Asse mine to the Morsleben repository. Investigating the contact zone of the Asse seal will be finished mainly this year. Concerning the drift seals present work is focussed on investigations to achieve a reliable data basis. Additionally, investigations will be planned regarding grouting.

Resuming the history of drift seal design it could be learnt, that first decisions are driven by qualitative decision criteria. However, quantification must be performed at an early stage of the project in order to detect uncertainties, which exclude a reliable safety proof in the very beginning. Omitting uncertainties will affect the evolution of requirements significantly.

It can be summarised that site independent high-level safety requirements do not change very much. Derived requirements linked to site and waste may change significantly with increasing knowledge, however. The example shows that derived requirements may develop in both directions becoming strengthened as well as obsolete.

5.2 Remarks on the coupling of structural safety proof and long-term safety assessment

With regard to multi-barrier systems difficulties may arise in guaranteeing a comparable safety level in case of normal respectively disturbed repository evolution, if there is a link missing in the safety related regulatory framework for instance not having defined a risk upper bound in Germany. This leads to the result that in the case of an HLW repository the safety level of the normal repository evolution might be less than in the case of disturbed evolution because the inherent safety related to the low probability is not taken into account. Additionally, a risk upper bound would simplify the coupling between long-term safety assessment and structural safety proofs of engineered barriers because according to the regulatory framework /34/ the safety of engineering structures is rated on basis of a risk upper bound. However, this objective is under discussion in Germany at present and the regulatory framework may change in future. In some cases this problem is overcome by applying both a deterministic as well as a probabilistic approach in long-term safety assessment showing that the individual annual dose of 0.3 mSv/a will not be exceeded with a level of confidence determined by the results and the number of realisations of the probabilistic approach.

For the closure of the Morsleben repository the missing link in regulatory framework is of minor importance because radiotoxicity of the inventory is relatively low. Thus, the calculated dose rate is only exceeded slightly in 1 case of 1 000 realisations due to an unrealistic parameter combination although having combined normal repository evolution and disturbed repository evolution. Additionally, probabilistic calculations on the multi-barrier system were performed to show the robustness of the multi-barrier system.

To design engineered barriers like shaft seals and drift seals being the most important engineered barriers in a salt host rock the European Standard [34], [35] is applied as well as some other German technical regulations. Thus, safety is guaranteed with a definite level of confidence and the requirements from long-term safety assessment are related to the deterministic approach. In the case of engineered structures a risk upper bound is defined, in the case of safety related issues, it is 10^{-6}/a.

A risk upper bound is helpful focussing the point when an additional barrier will not increase safety anymore within a multi-barrier system. For doing this a risk based approach is necessary to rate the multi-barrier system even in the case of normal evolution. (Unfortunately, a risk based approach is not exactly available presently. By way of precaution the coefficient of risk conversion is described diffusely by ICRP in particular for assessing a repository safety up to several million years.) In this assumptive case the radiological risk must be calculated from the dose rate including the probability [37]. If there is an annual risk below 10^{-5}/a being the risk upper bound in the case of disturbed repository evolution an additional barrier does not make sense anymore because then the safety level is ruled by the risk of disturbed repository evolution and no further optimisation is possible for lack of a reliable statistical approach.

5.3 Evolution of boundary conditions due to political decisions and societal changes

Regarding HLW for example relevant boundary conditions for planning a final repository in Germany are given in [2]. They changed due to political decisions, however. Until 1994 it was required that spent fuel has to be reprocessed. Recently, the Atomic Energy Act (22.04.2002) was modified. After a phase of transition until 30.06.2005 reprocessing abroad will phase out and spent fuel will become radioactive waste. Thus, a disposal concept must be sufficiently robust to account for different types of radioactive waste, which are not known in detail presently due to technological, economical or political changes. Remember the existence of fuel from the former Soviet Union, resulting from a political evolution that was not foreseen.

Sometimes political decisions play a fundamental role influencing the disposal concept, e.g. the decision of the German Government to look for alternative repository sites suited to dispose of all kinds of radioactive waste (LLW, ILW, HLW) in one single repository. Additional examples of political or societal changes are the discussion on retrievability or the definition of stylised situations and human intrusion scenarios. These types of boundary conditions are difficult to manage because they can change rapidly in comparison to the duration of site selection, exploration and repository construction procedures. Fortunately, these types of requirements can be influenced by discussion with politicians and the public leading to a reasonable solution in the long-term.

6. Approaches to documenting requirements and design decisions and quality assurance

In West Germany systematic documentation started with the beginning of performing site specific repository projects. The evolution of high level safety requirements need not to be documented because they are part of the legal framework and modification of the legal framework is evident. Nevertheless must they be mentioned in the so-called project structure plan. The first draft of the project structure plan shows the boundary conditions for planning when beginning the project. This project structure plan is discussed, an example of a draft project structure plan is given in Figure 9 [38]. It shows safety related requirements on one hand and the technical concept on the other hand. The overall header is the objective of the project, e.g. assessing suitability of a site. Technical concept and safety related issues must be linked in a logical way. After having created an agreed project structure plan, the project structure elements are broken down to the level of work packages. Every structural element carries a number, whose first digits are part of the work package number. Within the work packages the work to do is described. Documents related to a work package are identified by the project specification, the work package number followed by some letters and digits related to the contents of the document, then defining the document type, the number of the document and the revision status (Figure 10). Design decisions are documented in reports. By the project structure the documents are related to high level requirements. If requirements change or design is modified a revision is performed, the level of revision depending on the importance for the project. Thus, change of requirements and design decisions remain traceable. This system was created in early computer times for the Konrad project and has turned out to be practical and sufficient so that it is still in use. Despite long-term use it has been modified only slightly. Project structure plan and work package descriptions are archived as well as other relevant documents such as reports. This system has demonstrated its applicability to manage the documents for licensing of Konrad repository successfully.

In the context of licensing the Morsleben repository closure the experience was found that the number of documents is inflating and due to long-term planning periods new staff is involved not knowing in which document design decisions are described, because in the final document only the final design is described as it is of interest for licensing. Knowledge on design decisions become abandoned. Presently it is tested to write two reports, one containing the final design and a second with same title and carrying the appendix work report. In the work reports alternatives investigated (if there are any) are also mentioned, and the reasons why the alternatives were not selected are documented. This procedure is in the test phase.

Figure 9: Draft of a project structure plan

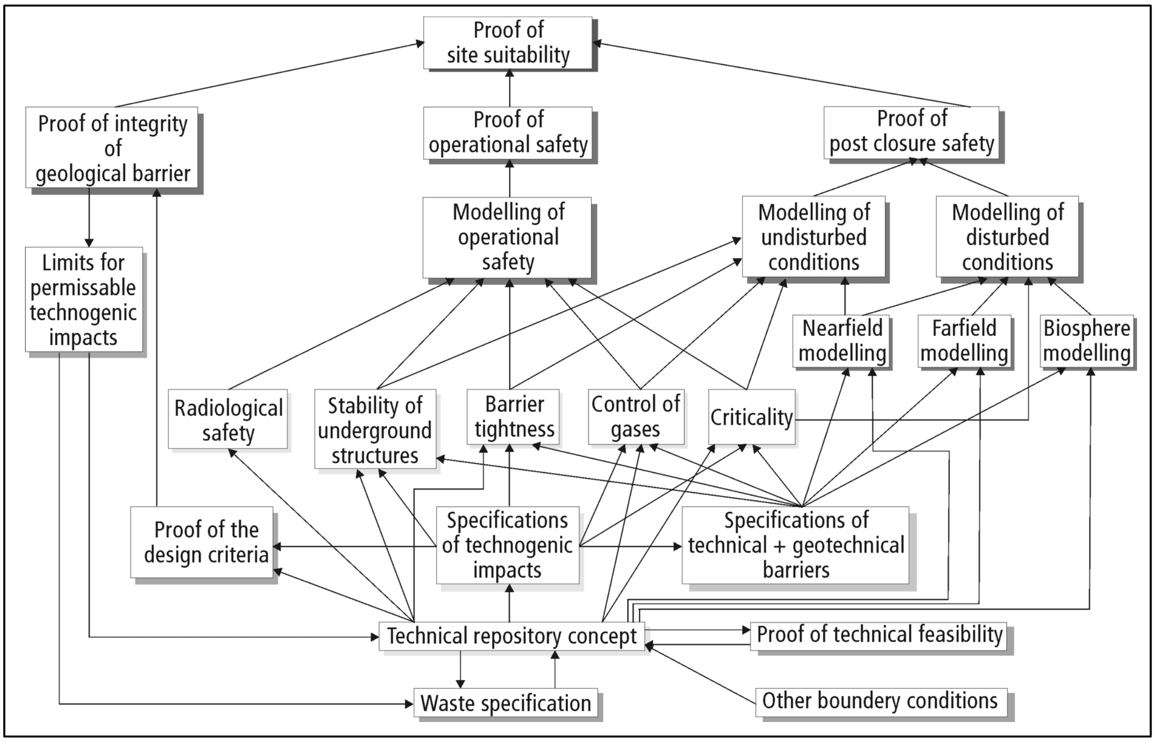
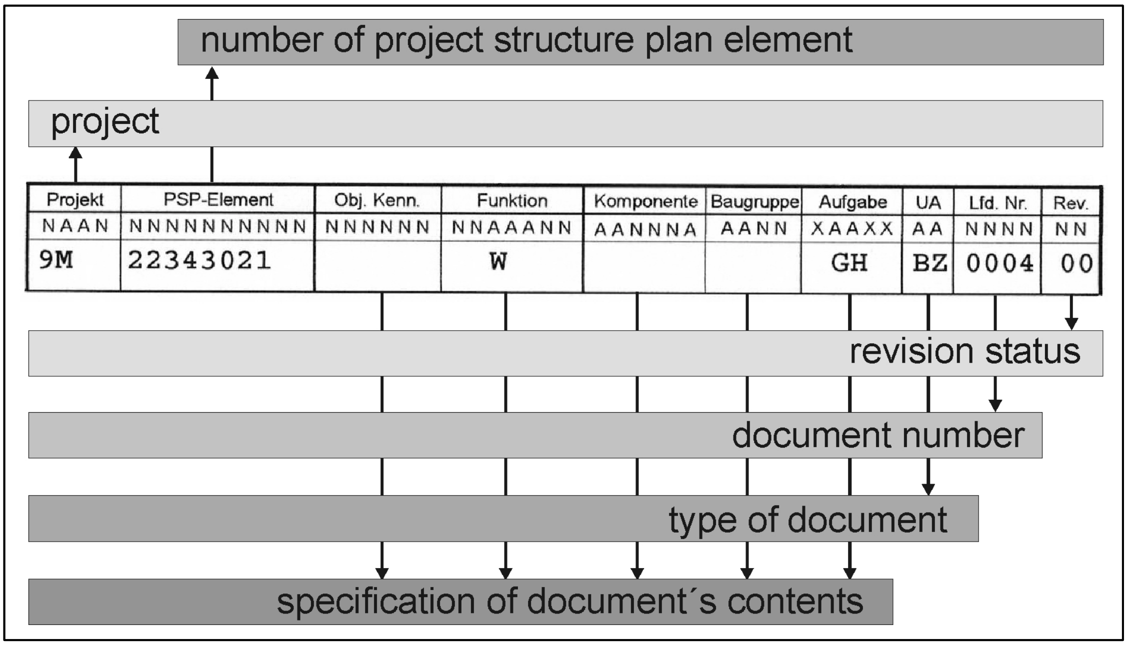


Figure 10: Example of document identification code



To assure quality of planning a special internal approval procedure “Freigabeverfahren” was developed. At DBE (and other contractors) the report is written by the author(s) and signed. They have full responsibility for the contents. Every organisational unit at DBE affected by the contents of the document has to review the document within the scope of its responsibility and sign it. One organisational unit is specified being responsible for managing the document status and to archive the original document. Finally, the project management signs, assuring that the project management knows the present project status. All this information is managed by a data bank system handled by everyone at DBE. Not everyone is allowed to read every document, but everyone can find out that a document related to a special topic is available and its status within the project. The same procedure is performed with documents from third companies, however the signatures for the contents are missing because responsibility is with these third companies. In the next step all documents are given to BfS for proving, e.g. proof of correctness and consistency. At BfS a comparable “Freigabeverfahren” is performed, finally it is decided, whether the document can be used solely within the project or already given to authorities. This status is marked on the overlay.

In Germany further quality assurance is given by the plan-approval procedure stipulated for licensing a repository for radioactive waste. A full description of the facility in the operational and post operational phase and its safety related issues must be available for licensing as well as the required proofs of safety. Within the licensing procedure these documents are proved by the authority and their technical consultants for expert services. This kind of quality assurance is expensive but helpful especially in the case that there will be legal actions against the license.

The high level requirements are fixed by natural science and a high quality assurance standard was applied to derived requirements and planning technical realisation. All actions are related to strategic and formal licensing procedural questions. This could not be foreseen 20 years ago, because it depends on societal changes and political decisions (e.g. the sufficiency of a legal action instituted by an association in the interest of its members or the general public) which are rapid in comparison with development of final disposal concepts.

7. Approaches to the integration of information from engineers, scientists and safety assessors

First a description of experience is given focussing on the role of engineers, scientists and safety assessors at different stages of a repository project.

When starting a repository project the problem to be solved has to be defined, i.e. what kind and amount of waste should be disposed of. A rough classification is sufficient restricted to the main characteristics. Potential technical solutions of waste disposal are discussed by engineers, scientists and safety assessors working closely together on the same level. In this conceptual stage there is not much information available and every partner can read all relevant reports. The first choice of a suitable host rock formation is task mainly of scientists and engineers, assessing suitability of a geological situation and the technical feasibility of constructing a final repository. High level requirements are the first yardstick for evaluating the host rock formation and the repository concept using them in a practical manner, e.g. requiring absence of water etc.

The involvement of scientists, engineers and safety assessors changes at different stages of the project, however. If a concept has been developed and the basic boundary conditions are defined it is due to the safety assessors, showing that high level requirements are not exceeded quantitatively by calculation using generic models of a geologic formation/host rock, a draft of a repository design and disposal concept and a draft of the related multi-barrier system. They are creating scenarios supported by engineers and scientists and models of the total repository system integrating models for subsystems, e.g. a radionuclide mobilisation model. The data basis is provisional assessed from literature or based on assumptions, estimates and empirical knowledge. The provisional data basis is fixed in one report, maybe with a few appendices [13], [23], [25], [39]. At that stage the data basis is not site specific, but some data is available, e.g. type of waste existing, eventually type of canister or container. Performing the safety assessment relevant missing data are identified. At that stage of the project subprojects may be created. Mainly scientists are involved to improve the data basis. Engineers are involved as advisers keeping solutions technically feasible. Safety assessors are controlling this stage of the project.

While determining missing data, in parallel several repository variants are investigated on a provisional data basis, showing sensitive parameters. First derived requirements relevant for the repository design become fixed, e.g. the maximum admissible temperature of 200°C for rock salt in the case of HLW disposal [24], [40]. Experience showed that at this stage of the project the costs of the repository project must already be specified. This is done by engineers. Criteria for site selection (e.g. dry site, absence of water, extension of site correlating to the amount of waste), are determined. Now it has to be decided (decision makers, e.g. politicians) to start the site selection procedure. Progress of projects depend on whether a site becomes selected or not.

In West Germany the Konrad and the Gorleben site were selected. In Germany at that stage the repository projects became complex because a lot of people were involved, site specific data became available as well as results from *in situ* experiments from the Asse research mine. Then a provisional site specific safety assessment should be performed. In the case of the Konrad project this step was realised, in the case of the Gorleben project it could not be realised due to the moratorium controlling the full set of safety related requirements available at that point of time.

In case of the Morsleben repository closure several attempts were made to develop closure concepts, see chapter 6. Scientists, engineers and safety assessors are working together. Introducing site specific data increasingly, the project became more and more controlled by the safety assessors evaluating compliance with high level requirements advised by engineers rating technical feasibility and supported by scientists improving reliability of the data basis and replacing assumptions. At that stage it could already be estimated that the selected technical solution could be realised successfully, but the final data basis is still not fixed. After having decided to stop waste emplacement work was focussed on realising the closure concept. The last phase is task of the engineers, performing final layout, establishing structural safety proofs, defining the construction schedule, and quality assurance procedures. In this phase the work of scientists is very rare and dedicated to a few single questions. Progress of science is too slow to be able to influencing the technical project significantly. Differences in thinking of scientists and engineers are of relevance because scientists often want to identify and solve new problems whereas engineers want to find a practical solution. Tendency of engineers is to decouple problems by engineering methods to keep the structure as simple and cheap as possible fulfilling the requirements with a definite level of confidence, establishing a structural proof of safety and defining quality assurance measures to assure its reliability. In this phase the safety assessor is the controller of the engineer assuring that the multi-barrier system fulfils the high level requirements due to human health and environmental protection.

Finally it may be resumed, that the project manager (management) must integrate the work of engineers, scientists and safety assessors differently at different stages of the project. The task is mainly analysed by scientists in the first stage defining basic phenomena supported by engineering experience. A first synthesis of all phenomena defined by scientists is done by safety assessors supported by scientists and engineers. When planning realisation at the beginning safety assessors and engineers are working closely together. Safety assessors define derived requirements and engineers create technical solutions and reliable structural safety proofs. The work of scientists is restricted to fix the data basis quantitatively in some cases. In the final planning phase engineers take on responsibility, defining layout and quality assurance being controlled by safety assessors. Scientists are not involved any more. Realisation is due to the engineers, safety assessors do not play a role any more because high level requirements were broken down to derived requirements the final layout has to comply with and quality assurance procedures are defined for reliability reasons.

Experiences made by engineers, scientist and safety assessors working together may be summarised as follows:

In the phase prior to siting not much information is available. Everyone has full access to information, be he scientist, engineer or safety assessor. In the planning and realisation phase following site selection the integration of information from scientists, engineers and safety assessors is essential and supports the quality assurance, see chapter 6.

8. Summary

For the disposal of HLW and heat generating ILW the Gorleben salt dome was selected as a candidate repository site. Site selection was performed in 1977, exploration started in 1979. Since 2002 exploration has been interrupted. For low- and intermediate-level waste the Konrad repository located in a former iron mine was licensed in 2002 after a 20-year-lasting plan-approval procedure. Presently, three communities and one individual brought an action against the license and now the legality of the license is proved by court. The Morsleben repository located in a former rock salt and potash mine is now under licensing for closure after having emplaced waste between 1978 and 1998.

Presently, it is decided politically to look for alternative candidate sites which are suited to constructing a repository for all kinds of radioactive waste.

For each site different safety strategies were applied linking type and amount of waste as well as host rock/site specific conditions and constraints to high level safety requirements given by the regulatory framework, aiming at protecting human health and the environment. Due to the safety strategy applied waste and site specific technical concepts are developed and the related multi-barrier system is drafted.

Different safety principles are given to evaluate the reliability of the multi-barrier system qualitatively and to evaluate a single engineered barrier in the conceptual stage. Quantitative requirements to single barriers may be derived linking high level quantitative requirements from radiological safety to barrier specific structural proofs of safety by performing a provisional long-term safety assessments. With increasing site specific knowledge and detailing the technical concepts the derived requirements may change significantly causing modifications of the multi-barrier system as well as single barrier design and layout. By repeating the assessment of long-term radiological safety several times compliance with high level requirements is guaranteed despite of technical modifications.

Within the repository project derived requirements and design decisions are documented in reports, quality assurance measures are described allowing traceability of requirement changes as well as design decisions.

The way in which information from engineers, scientists and safety assessors is integrated was investigated. At the conceptual level prior to siting engineers, scientists and safety assessors work together at comparable level. However, there is not much information available and it is possible to inform everybody familiar with the project. After siting the integration of information is a question of quality assurance of the planning process.

Finally, the following may be concluded:

High level quantitative safety requirements rule the requirements derived for single barriers of the multi-barrier system. They do not change very much. To achieve radiation protection different safety strategies may be applied leading to different technical concepts and related multi-barrier systems. Performing a safety assessment provisionally requirements to single barriers may be derived for establishing structural safety proofs. One has to rely on quantitative requirements which can be verified. They will be relevant for the licensing process. The repository system must be kept flexible with regard to the type and amount of waste. It may change with time. Society and politics can change rapidly in comparison with the duration of repository projects. Thus, safety related issues are the most stable ones and they may serve as a signpost for final repository projects.

References

[1] Safety Criteria for the Final Disposal of Radioactive Waste in a Mine (Sicherheitskriterien für die Endlagerung radioaktiver Abfälle in einem Bergwerk), GMBl. 1983, p. 220.

[2] Atomic Energy Act (Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren – Atomgesetz, AtG), BGBl. part I, 2000, p.1960.

[3] BfS, Plan – Endlager für radioaktive Abfälle – Kurzfassung – Stand: 9/86 in der Fassung 4/90 – Schachtanlage Konrad – Salzgitter.

[4] Gesetz über die Vermeidung und Entsorgung von Abfällen, Gesetzestext mit Begründungen und Anmerkungen; Rechtverordnungen und Verwaltungsvorschriften des Bundes; Richtlinien der Europäischen Gemeinschaft, Zusammenstellung und Anm. von Ruth Henselder-Ludwig – Köln, Bundesanzeiger, 1991.

[5] AkEnd: Auswahlverfahren für Endlagerstandorte, Empfehlungen des AkEnd – Arbeitskreis Auswahlverfahren Endlagerstandorte, Bericht, Dezember 2002.

[6] Federal Mining Act (Bundesberggesetz) of the 13 August 1980, BGBl. part I, p. 1714.

[7] Allgemeine Bundesbergverordnung vom 23. Oktober 1995,BGBl. I, S. 1466.

[8] Bechthold, W. *et al*: Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS Project), Final Report, European Commission, EUR 19124EN, 1999.

[9] Radiation Protection Ordinance (Verordnung über den Schutz vor Schäden durch ionisierende Strahlen – Strahlenschutzverordnung, StrlSchV), BGBl, part I, p. 1714.

[10] ICRP: Radiation Protection Principles for the Disposal of Solid Radioactive Waste, Publication 46, 1985.

[11] Ranft, M.; Wollrath, J. (2002): Time Scales in the Long-Term Safety Assessment of the Morsleben Repository, Germany, OECD/NEA Workshop on Handling of Time Scales in Assessing Post Closure Safety, April 16-18, 2002, Paris, France.

[12] Water Protection Act (Wasserhaushaltsgesetz) of the 27 July 1975, BGBl. part I, p. 1110.

[13] Bechthold, W.: Systemanalyse Mischkonzept, Hauptband, Kernforschungszentrum Karlsruhe, Dezember 1989.

[14] Wittke, W. *et al.*: Verschließkonzepte für Untertagedeponien – Entwurf und geotechnische Nachweise. – Geotechnik 21(1998)3. – S. 212 – 216.

[15] Boese, B.; Storck, R.; Brenner, J. *et al.*: Closure of the repository of Morsleben according to the pore reservoir concept and the sealing concept and model calculations for the long-term safety, Proc. Int. Conf. on Radioactive Waste Disposal, September 4-6, Berlin, DISTEC 2000, September 2000.

[16] Resele, G.; Oswald, S.; Wollrath, J. *et al.*: Morsleben nuclear waste repository – probabilistic safety assessment for the concept of extensive backfill, Proc. Int. Conf. on Radioactive Waste Disposal, September 4-6, Berlin, DISTEC 2000, September 2000.

[17] Mauke, R.; Wollrath, J.; Müller-Hoeppe, N: Closure Concept for the Moraleben LLW Reposity for Radioactive Waste Design of Drift Seals in a Former Salt Mine, Proc. NEA Workshop “Engineered Barrier Systems (EBS) in the Context of the Entire Safety Case, Oxford, UK; 25-27 September 2002.

[18] Preuss, J.; Müller-Hoeppe, N.; Schrimpf, C.: The interaction of the evidence of post closure safety and requirements to backfill materials for the Morsleben repository, Proc. Int. Conf. on

Radioactive Waste Disposal, September 4-6, Berlin, DISTEC 2000, September 2000.

[19] Preuss, J.; Eilers, G.; Mauke, R.; Engelhardt, H.J., Lerch, C.; Kreienmeyer, M.; Müller-Hoeppe, N.; Schrimpf, C.: Post Closure Safety of the Morsleben Repository, Proceedings WM´02 Conference, Tucson, AZ, USA, February 2002.

[20] Gesellschaft für Reaktorsicherheit: Deutsche Risikostudie Kernkraftwerke, Fachband 2 Zuverlässigkeitsanalyse, Verlag TÜV Rheinland, 1981.

[21] Müller-Hoeppe, N.; Pöhler, M.; Ein neuer Ansatz zur Bewertung von Barrieren im Endlager, Dokumentierte Erfahrung hinsichtlich dichter Dammbauwerke im Salinar, Abschlussbericht, Technischer Anhang 2, DBE; 1999.

[22] RSK. Empfehlungen der Reaktorsicherheitskommision (RSK), Abteilung 4, Anhänge zu Kapitel 4.2 vom 25. April 1979, 2. Rahmenspezifikation Basissicherheit (Banz. Nr. 167 a), RS-Handbuch, Stand Dezember 1992.

[23] Closs, K.D. *et al.* : Systemstudie Andere Entsorgungstechniken, Hauptband, Kernforschungszentrum Karlsruhe, 1984.

[24] Röthemeyer, H.: Das Endlagerkonzept für die radioaktiven Abfälle des deutschen Entsorgungszentrums, Chemie der Nuklearen Entsorgung, Teil III, Thiemig-Taschenbücher, Band 91, Verlag Karl Thiemig, München, 1980.

[25] Engelmann, H.J.; Wahl, A.: Direkte Endlagerung ausgedienter Brennelemente DEAB (02 E 8201), Systemanalyse Endlagerkonzepte Abschlußbericht, Hauptband, DEAB T59, DBE, Peine Oktober 1995.

[26] Jezierski, Schrimpf: Dammbau im Salzgebirge, Informationsseminar am 9. und 10.11.1983, Entwicklungsvorhaben Dammbau im Salzgebirge Band 9, Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE), 1984.

[27] Engelmann, H.J., Fischer, H. ; Hänsel, W., Wallner, M.: Dams as Sealing Systems in Rock Salt Formations – Test Dam Construction – , WM´88, Tucson, Az, Vol. I, 283-287.

[28] Stockmann, N. *et al.* : Dammbau im Salzgebirge, Abschlußbericht Projektphase II, Berichtszeitraum vom 01.07.1989 – 31.12.1992, GSF- Bericht 18/94.

[29] Bechthold, W.: Thermal Simulation of Drift Emplacement (TSS), Summary of Interim Results, Forschungszentrum Karlsruhe, FZKA-PTE Nr. 4, September 1997.

[30] Jessberger, H.L.: Gefrierschächte Gorleben, Beiträge zum Symposium Gefrierschächte Gorleben, Bochum, 21-22 September 1994, Balkema,, Rotterdam, Brookefield, 1995.

[31] Müller-Hoeppe, N.; Krone, J.: Ein neuer Ansatz zur Bewertung der Wirksamkeit von Barrieren im Endlager (02 E 9087), Abschlussbericht Hauptband, DBE, 1999.

[32] Lommerzheim, A.; Müller-Hoeppe, N.; Engelmann, H.J.: Repository Planning for the Gorleben Working Model, Proc. 5. Int. Conf. Radioactive Waste Management and Environmental Remediation (ICEM), Berlin, Sept. 3-9, ASME 1995.

[33] Fischle, W.R.; Schwieger, K.: Untersuchungen an einem Abschlussbauerk im Kalisalzbergwerk Hope, Kali und Steinsalz, Heft 11, Verlag Glückauf, Essen, 1987, 380-387.

[34] CEN: Eurocode 1, Grundlagen der Tragwerksplanung und Einwirkungen auf Tragwerke, Teil 1: Grundlagen der Tragwerksplanung, DIN V ENV 1991, Stand Oktober 1994.

[35] CEN: Eurocode 7; Entwurf, Berechnung und Bemessung in der Geotechnuk, DIN V ENV 1997-1, April 1996.

[36] DAfStb: DafStb-Richtlinie "Beton beim Umgang mit wassergefährdenden Stoffen", 1996.

[37] Müller-Hoeppe, N.; Krone, J.; Niehues, N.; Raitz von Frentz, R.: A new integrated approach to demonstrate the safe disposal of high-level radioactive waste and spent nuclear fuel in a geological repository, Proc. Int. Conf. Safety of Radioactive Waste Management, Cordoba, Spain 13-17, IAEA, March 2000.

[38] Engelmann, H.J. *et al.* : The Role of the Technical Repository Concept for Repository Siting and Implications of an Advanced Spent Fuel Management Concept – Part I and II- Proc. International Conference on Radioactive Waste Disposal, DISTEC 2000, September 4-6, 2000.

[39] Endlager für radioactive Abfälle Gorleben – Vorstudie zum Konzept, Bericht SE-IB-24, Physikalisch-Technische Bundesanstalt, 1989.

[40] Ploumen, P.: Numerische Langzeitberechnung dreidimensionaler Temperaturfelder mit Hilfe eines speziellen Finite Element Verfahrens am Beispiel der Endlagerung hochradioaktiver Abfälle im Salzgestein, Dissertation RWTH Aachen, 1980.

THE EC PROTOTYPE REPOSITORY PROJECT: IMPLICATIONS OF ASSESSMENTS FOR REFINING REPOSITORY DESIGN

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1. Introduction

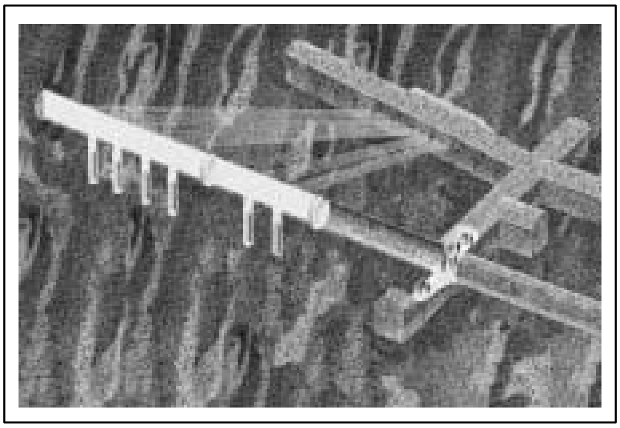
The most important issue in the evaluation of the repository performance is the long term safety of the repository. Analyses for this issue focuses on the "steady state" conditions which start at the time when the repository has been saturated and the groundwater table returned to its normal level. The bentonite buffer around the canisters is saturated and homogeneous, and the canister is located exactly in the centre of the buffer. The backfill in the tunnel has been saturated as well and fills the earlier open spaces in the tunnel completely.

The task of the activities taking places prior to the start of the "steady state" conditions, like excavation, deposition, backfilling and sealing, with due consideration to the processes and consequences they may cause in the long run, is to provide for these "ideal" conditions, as close as possible.

While studying these activities in detail it has become obvious that development of methods and techniques needs to be carefully addressed before the decision is made on how to apply them in the repository. One general finding is that the situation in engineering of details is not that much different from the situation in geological characterisation of a site in detail; one more detail of engineering and the consequences it brings often complicates the situation rather than supports the solution prioritised so far.

Many of the practical issues have been studied in the Prototype Repository project in the AEspoe Hard Rock Laboratory (Pusch *et al.*, 2000).

Figure 1. Prototype Repository. All cables are placed in lead-throughs with water-tight connections to the adjacent drift



The Prototype Repository consists of two sections with four respectively two deposition holes with bentonite buffer and canister, the latter holding electrical heaters. The sections are separated by a concrete plug, and the whole test is to be separated from the rest of the laboratory by an outer plug.

The project has two objectives:

1. To demonstrate the integrated function of the deep repository components under realistic conditions and to compare results with models and assumptions.
2. To develop, test, and demonstrate engineering standards and quality assurance methods.

Only the latter objective is addressed in this paper.

The development, testing and demonstration of engineering issues concerned methods and processes which start with boring of deposition holes and ends with backfilled and plugged test tunnel. Two parameters were of special concern: temperature on the surface of the canister and saturated density of the bentonite buffer around the canister.

2. Practical emplacement of buffer and canister

Conceptual models of a deposition hole has for a long time assumed an outer slot between the bentonite block before swelling and the rock of 50 mm and an inner slot between the bentonite block and the canister of 10 mm, which was the best the deposition technique was considered able to do (SKB, 1983). Still the amount of bentonite in the deposition hole would be too little to reach the targeted density, a problem, which was solved by filling the outer slot with bentonite pellets. This complex combination of practical issues contains the following:

- Accuracy in boring the deposition holes.
- Water inflow and means of decreasing the flow.
- Installation of the bentonite column with a vertical opening in the centre for disposal of the canister. (The bentonite column is in the future repository going to be installed first in order to provide a radiation shielded working environment in the deposition drift; a start with the canister would mean a naked canister in the deposition hole.).
- Deposition of the canister weighing approximately 25 tonnes.
- Complete backfilling of the tunnel.

The backfilling aims at filling the tunnel above the deposition holes with a material that has a swelling capacity toward the roof during a long time after closure. The rationale is that soil or sand materials settle with time, as the pore volumes between the particles decrease with time. In an underground tunnel this results in the development of channels in the roof region. The solution chosen is to use bentonite, and to mix it with sand or crushed rock for economical reasons. The content of bentonite depends on the salt content of the ground water. In fresh water provides 10% bentonite a swelling capacity, while the same swelling capacity needs approx 30% bentonite in water with 1% salt (TDS) (Boergesson *et al.*, 2001).

2.1 Accurate boring of deposition holes

The boring of the deposition holes was the key to the whole process. Proven technology was adapted to the specific circumstances and demands. In a first step the technical feasibility of boring holes was tested at Olkiluoto. For that test a raise boring equipment was used which just was converted to “down hole” boring instead of reaming from a tunnel below, which is the natural way in raise boring. In practice the whole bore head – 5 feet in diameter – was pushed downwards and the muck evacuated by vacuum suction. Not that much attention was put on the steering of the direction; best practice was applied. The test was a success.

For the AEspoe tests a detailed specification was made covering the deviation of the whole, the degree of “banana” shape, the decrease in diameter and the roughness of the surface. The Robbins company was able to provide the requested specifications and used a TBM machine of their construction with a diameter of 1.75 m and without the gripper sections; the machine was pushed downwards by hydraulic jacks. One advantage with the construction is that full force can be applied on the machine and the damage on the rock wall, i.e. EDZ, can be measured *in situ*. Muck was also removed in this case by vacuum suction.

The result in the 13 holes bored was that all specifications were met, and that the crucial parameter, the deviation, was less than specified – maximum 15 mm versus 25 mm in the specification (Andersson *et al.*, 2002). If this lower value can be maintained the bentonite blocks can be made a bit wider so that the final density after saturation is achieved without using bentonite pellets in the outer slot. Besides the advantage of excluding the handling of pellets is the exclusion also contributing to a more homogeneous buffer around the canister. With only bentonite blocks is the amount of bentonite very homogeneously distributed around the canister. With pellets is even a very small inclination of the hole resulting in an inhomogeneous distribution of bentonite around the canister; more pellets on the side where the slot is the widest.

2.2 Water inflow and means of decreasing the inflow

High water inflows have always been looked upon as a problem, and are listed as one of the issues in the judgement of whether or not a specific deposition hole should be accepted or rejected. The exact level of what can be accepted has not been determined. In the course of the Prototype Repository project and other projects involving full scale bentonite buffer two lessons were learnt. One is that the top blocks start to swell and expand upwards quicker than expected. The consequence of this is that the time for the prioritised in situ backfilling method is too long and that either a faster backfilling method is developed or that the deposition and backfilling is made in sequences. A second is that engineering means can be developed for handling of large rates of water inflow. A method tested with success was to line the deposition hole prior to deposition of the bentonite column. Plastic was used in the test. This plastic was attached to the bottom slab so that a water tight bag was obtained for the bentonite. When the canister had been deposited and the top blocks also emplaced, the bag was closed and the air condition inside adapted to the precise relative humidity that kept the bentonite from either shrinking or swelling. The bag was removed just prior to the backfilling of the part of the tunnel that passed over the deposition hole. With such a method with protective lining the water inflow rate is not an issue in the disposal process.

2.3 Installation of the bentonite block column

An existing press, which SKB has access to is powerful, and can make full diameter blocks at 100 MPa pressure, but only with a height of 0.5 m (Johannesson, 2002). Consequently will the column in the hole consist of 10 cylindrical blocks up to the top of the canister, one block below the canister and three blocks above the canister. The blocks have to be very accurately positioned, mm accuracy, as the inner hole is going to be only 20 mm wider than the canister. The project verified that this accuracy is perfectly possible to obtain (Boergesson *et al.*, 2002).

The correct vertical alignment of the column is also dependent on the bottom slab, which need to be very horizontal. Each deviation from the horizontal generates a manifold deviation of the bentonite column. The bottom slab in the Prototype Repository was made by floating concrete on top for self-adjusting to the horizontal of the surface.

The actual building of the column was made with a gantry crane having bands which were tided under the bottom of the blocks running in groves made for the bands. These were recovered when the block was in place. Although having steering devices under the block the final adjustment was made by man.

Higher blocks would mean faster building of the column and more accurate positioning of it with less risk for missing one block's position too much.

2.4 Deposition of canister

Once the bentonite column was in place was the deposition machine with the canister positioned over the hole and the bed with the canister exactly fixed to its position. The canister was tilted down until it was hanging vertically in the top of the deposition hole, above the top bentonite block. The alignment by gravity was perfect, as the canister is very symmetric in design and homogeneous. Lowering the canister created no problem, and the allowed slot of 10 mm between bentonite blocks and canister was more than enough (Boergesson *et al.*, 2002).

The deposition was made more times than expected because of wrongly made electrical connection to the heaters inside the canisters. Two canisters in different projects, of which one was installed in the Prototype Repository, had to be retrieved and the electrical circuits repaired, where after the canisters were deposited again, with the same precision.

2.5 Backfilling of the tunnel

The backfill has to be emplaced shortly after the start of swelling of the bentonite in the deposition hole, in order to prevent a too high up-swelling. The prioritised method is to place the loose backfill mixture in layers and compact them *in situ*. For this purpose has an ordinary vibrator system, which is used in surface road construction, been adapted to working on inclined slopes. The vibrator is mounted on a boom for good access over the area to be compacted. The original idea was to place a horizontal layer in the tunnel, up to about mid-height and on this place the top part in an inclined mode. Layers would be about 300 mm thick and compacted to 200 mm. This worked in the Stripa Test Mine, but not in AEspoe Hard Rck Laboratory, because of the water dripping from the roof there. Instead the backfilling had to be made in one step. The inclination of the layer was selected with respect to the angel for a stable slope in soil materials, which is about 30 degree from the horizontal plane. Otherwise would the so carefully mixed material segregate in the tunnel with the larger particles rolling down to the floor. The same type of compaction method as originally planned was applied (Boergesson *et al.*, 2001).

In different tests in other projects in the AEspoe Hard Rock Laboratory have different backfill materials been investigated. Compared to the standard Proctor compaction procedure are the differences, that crushed rock only can be compacted with the used equipment to about 110% Proctor, a mixture of 30% bentonite and 70% crushed rock to about 85% Proctor and a natural bentonite-rich clay to about 60-65% Proctor. This is obtained with well mixed and homogeneous materials, and indicates that higher impacts are required than the tested equipment can provide, if the backfill material is changed from a type dominated by sand or crushed rock to a type dominated by clay.

The mixing of bentonite, crushed rock and water (not optimal water content in the natural products) is sensitive and investigations in other tests reviled that the most intense mixing of such materials is done in an Eirich type of mixture, which is common in the material industry. The principle is based on rotating blades in the same fashion as e.g. the household mixer (Gunnarsson, 2002).

2.6 Temperature limitation

The key parameter for the design of a repository is the maximum temperature that can be accepted on the surface of the canister or in the bentonite. In Sweden and Finland is the criterion 100°C on the surface of the canister. Calculations for this value results in a centre distance of canisters with 6-7 m and a distance between deposition tunnels of 20-40 m. These results are only valid in the case that the bentonite has a thermal conductivity that is close to the one of saturated bentonite. Dry bentonite or a rock with distinct lower thermal conductivity than that of granite require much larger distances 8or less fuel per canister). Exactly 6 m distance was chosen in the Prototype Repository and the highest temperature was calculated to be 90°C on the surface of the hottest canister. The bentonite blocks were all fabricated with a high initial water ratio, which has a thermal conductivity close to that of fully saturated bentonite.

In the long run, when the buffer has been fully saturated and good contacts exist between all repository components the conditions are good for accurate prediction of heat conduction and temperature increase. During the saturation phase, before water fills up the slots and/or the bentonite swells and makes good contacts with the canister and rock respectively, all voids decreases the accuracy in the predictions. Still the temperature increase is a phenomenon that in other rock laboratories as well as in other tests in AEspoe Hard Rock Laboratory has proved to be accurate to model and predict. So far the inner section of the Prototype Repository with four canister positions has indicated a difference in the temperature compared to predictions between the very “wet” hole and the very “dry” hole (Goudarzi *et al.*, 2003). Good conduction keeps the temperature down. As an example has a slot of 10 mm between the canister and the bentonite blocks been calculated to represent a temperature drop of 20°C, as long as the slot remains. Such numbers has a major impact on the design of the repository, because the models indicate that every degree results in a substantial increase in the distance between the canisters. In the Swedish case was conceptually a “safety factor” of 20°C used, i.e. the design aimed at a maximum of 80°C on the surface of the canister. The present situation is that this “safety factor” has been reduced to 10°C, and the Prototype Repository project is expected to confirm that this is feasible.

3 Results and conclusions

Construction and deposition processes mainly aim at providing the conditions necessary for the repository to reach the steady state conditions specified for a safe disposal in the long run. Many issues are of practical nature and smooth and efficiently working methods and equipment need to be developed, basically from existing and proven technology. The Prototype Repository Project has been designed to address among other things a number of these practical issues, which affect the design of the repository. The result and conclusions from topics raised in this paper are in brief:

- Very accurate deposition hole boring is possible and may allow less wide slots, and exclude the need of bentonite pellets.
- Larger bentonite blocks would simplify the deposition process and help to limit the width of needed slots.
- The inner slot of 10 mm is more than enough for the canister deposition.
- Engineering measures can handle very high water inflow rates into holes and tunnels.

- Without such measures the swelling and displacement of the bentonite top go faster than expected; deposition and backfilling sequences have to be redesigned.
- *In situ* compaction of 30/70 backfill mixtures can be made to requested density with the tested method. Higher bentonite content would need a higher impact force.
- The *in situ* compaction method tested is not efficient with respect to material transport to the front.

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References

Andersson C, Johansson AE, 2002. Boring of full scale deposition holes at the AEspoe Hard Rock Laboratory – Operational experience including boring performance and a work time analysis. Technical Report TR-02-26, Swedish Nuclear Fuel and Waste Management Company, Sweden.

Boergesson L, Johannesson L-E, Gunnarsson D, 2001. Backfilling of the tunnel in the Prototype Repository. Results of pre-tests. Design of material, production technique and compaction technique. AEspoe Hard Rock Laboratory International Progress Report IPR-01-11. Swedish Nuclear Fuel and Waste Management Company, Sweden.

Boergesson L, Gunnarsson D, Johannesson L-E, Sandén T, 2002. Prototype Repository Installation of buffer, canisters, backfill and instruments in Section I. AEspoe Hard Rock Laboratory International Progress Report IPR-02-23. Swedish Nuclear Fuel and Waste Management Company, Sweden.

Goudarzi R, Boergesson L, 2003. Prototype Repository Sensors data report (Period: 010917-030301) Report No: 5. AEspoe Hard Rock Laboratory International Progress Report IPR-03-23. Swedish Nuclear Fuel and Waste Management Company, Sweden.

Gunnarsson D, 2002. Backfill production for the Prototype Repository. AEspoe Hard Rock Laboratory International Progress Report IPR-02-20. Swedish Nuclear Fuel and Waste Management Company, Sweden.

Johannesson L-E, 2002. Manufacturing of bentonite buffer for Prototype Repository. AEspoe Hard Rock Laboratory International Progress Report IPR-02-19. Swedish Nuclear Fuel and Waste Management Company, Sweden.

Pusch R, Svemar C, 2000. Prototype Repository, Project description. AEspoe Hard Rock Laboratory International Progress Report IPR-00-30. Swedish Nuclear Fuel and Waste Management Company, Sweden.

SKB, 1983. Final Storage of Spent Nuclear Fuel – SKB 3. Volume I General. Swedish Nuclear Fuel and Waste Management Company, Sweden.

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Chairperson: J-P. Boyazis

Rapporteur: S. Voinis

Participants: D.G. Bennett, J. Hansen, L. Moren, M. Raynal and H. Ueda

Working Group B **Practical Approaches to Defining Design Requirements and Accounting for Uncertainty and Constraints**

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Working Group C **Practical Approaches to Developing/Evaluating/Selecting between Alternative Design Options and Refining Selected Designs.**

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Working Group D **Practical Approaches to Linking “High-level” requrements to Detailed Desigh Requiremnts/Specifications**

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