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Safety functions, performance targets and technical design requirements for a KBS-3V repository

Conclusions and recommendations from a joint SKB and Posiva working group

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Preface

One of the strategic goals for the cooperation between Posiva and SKB is formulating jointly the long-term safety principles guiding the design and production of a spent nuclear fuel repository. This report presents the joint bases for the technical design requirements, performance targets and safety functions of a KBS-3V repository. The work was initiated by the Posiva-SKB joint steering group for cooperation.

The project leader at SKB was Johan Andersson and, at Posiva, Juhani Vira (until 2015) followed by Jukka-Pekka Salo. Several technical experts and long-term safety assessors working for Posiva and SKB have contributed to the presented requirements as well as to their rationale and justification.

The report has been compiled by an editorial group consisting of Lena Morén and Karin Pers from SKB, Barbara Pastina from Posiva and Pirjo Hellä from Saanio & Riekkola.

Contents

1 Introduction

1.1 Background

The strategy for direct disposal of spent nuclear fuel in a KBS-3 repository is similar in Sweden and Finland, and there has been extensive cooperation between the waste management organizations in the two countries over the years. Since both programmes are now entering a stage of final design and implementation this cooperation will be deepened, aiming when possible for the same technical design.

In March 2011, the Swedish Nuclear Fuel and Waste Management Co. (SKB) submitted license applications according to the Act on Nuclear Activities and the Environmental Code for a final repository at Forsmark, Sweden. A comprehensive licensing review is currently being undertaken by the Swedish Radiation Safety Authority (SSM) and the Environmental Court. Construction of the repository cannot begin until the necessary licenses have been granted.

In December 2012, Posiva Oy submitted a construction license application for the encapsulation plant and the disposal facility at Olkiluoto for the spent nuclear fuel produced in Finland. The Radiation and Nuclear Safety Authority in Finland (STUK), provided a favourable statement to the Ministry of Environment and Energy and additional requirements for Posiva to fulfil before the submittal of the Operations License Application. On November 12th, 2015, the construction licence was granted to Posiva by the Finnish Government.

To guide the future co-operation the two companies have developed a shared vision. This vision '*Operating optimized facilities in 2030*' marks the objective and readiness to execute a plan for safe and economically optimized repository production and facility operation. The realisations of the vision means, by joining forces, an attempt to ensure that the burden on customers is minimized by licensing, manufacturing and procuring components jointly, by streamlining the operational procedures and supporting facilities, and by aiming at further improvements.

To facilitate the efforts towards this shared company vision, joint strategic goals have been set. The most important is a consensus on the design principles and premises that optimally take into account the constraints that exist and opportunities that are offered by the similarities in the spent nuclear fuel types, the available technology and the selected repository sites in the two countries. In the end, there may be some differences in design requirements and designs adopted by SKB and Posiva, respectively, because of somewhat different site conditions, fuel types and regulatory framework, but the vision of optimised facilities implies that unexplained and unjustified differences in the design requirements and the designs should be avoided. Having set this as a strategic goal, the work to harmonize the requirements is initiated in through this report. The requirements presented in this report will form the basis for the future cooperation in the design and development of final repositories for spent fuel.

1.2 Basis for the report

1.2.1 The KBS-3 repository

As stated in Section 1.1, Posiva and SKB intend to dispose of the Finnish and Swedish spent nuclear fuel in KBS-3 repositories. In a KBS-3 repository:

- the spent fuel is encapsulated in tight, corrosion resistant and load-bearing canisters,
- the canisters are disposed in crystalline bedrock at a depth sufficient to isolate the encapsulated spent fuel from the surface environment,
- the canisters are surrounded by a buffer that prevents the flow of water and protects them, and
- the cavities in the rock that are required for the deposition of canisters are backfilled and closed.

A KBS-3 repository consists of the rock at the repository site, the canisters containing spent nuclear fuel, the buffer surrounding them, backfill and closures, as well as engineered and residual materials that remain in the rock once the underground openings have been backfilled and closed.

In a KBS-3 repository, the encapsulated spent nuclear fuel can be disposed of vertically in holes drilled from the bottom of deposition tunnels (KBS-3V) or horizontally in long near-horizontal deposition holes or drifts containing multiple canisters (KBS-3H). This report concerns a KBS-3V repository with vertically disposed canisters, with one canister per deposition hole. Since, most of the presented safety functions, performance targets and technical design requirements, e.g. those for the canister, buffer, closure and host rock, are valid for both the KBS-3V and the KBS-3H designs, the term "KBS-3 repository" is used throughout the report. The KBS-3H concept and the specific requirements for horizontal deposition are currently being developed in a joint Posiva-SKB project and are not discussed in the present report.

1.2.2 Regulatory basis

STUK (Finish Radiation and Nuclear Safety Authority) in Finland and SSM (Swedish Radiation Safety Authority) in Sweden issue regulations, guidelines and general advice for the safe disposal of spent nuclear fuel. Both authorities report to the ministries and governments in Finland and Sweden, respectively, and they both have a broad responsibility for the protection of people and the environment from the undesirable effects of all kinds of radiation.

STUK and SSM review the work of Posiva and SKB, respectively. They will also inspect the construction and operation of the facilities and transport systems required to encapsulate and handle the spent nuclear fuel, and the construction of the KBS-3 repository and its engineered barriers. Posiva and SKB are obliged to follow the regulations and guidelines issued by the national authorities as well as the terms and conditions stated within their reviews and reports on inspections.

The national regulations as well as the terms and conditions stated by STUK and SSM are somewhat different. However, there are also many similarities, since the Finnish and Swedish regulations are based on common and internationally accepted and agreed radiation protection and safety principles, and since both countries plan for geological disposal.

The requirements for a KBS-3 repository originates firstly from the principle that future generations should not be exposed to radiation doses larger than those currently accepted for nuclear facilities or activities, and secondly from the multi-barrier principle. According to the multi-barrier principle the post-closure radiation safety of a final repository shall be based on a system of passive barriers that act in different ways, either directly or indirectly by protecting other barriers in the barrier system, so as to:

- isolate the repository from the surface environment,
- contain the radionuclides,
- retain the radionuclides and retard their dispersion into the environment.

These principles and required safety functions are expressed in different ways in STUK's and SSM's regulations. In line with the IAEA glossary and safety standards *isolation from the surface environment*, the *containment of radionuclides*, to *retain radionuclides and retard their dispersion* into the environment and to *protect and preserve the safety functions of the barrier system* can be referred to as *main safety functions* of final repositories (IAEA 2007, 2012). In addition to these, and also in line with IAEA standards, to *maintain sub-criticality* can be considered to be a main safety function of final repositories for spent nuclear fuel.

In its fundamental safety principles, IAEA states that, to avoid harmful consequences of radiation, the occurrence of failures and their escalation shall be prevented. Further, it is stated that this can be achieved by an effective management system, adequate site selection and the incorporation of good design and engineering features providing safety margins. To provide safety a design technology and materials of high quality and reliability and an appropriate combination of inherent and engineered safety features shall be used (IAEA 2006, Sections 3.30–3.32). These are means to provide defence in depth in a nuclear facility in operation. These means to achieve safety can also be applied to the

passive barriers of a final repository. In nuclear facilities in operation, active inspections, control of systems maintaining safety functions and mitigating measures taken in case they should fail are additional and important parts of the defence in depth. The defence in depth principle can be applied to the design, development and production of final repositories. The design shall be robust i.e. durable with respect of the conditions expected during the long-term evolution and insensitive to variations that are expected to occur in the production or in the final repository. The production shall be reliable and insensitive to disturbances, and the design as well as the production shall be quality assured. These principles are in different ways expressed in STUK's and SSM's regulations.

1.2.3 Posiva's and SKB's requirements and requirement management

The design of a KBS-3 repository is the result of an iterative design and development process. The design cannot be determined directly from the radiation protection and safety principles and the main safety functions of final repositories introduced in Section 1.2.2. Instead, the principles and main safety functions form the basis for the development of technically feasible repository designs. The ability of the designs to maintain safety are then analysed in post-closure safety assessments. The safety assessments will provide more detailed requirements for the design as well as feedback on how the assessed designs may be improved to promote post-closure safety. The iterative design process is further discussed in Section 2.1.

The current design requirements for the post-closure safety of a KBS-3-repository are specified in the SKB and Posiva license applications, respectively. SKB has presented requirements referred to as *design premises* relating to post-closure safety (SKB 2009), and demonstrated, in the post-closure safety assessment SR-Site (SKB 2011), that an as-built repository design that conforms to these design premises will maintain post-closure safety. In a similar manner, Posiva submitted their requirements, called *design basis* (Posiva 2012a) as part of the license application submitted in December 2012. The post-closure safety of the resulting designs was assessed in TURVA-2012 (Posiva 2012a), which is Posiva's safety case in support of application for a construction license for a disposal facility for spent nuclear fuel at the Olkiluoto site. This Posiva safety assessment demonstrated that satisfactory post-closure safety of a KBS-3-repository can be achieved. The updating of the requirements and the development of the design, methods, processes and technical systems to produce and quality assure a KBS-3 repository have proceeded on the basis of the results of the safety assessments and the regulatory feedback received thus far.

To support quality management and the correct handling of requirements in the design and development of a final repository and to achieve conformity with those requirements, Posiva and SKB have developed requirement management systems. As part of their requirement management systems, both Posiva and SKB account for how the requirements in the regulations are interpreted and applied in terms of their requirements on a KBS-3 repository and its design. The requirement management systems comprises databases where the different kinds of requirements and relations between them are documented, as well as rules and instructions on how and by whom they shall be formulated, decided, verified and validated. At Posiva, the database is called *VAHA* (from the Finnish acronym for requirements management) whereas at SKB it is referred to as *the requirement database*.

1.2.4 Terminology in the report

As mentioned in Section 1.2.2, there are some regulatory differences between Finland and Sweden. In addition, there are differences in the nuclear power programmes and corresponding programmes for the management of spent nuclear fuel, as well as in Posiva's and SKB's responsibilities, policies, objectives and organisations, and how the organisations are directed and controlled with regard to quality. Further, the structures of the requirement databases and safety assessments differ between the two countries. This has resulted in differences, for example, in terms and definitions, as well as in different formulations of requirements.

However, as pointed out in the previous sections, there are also many similarities in the requirements as well as in the assessments as to whether they are fulfilled. The radiation safety of the KBS-3 repositories planned to be constructed in Olkiluoto and Forsmark will be maintained in a similar manner and thus they are required to fulfil similar requirements. The requirements stated in

this report are based on these similarities. For this purpose, a terminology to be applied in this report is established based on the currently applied terminologies in Finland and Sweden, respectively. The intention is that the stated requirements shall be easy to incorporate into the contexts of the national regulations and the nationally established format of the safety assessment reports and requirement management systems. The terminology is presented in Table 1-1.

Table 1-1. Terminology applied in this report to state requirements on the safety functions and design of a KBS-3 repository.

Term	Definition in this report	Presented in this report
safety function	(in a KBS-3 repository) function that contributes to isolation from the surface environment, to containment of radionuclides and/or to retention of them, and to retardation of their dispersion into the environment, either directly or indirectly by protecting the barriers in the repository Note 1: In IAEA Safety Glossary (IAEA 2007) safety function is defined as a purpose that must be accomplished for safety. Safety refers to nuclear safety and protection and safety, whose common purpose is to protect people and the environment against harmful effects of radiation. In final repositories, radiation safety shall be maintained by a system of passive barriers. In line with the IAEA Safety Glossary and safety standards (e.g. IAEA 2012) i) isolation from the surface environment ii) containment; iii) to retain and retard the dispersion of radionuclides and iv) to protect and preserve the safety functions of the barrier system can be regarded as *main safety functions* of final repositories. In addition, to maintain sub-criticality can be considered to be a main safety function. Note 2: Safety functions are evaluated, assessed or verified in post-closure safety assessments. Note 3: The sets of safety functions used by SKB and by Posiva are similar but not identical, see further Section 1.3.	The safety functions to be maintained by each part of a KBS-3 repository are identified and named.
performance target	measurable or calculable quantity or characteristic through which the maintenance of a safety function can be quantitatively evaluated, and when met implies that the safety function is upheld Note 1: Concerns post-closure safety and individual parts of the multi-barrier system. Note 2: If met, this implies that the safety function of the individual part of the repository is upheld. If not met, this implies that the safety function is impaired, but neither that it is necessarily totally lost nor that the safety of the repository as a whole is not upheld, but rather that additional analyses are needed to demonstrate post-closure safety. Note 3: The assessment of fulfilment of the performance targets requires modelling or other types of analyses. These are carried out within the post-closure safety assessments.	Common performance targets, as far as possible quantitative, are stated and justified.
technical design requirement	requirement that a characteristic of an engineered barrier or underground opening shall fulfil to be approved as a part of a KBS-3 repository Note 1: The characteristics to be complied with in the design are generally stated in design requirements. Note 2: For an as-built KBS-3 repository that fulfils the technical design requirements, it shall be possible to evaluate whether performance targets will be met in the long-term evolution, and to show that the post-closure safety of the repository can be maintained. Note 3: Must be technically achievable and possible to verify at the latest at the time of final installation, deposition or backfilling. Verification can be achieved by testing of finished parts or components, or by measuring or controlling process parameters related to the characteristics of importance for requirement compliance.	Common technical design requirements that any specific design shall fulfil are stated and justified.

Term	Definition in this report	Presented in this report
design specification	the design parameters that define the engineered barrier or underground opening characteristics, and their acceptable values and tolerances Note: It must be possible to measure, test, inspect or control the design parameters during the construction of a KBS-3 repository and production of its engineered barriers and underground openings.	The design specifications are not within the scope of this report, the design parameters are simply outlined. Design specifications are defined within the design and development of the different parts of the repository.
as-built	describing or representing the actual appearance and characteristics Note 1: The as-built characteristics of the engineered barriers and underground openings can be used to define their initial state in the assessment of the post-closure safety of a KBS-3 repository. Note 2: Before the actual construction and production is initiated as-built refers to the actual appearance and characteristics that can be expected based on performed trials and available experience from similar procedures. After the construction and production is initiated, as-built refers to the measured, tested, inspected and documented appearance and characteristics of the actual repository or part in the repository.	How the characteristics or the design parameters can be determined and verified in the production is outlined in general terms. No quantitative measures for the as-built appearance are given.

In addition to the terms defined in Table 1-1 the terms in ISO 9000:2005 Quality management systems – Fundamentals and vocabulary are used in this report.

1.2.5 Requirement structure in the report

The relations between the terms introduced in Table 1-1, and the level of detail in the design and development of a final repository are illustrated in Figure 1-1. The requirements on each level of detail in the design provide specifications for a KBS-3 repository, individual barriers and barrier designs respectively. The figure also includes the criteria or terms used for evaluation of requirement conformity. The basis for the terminology and requirement structure is presented in the following text.

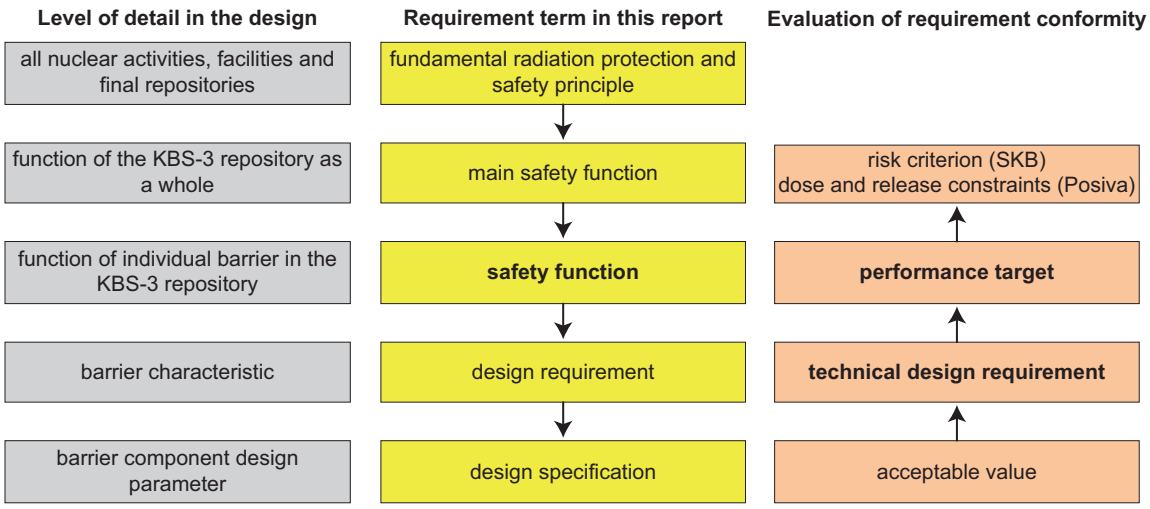

Figure 1-1. *Relations between level of detail in the design, requirement terms used in this report and evaluation of requirement conformity. This report focuses on safety functions, performance targets and technical design requirements, and these are indicated in bold text.*

The final repository as a whole shall apply the fundamental radiation protection and safety principles and maintain the *main safety functions*. The overall criterion for evaluating repository safety is in Sweden the risk criterion issued by SSM and in Finland the dose and release constraints issued by STUK. As further elaborated in SKB's safety assessment SR-Site (SKB 2011, Section 8.2) these are criteria related to the safety of a KBS-3 repository as a whole. Their evaluation requires input from numerous analyses of external conditions, the barriers and the repository barrier system. The assessment of the overall safety of a KBS-3 repository is thus the result of several integrated analyses comprising various model evaluations using a large set of input data.

The detailed and quantitative understanding and assessment of repository safety requires a more elaborated description of how the main safety functions of containment, retardation and protection of other barriers are maintained by the system of passive barriers of the repository. Based on the understanding of the characteristics of the components and the long-term evolution of the barrier system, a number of subordinate *safety functions* to containment, retardation and protection of other barriers can be identified and assigned to the different parts of a KBS-3 repository.

All safety functions assigned to an individual barrier belong to the same level of detail in the design. The safety functions are however of differing importance for radiation safety and design, and they are also of different character. The safety functions of most importance for repository safety and design are generally related to the main safety functions of the repository, and are assigned quantitative performance targets.

Some safety functions can rather be regarded as intrinsic features affecting safety, than safety functions that are specifically assigned to the different parts of the barrier system, and that they are designed to maintain in order for the repository as whole to maintain safety. Some of these features need to be controlled by design measures for the design to be incentive to disturbances and deviations that may occur, whereas others are credited as contributing to safety. For example, the different parts of the barrier system shall be compatible, and intrinsic features, e.g. impurities in the materials used, that may act to degrade safety functions need to be limited and controlled by design measures. An example of an intrinsic feature credited as contributing to safety is the ability of the fuel pellets to retain radionuclides. Whether these, and similar, features are referred to as safety functions may differ between Posiva and SKB. Within this report, they all belong to the safety function level of detail in the design in Figure 1-1, and are assigned performance targets. Some such features common for several barriers are further discussed in Section 2.2. The safety functions specifically assigned to the canister, buffer, backfill, closure and the rock with its underground openings and how they contribute to the main safety functions of the repository are discussed for each barrier.

In order to quantitatively evaluate safety, it is desirable to relate or express the safety functions in terms of measurable or calculable quantities, often in the form of barrier conditions. Furthermore, in order to determine whether safety functions are maintained or not, it is desirable to have quantitative criteria against which the maintenance of each safety function can be evaluated. In the vocabulary of SKB, these criteria are called *safety function indicator criteria*, whereas Posiva uses *performance targets*. In this report, the term *performance target* with the definition in Table 1-1, and as illustrated in Figure 1-1, is used.

It is emphasised that the breaching of a performance target does not necessarily mean that the safety function is totally lost. Neither does it necessarily mean that the repository as a whole will not maintain safety or comply with dose or risk limits. Breaching a performance target is an implication of caution. If a performance target is breached, more elaborate analyses are required in order to evaluate safety.

The as-built KBS-3 repository shall be able to maintain safety from the moment the engineered barriers are finalised in the underground openings of a KBS-3 repository facility and as long as required with respect to the radiation safety of the closed and sealed KBS-3 repository. With respect to this, the characteristics of the engineered barriers that impact their ability to maintain the safety functions must be designed to withstand the conditions and stresses that may occur at the repository site. The underground openings must be adapted to the host rock so that the rock can maintain its safety functions. For the characteristics of the engineered barriers and underground openings that

contribute to maintaining the safety functions, technical design requirements that can be inspected and verified in the production of the repository are stated. The technical design requirements are based on the assessment of the post-closure evolution of the performance targets and available technology. The characteristics of the barrier system shall fulfil the technical design requirements when the spent fuel is finally encapsulated, the canister finally disposed of and the buffer, backfill and closure finally installed in the underground openings.

In design specifications the characteristics are specified in more detail by design parameters and their acceptable values, e.g. a required buffer density may be defined by the weight, dimensions and water content of buffer components. The design specifications are used in the production, and it is required that it shall be possible to determine and quality assure the design parameters, either by controlling manufacturing processes, or by tests and measurements of their products or a combination of the two.

1.3 Objectives and limitations

The common Posiva-SKB objective of this report is to state the technical design requirements that an as-built KBS-3 repository shall fulfil with respect to post-closure safety.

In so doing, the safety functions that the different parts of a KBS-3 repository should provide play a decisive role, as do the performance targets for these safety functions. The sets of safety functions used by SKB and by Posiva are similar but not identical. The set of safety functions used in this report are based on those included in SKB's SR-Site report and Posiva's TURVA-2012. The present report does not prescribe in detail the safety functions to be used in either organisation's future safety assessments. However, it is expected that these assessments will largely apply the safety functions that are presented in this report.

The performance targets in this report are updates of those established in SR-Site and TURVA-2012. They are intended to be used in SKB's and Posiva's future safety assessments. Any changes or additions to the performance targets presented here will be justified in the safety assessment reports from the individual organisations.

The technical design requirements and the characteristics of the different parts of a KBS-3 repository that shall conform to them are stated on a common basis. These commonly stated technical design requirements and characteristics to be taken into account in the design are to be used in the future common development of a KBS-3 repository design and of production systems.

This report presents the safety functions, performance targets and technical design requirements that constitute an adequate basis for future cooperation in design and development of the barrier system and its production system. The report does not discuss how the presented safety functions, performance targets and technical design requirements are incorporated into the national specific requirement management systems and safety assessment reports, or how they are to be used to address compliance with national regulations.

The presented safety functions, performance targets and technical design requirements are explained and justified. Implications for the design and the verification of the technical design requirements and their related characteristics and design parameters are outlined. Design specifications are not included in this report, as they are part of future design and development. Further details on requirements verification will be given in the safety analysis reports or as part of the future design and development and are not included in this report.

The report only includes post-closure safety functions and technical requirements to be fulfilled by the different parts of a KBS-3 repository. Requirements on the systems and procedures used to produce these parts, or on their handling during the operation of the transport systems, encapsulation or repository facilities, are not included. Requirements on the design resulting from the production or handling systems are also out of scope of the report. Neither are operational safety-related functions and requirements addressed in this report.

The presented safety functions, performance targets and technical design requirements concerns the KBS-3V design variant of a KBS-3 repository. The adaptations required for the KBS-3H design are not included, also see Section 1.2.1.

In Finland, the retrievability of the canisters after disposal was defined as a requirement in the parliamentary hearing on the Decision-in-Principle in 2001. In Sweden, retrieval shall be possible as long as the KBS-3 repository facility has not been decommissioned and finally closed. Retrievability and requirements concerning the possibility of retrieving disposed spent fuel are not discussed in this report.

1.4 Structure and content of the report

In Chapter 2, the iterative design and assessment process required to develop the safety functions, performance targets and technical design requirements introduced in Section 1.2.4 is described. The chapter also presents features that impact safety and are common to all or several barriers in a KBS-3 repository.

In Chapter 3, the spent fuel to be disposed of and how it impacts the design, radiation safety and safety assessment of a KBS-3 repository are discussed. The features and characteristics of the spent fuel that contribute to or impact the radiation safety of a KBS-3 repository are stated.

In Chapters 4 to 8 the conceptual designs, safety functions and their performance targets as well as the technical design requirements are presented for the engineered barriers, the underground openings and the rock. The safety functions with their performance targets and the technical design requirements are compiled in tables directly under sub-titles stating the safety function or, for the technical design requirements, the characteristic to be designed. Each safety function, performance target and technical design requirement is justified, and the conditions to be considered when assessing them as well as the implications for design and verification are outlined. For clarification and traceability, SKB's and Posiva's requirements on the functions of the different parts of the barrier system exactly as they were stated within SKB's and Posiva's requirement management systems for the SR-Site and TURVA-2012 safety assessments are presented. After each presented requirement, a reference to the requirement databases is given as "Requirement" followed by the id-code of the requirement.

In Chapter 9, the conclusions and recommendations for future work from the joint SKB and Posiva working group are stated.

2 Common basis for the design and development of a KBS-3 repository

2.1 The iterative design and development process

The different kinds of requirements used in this report, and their corresponding degree of detail in the design are illustrated in Figure 1-1. The development of the requirements, and a design of a final repository and its engineered barriers and underground openings, is an iterative process. The iterative design and development process is illustrated in Figure 2-1 and briefly discussed in the following text.

The iterative development of requirements and design starts from the internationally accepted fundamental radiation protection and safety principles introduced in Section 1.2.2, and national legislations and regulations. Based on them, *main safety functions* of the repository as a whole are stated. Risk criterion (SKB) and dose and release constraints (Posiva) are used to assess whether the repository as a whole maintains safety, also see Figure 1-1.

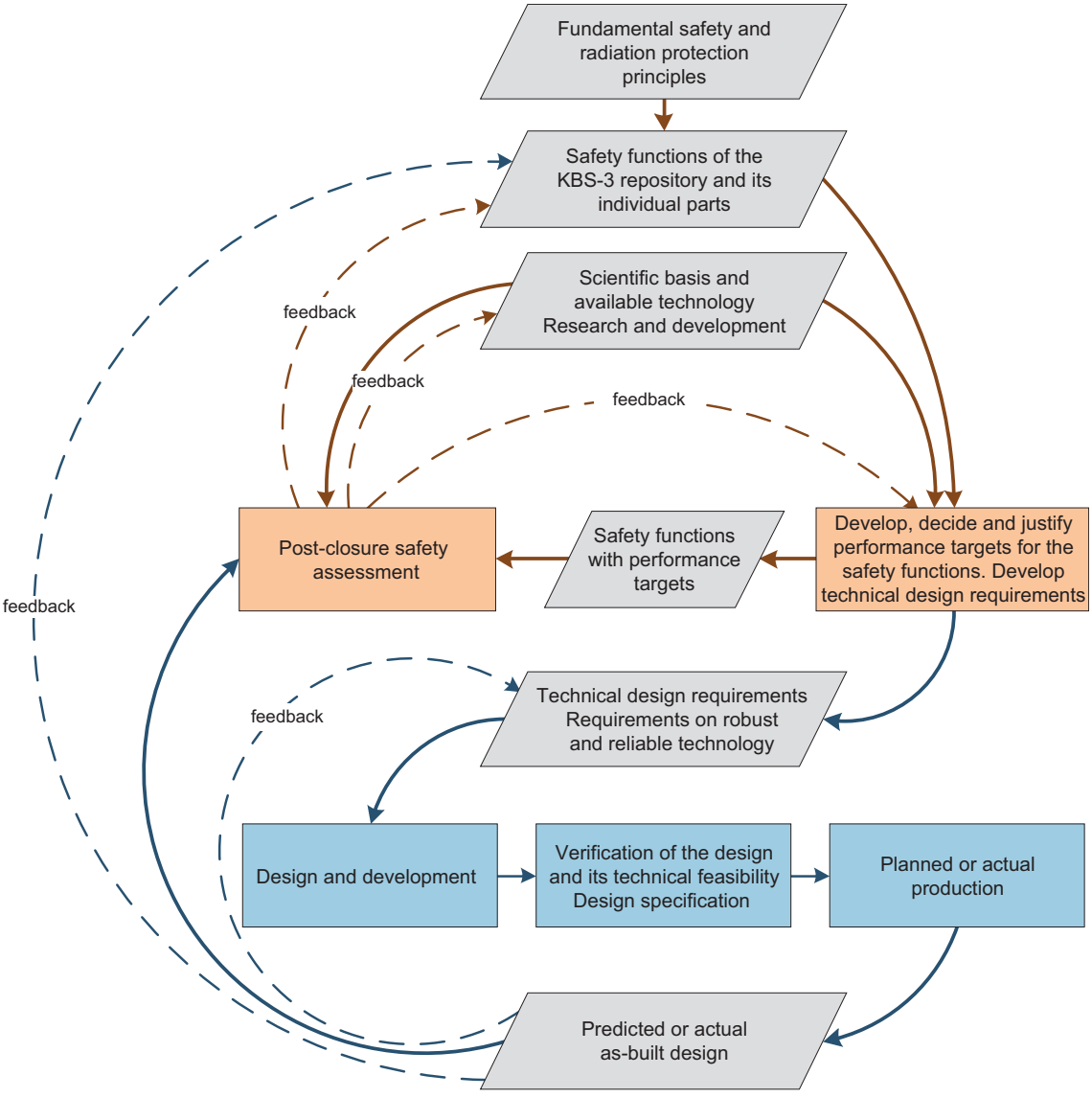

Figure 2-1. *The iterative process of designing a final repository for spent nuclear fuel with loops for safety analysis (red arrows) and technique development (blue arrows).*

Any assessment of the post-closure safety is based on a design, which depending on the stage of development can be outlined, proposed, expected or built. The design cannot be determined from the main safety functions. In a KBS-3 repository, the main safety functions of isolation, containment, retention, retardation and protection of other barriers are maintained by *barrier-specific safety functions* assigned to the canister, buffer, backfill, closure and the rock with its underground openings. *Performance targets* are used to quantitatively evaluate the barrier-specific safety functions, also see Figure 1-1. The barrier-specific safety functions specify how each part of the barrier system contributes to the safety of the repository as a whole, and are essential in the assessment of the post-closure safety. Within the safety assessment, scenarios of the post-closure development including interactions between barriers, potentially occurring conditions, loads and stresses during which the safety functions shall be maintained are compiled and assessed. As part of the assessment the performance targets are assessed and developed.

The barrier specific safety functions together with the conditions and stresses identified in the scenarios form the basis for the development of *technical design requirements* and a design with characteristics that are potentially capable of maintaining the safety functions in a long-term perspective, also see Figure 1-1. In addition, any design must be robust. It must be able to withstand post-closure conditions and processes and possible to be produced in a way that the required characteristics can be achieved with high reliability. Consequently, in addition to the post-closure development available materials, techniques and possibilities to verify the design and quality assure the produced components of the final repository must be considered in the development of the repository design. Analyses, trial production and tests performed within the design and development process will provide feedback for improvements. The resulting as-built, technically feasible design is required to conform to the technical design requirements and be able to maintain post-closure safety.

The ability of the technically feasible designs to maintain safety are analysed in post-closure safety assessments. Within the safety assessment the as-built properties of one or a few technically feasible designs are used to define the initial state of the repository. The safety assessment only addresses the currently outlined, proposed, expected or actual as-built designs. There may very well be other designs, possibly easier to produce, that can provide adequate safety. Based on the integrated analysis of the long-term evolution of the barrier system the performance targets as well as the technical design requirements for each barrier are developed. The technical design requirements are often the result of a combination of naturally occurring processes such as climate change or plate tectonics and the design, e.g. the maximum isostatic load on the canister which is the sum of the hydrostatic pressures resulting from a future ice sheet and the repository depth and the swelling pressure of the buffer. The technical design requirements may also be derived from the as-built state of the repository and the interactions between its different parts. Such technical design requirements are determined so as to ensure that each part of the repository is only exposed to conditions that are acceptable with respect to the maintenance of its safety functions, e.g. the heat transfer from the spent fuel is constrained to achieve acceptable temperatures for the different parts of the repository. There may also be analyses within the assessment that are not valid unless the design characteristics or design parameters lie within specific limits e.g. in respect of criticality analysis and canister material properties.

With respect to this, two loops can be identified in the iterative design process. Firstly, the safety assessment loop, illustrated in red colours in Figure 2-1, where the safety functions and technical design requirements are developed and quantified based on the proposed or as-built repository's capability to maintain safety, and secondly, the technique development loop, illustrated in blue colours in Figure 2-1, where the characteristics that shall maintain the safety functions and fulfil the technical design requirements are developed based on the possibilities to achieve and verify them in the production.

The different parts of the repository interacts both after closure of the completed repository and during the production of the repository in the repository facility. If a characteristic assigned to an individual engineered barrier or to the underground openings is hard, or even impossible to achieve, it may be relaxed by altering the requirements on another part of the barrier system, e.g. the isostatic load on the canister may be relaxed by altering the repository depth or buffer design. Consequently, as a result of the iterative design process and the fact that the maintaining of the safety functions and safety cannot be verified unless a design is provided, the technical design requirements will not only be used to determine the design, but will also depend on it.

2.2 Features that impact safety and are common for several barriers

To *maintain the safety functions in a long-term perspective*, and *compatibility and reliability of production* are features that can be assigned to all barriers in the barrier system of a KBS-3 repository. The *sorption of radionuclides* and the feature to thereby retain them and retard their dispersion can be assigned to the buffer, backfill and rock. Since these features are common for all or several barriers in the barrier system they are commonly presented and justified in this section. This section also discusses the conditions that need to be considered and assessed with respect to each feature. How these considerations are addressed in the design is barrier specific, and discussed in the sections presenting technical design requirements for each barrier.

2.2.1 Maintain the safety functions in a long-term perspective

Rationale

In a KBS-3 repository, the main safety functions of isolation, containment, retention, retardation and protection of other barriers are maintained by barrier-specific safety functions assigned to the canister, buffer, backfill, closure and the rock with its underground openings. These barrier-specific safety functions specify how each part of the barrier system contributes to the safety of the repository as a whole. A KBS-3 repository must maintain radiation safety as long as required with respect to the radiotoxicity of the disposed spent nuclear fuel. This implies that each barrier in the barrier system must be capable of maintaining its safety functions in a long-term perspective. Both in Finland and Sweden, the post-closure safety assessment covers periods of several hundreds of thousand years and of up to one million years, or in some cases even longer.

In a KBS-3 repository, the role of the host rock is to provide a favourable, stable and predictable environment for the engineered barriers within which their safety functions can be preserved in a long time perspective, see Sections 8.2.1 to 8.2.5. The repository site, repository depth and rock volumes to house the repository are selected considering this. The engineered barriers of a KBS-3 repository must be designed with respect to the naturally occurring conditions that can be expected in the host rock, and, vice versa, the underground openings must be adapted to the host rock to provide favourable conditions for the engineered barriers. In addition, the altered conditions arising from the deposition of the spent nuclear fuel must be considered in the design of the repository. The safety functions of the barrier system must be maintained in a long-term perspective both with respect to naturally occurring conditions, see Sections 8.2.1 to 8.2.5, and conditions resulting from the deposition of the spent nuclear fuel, see Sections 3.2 to 3.6.

Conditions to be considered and assessed

The thermal, hydrological and transport, chemical and mechanical conditions in the host rock and its long-term evolution due to tectonic processes and the consequences of climate changes such as future glaciations must be considered in the design of the repository. Regarding the thermal conditions, additionally the deposition of the spent fuel and the temperature increase due to its decay power must be considered. The maintenance of the safety functions in a long-term perspective is fundamental for the safety of final repositories for spent nuclear fuel. Long-term stability is considered in the design and development of the engineered barriers and in the adaptation of the underground openings to the host rock, and vice versa. Long-term stability and the design of the engineered barriers form the basis for the performance targets for favourable conditions in the host rock and underground openings. For the engineered barriers, long-term stability is always considered, it can also be expressed in barrier-specific safety functions and performance targets leading to technical design requirements that shall be fulfilled in the design.

However, in defining suitable thermal conditions, the performance targets are stated with respect to the swelling clay materials used for the buffer whereas the technical design requirements also concern other parts of the barrier system. The buffer is assigned performance targets expressed as lowest and highest acceptable temperatures, see Sections 5.2.5 and 5.2.6. The temperatures should stay within these limits for the thermal conditions to be favourable and the buffer to maintain its safety functions in a long-term perspective. The technical design requirements for fulfilling the performance target for the lowest acceptable temperature concern the rock and underground

openings, see Section 8.3.1. With respect to the highest acceptable temperature in the repository the decay power of the encapsulated spent fuel must be limited and known, see Sections 3.3 and 3.7. The highest acceptable temperature in the buffer will also result in technical design requirements for the thermal properties of the canister and buffer, see Sections 4.3.1 and 5.3.7, respectively, as well as for the distances between deposition holes, see Section 8.3.2. The determination of limits for decay power, thermal properties of the canister and buffer, and the distances between deposition holes requires an integrated analysis of the repository as a whole (see e.g. Hökmark et al. 2009 and Ikonen and Raiko 2012).

2.2.2 Compatibility and reliability of production

Rationale

The barrier system of a KBS-3 repository must function as a whole. As a consequence, there are safety functions assigned to individual barriers concerning their ability to preserve and protect the safety functions of the barrier system. In addition, each engineered barrier and the underground openings must be designed so they are compatible with each other, and will not significantly impair the safety functions of the engineered barriers or the rock. The barrier system must also be produced in a reliable way so that its required characteristics are achieved. Further, the different parts of the repository must be adapted to each other so that the installation of the engineered barriers in the underground openings and the deposition of the canister can be carried out with high reliability. Compatibility with the other parts of the barrier system and reliability in the production are thus features affecting safety that can be assigned to all parts of a KBS-3 repository, also see Section 1.2.5.

The selection of crystalline bedrock, copper, cast iron and swelling clays for the barrier system of a KBS-3 repository is based on the ability of each barrier to contribute to the containment of radionuclides; the retention and retardation of their dispersion into the environment or the protection and preservation of the safety functions of the barrier system. The selection of materials, designs and production systems for the engineered barriers, and the design and construction of the underground openings will also inevitably result in a set of characteristics that are not designed to provide or enhance the main safety functions, but that must be designed or inspected in the production not to degrade them.

The required compatibility between different parts of the barrier system, and reliability in the production, are related to the safety principle that safety shall be achieved by a robust design and engineering features providing safety margins. With respect to this, the barrier system as well as the production of its components shall be robust, i.e. insensitive to disturbances that can be expected to occur, and based on predictable, well proven and reliable technology. Considering this the following performance targets can be stated with respect to compatibility and reliability of production.

- Alterations caused by the design and production of the repository must not exceed quantitative limits based on what is acceptable with respect to the post-closure safety of the repository.
- The materials used shall have limited potential to act as copper corrodants.

The performance targets apply to the engineered barriers as well as to the underground openings. The limits acceptable with respect to post-closure safety are determined within the safety assessment, and are stated in technical design requirements for the engineered barriers and underground openings. The assessment and determination of these limits is based on the predicted or actual as-built design of the barrier system.

Conditions to be considered and assessed

The range of variations of the chemical, thermal, hydrological and transport and mechanical conditions caused by the design and construction of the repository and the characteristics that are important with respect to repository safety functions and safety need to be assessed. The assessment forms a basis for the identification of barrier characteristics that need to be considered with respect to their potential impact on safety. In the design and development of the barrier system, the material compositions and properties of the engineered barriers, as well as the materials, methods, auxiliary equipment and components used in the production of the engineered barriers and underground openings need to be investigated. Material and chemical compositions, amount and location of materials

remaining in the repository, and the extent of mechanical and hydrological disturbances need to be assessed and quantified.

Within the safety assessment, the impact of the characteristics that are inevitably results of the chosen designs or production systems on the safety functions of the barrier system and on safety are analysed. Based on the assessment, a set of technical design requirements can be stated for the characteristics that may impair the safety functions of the barrier system. These technical design requirements state the characteristics that may impair the safety functions and their acceptable values with respect to the safety of the repository. A summary of the identified characteristics, the part of the repository they concern and the sections where the technical design requirements are stated and justified is given in Table 2-1.

Table 2-1. Characteristics of the different parts in the repository that may impair the safety functions and safety of the repository.

Part in the repository	Characteristic that may impact safety	Section
canister	content of organic materials in the insert	4.3.2
buffer	content of impurities	5.3.6
	gas transport properties	5.3.8
backfill and plug	plug material composition	6.5.2
	content of impurities in the backfill	6.3.5
underground openings	alignment of deposition tunnels	8.3.2
	location with respect to other underground openings	8.3.3
	inflow to underground openings	8.3.4
	excavation damage zone (EDZ)	8.3.5
	geometry of the underground openings	8.3.6
	composition, amount and location of engineered and residual materials	8.3.7

2.2.3 Sorption of radionuclides

Rationale

Sorption is a broad concept that describes the processes by which dissolved solutes are sorbed (adsorbed or absorbed) on or in another substance. If breached canisters should occur and radionuclides should be released from the spent fuel and canister, sorption in the buffer, backfill and host rock will contribute to the main safety function of a KBS-3 repository to retain radionuclides and retard their dispersion into the environment, see Section 1.2.2. Thus, sorption is a feature contributing to safety that can be assigned to the buffer, backfill and rock. In the assessment of post-closure safety, sorption is credited as contributing to the radiation safety of the repository.

Conditions to be considered and assessed

Empirical sorption distribution coefficients (K_d), expressing the ratio of the concentration of a radionuclide on a solid clay or rock and the equilibrium concentration in the contacting ground- or porewater are suitable indicators of this feature contributing to safety. Sorption and sorption distribution coefficients depend on the characteristics of the radionuclide, the composition of the water in contact with the clay or rock, and the inherent characteristics of the clay materials and rock. The clay materials used for the buffer, backfill and closure will, due to having a structure with large specific surface area and substantial cation exchange capacity, greatly contribute to sorption. However, since sorption depends on the radionuclide, the composition of the water and the characteristics of the clay material or rock, it is not possible to state single, barrier-specific performance targets for sorption.

Since sorption is credited as contributing to safety, it is important to verify and validate the approach of applying sorption distribution coefficients as well as the data used when assigning the values of the coefficients. This is important for the quality assurance of the safety assessment models and data, but it is not an issue for the design of the engineered barriers or underground openings. However, the materials used for buffer and backfill should be well characterised so that sorption properties can be derived and their variation predicted during the long-term evolution of the disposal system.

3 Spent nuclear fuel

3.1 The spent fuel to be disposed

Spent nuclear fuel refers to nuclear fuel that has been discharged from the reactor and shall be permanently disposed of and not re-used.

The purpose of a KBS-3 repository is to finally dispose of spent nuclear fuel so that man and the environment are protected from harmful effects of radiation as long as required with respect to the radiotoxicity of the spent nuclear fuel. Consequently, the characteristics of the spent fuel are one of the starting points for the design of a KBS-3 repository and for its radiation safety.

The types and amounts of spent nuclear fuel to finally dispose of depend on the nuclear power programmes, i.e. the number of reactors, their types and operation, in Finland and Sweden, respectively. The nuclear power programmes will result in differences that will impact the design of the repository e.g. different amounts of spent fuel to handle and dispose of and different distributions of enrichments, burnup and decay power. Further, the different types of reactors will result in variations in fuel characteristics, such as dimensions and materials. However, a set of common characteristics of importance for repository design and safety can be identified.

Common general characteristics of the spent fuel to be handled and disposed of by SKB and Posiva are:

- the fuel has been used in light water reactors, BWR, PWR[1] or VVER type,
- the fuel pellets are in oxide form, generally UO_2 or, for a few assemblies for SKB to handle, mixed U- and Pu-oxide, MOX,
- the fuel pellets are encapsulated in zirconium-alloy based cladding,
- the structural materials of the assemblies e.g. spacers, springs, fuel ends, consist of zirconium alloys, high-performance steel or nickel alloys.

Further, both Posiva and SKB intend to encapsulate control rod clusters for PWR- assemblies together with the assemblies. The BWR, PWR and VVER assemblies to be disposed of by SKB and Posiva are illustrated in Figure 3-1.

The spent nuclear fuel assemblies contain the radionuclides that may cause harmful effects of radiation. Consequently, the radionuclide inventory of the fuel assemblies to be disposed of need to be known in order to assess the post-closure safety. Not only the radionuclide inventory, but also its availability or potential to be released from the spent fuel and dispersed into the surroundings need to be known in order to assess the safety. The radionuclide inventory and its implications for safety assessment are further discussed in Section 3.2.

The radionuclides in the spent fuel, or rather their radioactive decay, will result in the development of decay power and radiation. The decay power and emitted radiation need to be considered both in the repository design and handling of the spent nuclear fuel. Too high temperatures or dose rates may impact the engineered barriers of the repository. The decay power and radiation dose rate and their impact on repository design and safety are further discussed in Sections 3.3 and 3.4, respectively.

To enable encapsulation of the spent fuel assemblies the dimensions of the canister need to be adapted to those of the fuel assemblies. The assemblies have been wet stored during the cooling phase and need to be dried before encapsulation. This is discussed in Section 3.5.

Reactivity must always be controlled and it is required that criticality shall never occur outside reactor vessels. The control of reactivity and sub-criticality are main safety functions common for nuclear power plants and all nuclear facilities, and systems included in the manufacturing, handling, storage and disposal of nuclear fuel.

[1] In Sweden there are also a few assemblies (222 out of approximately 54 000) from the pressurised heavy water reactor (PHRW) in Ågesta outside Stockholm to deposit.

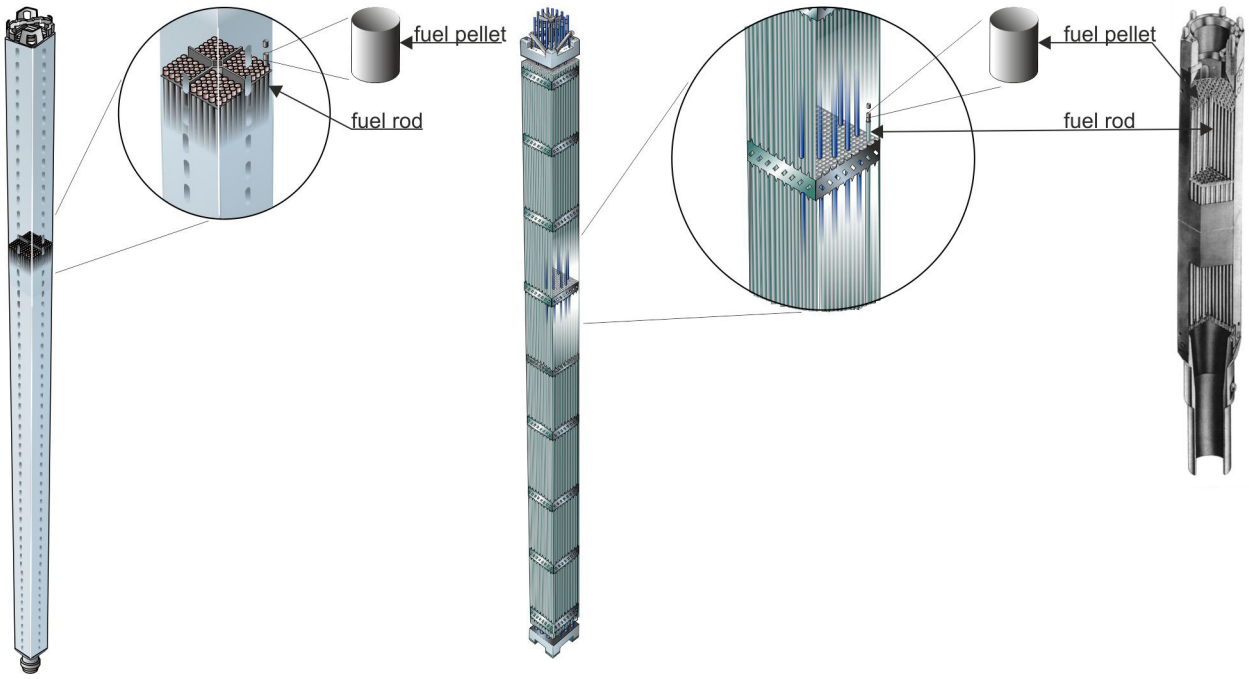

Figure 3-1. *Illustrative BWR, (left), PWR (middle) and VVER assemblies. The fuel pellets are placed in fuel rods with zirconium alloy cladding.*

The bulk of the radionuclide inventory of the fuel assemblies is embedded in the fuel pellets. The matrix of the fuel pellets has an extremely low dissolution rate in the repository environment. If the containment is breached, the low solubility is a feature of the fuel pellets that will contribute to the main safety function of a KBS-3 repository to retain radionuclides and retard their dispersion into the environment. During the operation in the reactor part of the radionuclide inventory will be released from the fuel pellet matrix to the gap between pellet and cladding. This part, referred to as the gap inventory, is important for the safety of the repository, see Section 3.2. Activation products are formed during the irradiation in the reactor, mainly in the structural parts of the fuel assemblies, but also in impurities and additives in the fuel pellets. The low corrosion rates of the structural materials contribute to retaining the activation products and retarding their dispersion into the environment. The low release rates of radionuclides from the fuel assemblies are important for the safety of a KBS-3 repository.

Even though the spent nuclear fuel is the radioactive, and potentially harmful, material to be safely disposed of, it has features that impact or contribute to the main safety functions of a KBS-3 repository. Considering this, to *maintain sub-criticality* and *limit the release of radionuclides* are *features contributing to safety* that can be assigned to the spent fuel in a similar way as safety functions can be assigned to the engineered barriers and rock with its underground openings, also see Section 1.2.5. These spent fuel features contributing to safety are assigned performance targets, and are, in Sections 3.6.1 and 3.6.2, presented and justified in a similar way as the safety functions assigned to the engineered barriers, and rock with its underground openings.

In general, the spent fuel characteristics that impact safety, design or the assessment of the post closure safety need to be known and determined with sufficient accuracy. In line with fundamental safety principles, characteristics that are credited as contributing to safety must also be verified to lie within limits acceptable with respect to safety. This is the case for the spent fuel characteristics that impact the maintenance of sub-criticality or contribute to the low release rates of radionuclides, since sub-criticality and low release rates of radionuclides are credited as contributing to the radiation safety of the repository. This is also the case for the spent fuel characteristics that unless constrained may impair the safety functions of the engineered barriers. Common to all spent fuel characteristics of interest for final deposition is that SKB and Posiva need to state which information that is needed and when in the fuel cycle the information shall be provided. The characteristics that need to be known, determined and possibly verified during the handling are introduced in Sections 3.2 to 3.6, and compiled and justified in Section 3.7.

3.2 Radionuclide inventory

The radionuclide inventory needs to be known in order to assess the safety. To perform safety assessments, SKB and Posiva need to have the information required to determine the radionuclide inventory with sufficient accuracy. The radionuclide inventory constitutes input to the assessment of the potential doses and risks arising from a KBS-3-repository and thus the radiation safety of the repository as a whole. The radionuclide inventory consists of:

- fission products,
- actinides,
- activation products.

The major part of the fission products and actinides are bound in the uranium oxide matrix of the fuel pellets. A part of the radionuclide inventory will be located in the gap between the fuel pellets and cladding and at fractures in the fuel pellets, as well as at the fuel grain boundaries. This part of the radionuclide inventory is referred to as the gap inventory. The activation products are mainly formed in the cladding and structural parts of the assemblies during irradiation in the reactor. An illustrative fuel pellet from a light water reactor is shown in Figure 3-2.

In the following text, the gap refers to all space not occupied by fuel matrix inside the cladding, see Figure 3-2. The radionuclides in the gap inventory will be released very rapidly in comparison with the inventory in the spent fuel pellet matrix, if the pellets are exposed to vapour or water. The activation products in the cladding and structural materials are released at a rate corresponding to the corrosion rate of the component.

During the operation of the reactor, corrosion occurs, and corrosion products, crud, are released to the cooling water. Part of the crud will form a coating on the parts of the fuel assemblies in contact with the coolant. Within the crud there are activation products. Should leaking cladding occur in the reactor the crud can also contain fission products and actinides released from the fuel pellets. In contact with water or vapour, the inventory of the crud will be released rapidly in comparison with the activation products cladding and structural parts and the inventory in the fuel pellets.

The calculated doses and risks arising from a final repository will depend on the ability of the repository to contain the radionuclides and retard their dispersion into the environment. The potential transport of radionuclides from a canister, should the containment be breached, will depend on the release rates from the spent nuclear fuel and on the properties of the released substances, i.e. their propensity to be transported through the barrier system and reach the surface and cause harm to man and the environment. Thus, with respect to safety it is important to know the composition of the radionuclide inventory and its distribution in fuel pellets, gap between pellet and cladding and structural materials. In addition, the crud and its content of radionuclides is of interest for the assessment of post-closure safety. Note that nuclides that represent insignificant parts of the radioactivity and radiotoxicity of an assembly may, with respect to their propensity to be released from the assembly and transported through the repository, have a significant impact on the doses and risks arising from the repository.

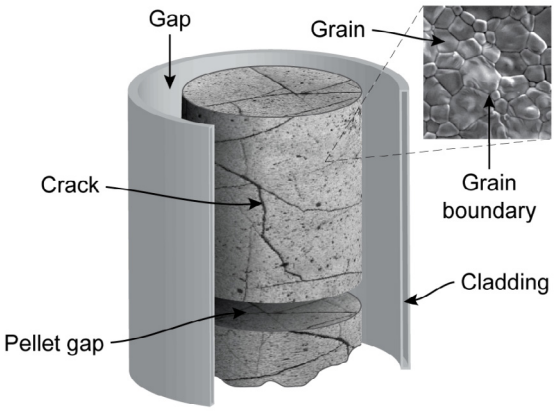

Figure 3-2. *The macro- and microstructure of an illustrative light water reactor fuel pellet, illustrating the irradiated pellet and the gap (based on Fors et al. 2009).*

The radionuclide inventory will depend on the characteristics of the un-irradiated assembly, the irradiation history and cooling time. SKB and Posiva need sufficient information to determine the radionuclide inventory and its distribution with sufficient accuracy. This information resides with the nuclear power plant operators. Unless there are any facility or repository specific constraints on the radionuclide inventory that is allowed to be handled or disposed, there are no requirements or limiting values assigned to the radionuclide inventory as such.

3.3 Decay power

The radionuclides generate decay power due to their radioactive decay. The highest temperatures in the repository will occur as a result of the deposition of the spent nuclear fuel. If not limited, the heat release due to the decay power may give rise to temperatures sufficient to cause degradation of technical barriers or fracturing of the rock. Further, the material models used for cast iron and copper in the assessment of the canister are only valid within a defined temperature interval. For disposed encapsulated spent fuel, the temperatures in the fuel, canister, buffer and surrounding rock will depend on the decay power, the thermal properties and dimensions of the surrounding materials and the distances between deposition holes. With respect to repository design and the safety functions of the barrier system, the total decay power in each canister need to be limited and known, see also Section 2.2.1.

Based on the spent fuel to be disposed by SKB and Posiva, respectively, and provided that all fuel assembly positions in all canisters are filled, the decay power in each canister can be determined from the total decay power of all assemblies to be disposed and the encapsulation and deposition period. In summary, the accepted decay power will depend on the fuel to be disposed, its decay power and decay time, the operational periods of SKB's and Posiva's facilities, and the thermal properties of the barrier system. Since the nuclear power programmes, operational periods of SKB's and Posiva's facilities, as well as the thermal properties of the rock will not be the same in Finland and Sweden, the accepted level for decay power in a canister may differ between Posiva and SKB and also during the deposition period or for different parts of the repository. But the fact that a limit needs to be set and that the encapsulated decay power needs to be verified will be common. The verification can be made by measurements, or by calculations, or a combination of measurements and calculations. Further, common for both Posiva and SKB is that the operators of the nuclear power plants should provide the information required to determine the decay power.

3.4 Radiation dose rate

The radioactive decay of the radionuclide inventory will give rise to radiation. In a KBS-3 repository the radiation from the spent fuel may cause formation of corrosive substances. These may adversely affect the corrosion rate and the lifetime of the copper canister. Analysis has shown that increased corrosion due to radiolysis can be neglected if the radiation dose rate at the canister surface is less than 1 Gray/h at the time of deposition in the final repository (SKB 2010a, Section 3.5.4). The radiation dose rate at the canister surface depends on the spent fuel geometry and radionuclide inventory, the canister loading pattern, the geometrical configuration of the assemblies in the insert and the radiation attenuation and shielding provided by the insert and copper shell. Given the information on the fuel assemblies to be encapsulated and the canister design, the dose rate limits at the canister surface should be verified, either by calculation or by measurement, at the latest at the time of encapsulation. For the canister this implies that the properties with a significant impact on the radiation attenuation and dose rate must not yield a dose rate above 1 Gray/h at the canister surface, see Section 4.3.1, and for the spent fuel assemblies the radiation dose rate need to be verified. The nuclear power plant operators should provide the information required for the calculation of the dose rate.

3.5 Dimensions and water content

3.5.1 Dimensions

The existing and anticipated fuel assembly designs have been the basis for the design of the fuel channels in the canister insert. There exist different canister designs for the different reactor types and the canister dimensions vary in Posiva's and SKB's designs. If new fuel designs are planned to be taken

into use, their cross section and total length, including the induced length increase at maximum design burnup, should be checked against the dimensions of the existing canister designs in order to ensure compatibility with the canister, or if not compatible, to provide input to design changes.

3.5.2 Water content

Water inside the canister may, due to radiolysis of the water or of moist air, cause the formation of corrosive substances and internal corrosion of the canister. The water may also give rise to increased pressures inside the canister. The maximum amount of water that can be accepted inside the sealed canister is stated in Section 4.3.6. The fuel assemblies to be encapsulated must not have a water content that result in this limit being exceeded.

3.6 Features contributing to safety and performance targets

3.6.1 Maintain sub-criticality

SKB requirement (SR-Site)	Fuel assemblies to be encapsulated in a specific canister shall be selected with respect to enrichment, burnup, burnable absorbers (BA), geometrical configuration and materials in the canister so that criticality will not occur during handling or final storage even if the canister is filled with water (Requirement SFH13).
Posiva requirement (TURVA 2012)	The canister shall be subcritical in all postulated operational and repository conditions including intrusion of water through a damaged canister wall (Requirement L3-CAN-14).
Feature contributing to safety	maintain sub-criticality
Performance targets	reactivity k_{eff} < 0.95 for the canister filled with water reactivity k_{eff} < 0.98 for altered geometries and materials acting to increase the reactivity*
Characteristics to be determined and verified for the fuel to be disposed	enrichment BA (burnable absorbers) burnup

*) May be based on low probability and/or low-consequence justification, subject to regulatory approval, see rationale and Section 3.7.2.

Rationale of the feature contributing to safety and performance target

Sub-criticality, i.e. $k_{eff} < 1$, is an essential safety function in all handling and storage of nuclear fuel. The maintenance of sub-criticality is also important for the post-closure safety of a KBS-3 repository. If criticality was to occur in a KBS-3 repository, the energy release might impact the engineered barriers and rock. Further, the radionuclide inventory would be altered. This could potentially result in an enhanced release of radionuclides from the repository.

The performance target that the effective multiplication factor (k_{eff}) shall be less than 0.95 is usually applied as a criterion when evaluating criticality safety. In addition, various uncertainties shall be taken into account in the estimation of the maximum k_{eff}. When assessing criticality safety all credible situations or events that may act to increase k_{eff} shall be investigated (IAEA 2014). Criticality requires the presence of a moderator, and in a KBS-3 repository criticality is not possible without the presence of water. The canister is disposed below the groundwater table and its tightness cannot be warranted forever. With respect to this, it is reasonable to assess criticality for a canister filled with water. Demonstrating that $k_{eff} < 0.95$ for a water filled canister, with consideration taken of the canister dimensions and material properties acting to increase k_{eff} and with the fuel assemblies placed at the most reactive distance from each other, gives a margin to actually reach a critical state in the repository.

Sometimes a lower margin, $k_{eff} < 0.98$, is acceptable provided that the probability for the event to occur can be justified or demonstrated to be very low. It may also be possible to justify the use of a lower margin based on low consequences of the criticality event. Based on this, it is reasonable to apply the criterion $k_{eff} < 0.98$ for postulated post-closure events and evolutions provided that it can be demonstrated that the probability or consequences are low, or that the combination low probability low consequences justifies a less strict criterion.

Conditions to be considered and assessed

The development of criticality will depend on the presence of fissionable nuclei, their geometrical configuration and the surrounding solid materials, liquids and gases. For a given fuel type and surroundings, the fuel characteristics of most importance for the reactivity are enrichment, content of burnable absorbers (BA) and burnup.

Sub-criticality is readily demonstrated, and k_{eff} far below 0.95, for a dry canister loaded with fresh fuel assemblies with enrichment up to 5 % and without burnable absorbers. Criticality cannot occur unless the canister is filled with water. Since this cannot be excluded in a long term perspective prior to encapsulation, it is verified that $k_{eff} < 0.95$ for the assemblies to be encapsulated, even if the canister is filled with water. Furthermore, $k_{eff} < 0.98$ is proposed to be used to assess postulated post-closure events and evolutions. The geometries, surrounding solid materials, liquids and gases in the canister and their conceivable alterations acting to increase k_{eff} are discussed in Sections 3.7.2 and 4.3.6.

Both SSM and STUK have requested analysis of the consequences of criticality in the final repository. In the framework of the review of SKB's licence application, the consequences of nuclear criticality in a KBS-3 repository have been assessed (Hedin et al. 2013). In the assessment, a critical configuration in a breached canister is assumed. The development of the chain reaction and its impact on the barrier system, dissolution of the fuel pellets and release of radionuclides as well as the resulting doses to man were assessed. For an assumed steady state case, it was concluded that the temperature in the critical canister is limited by the boiling point of water in the repository. The power developed is limited by the capacity of the rock to carry away the heat. The resulting increase in temperature will not damage buffer or rock in adjacent deposition holes. The dissolution rate of the fuel pellets is judged to increase and this is estimated to result in an increase of the calculated dose to man by a factor of six. Currently there is no known process that could lead to a critical configuration in the repository. Thus the situation is regarded as a "what if" case.

3.6.2 Low release rate of radionuclides

SKB requirement (SR-Site)	The spent fuel to be disposed in the KBS-3 repository shall have low solubility in the repository environment (Requirement SF2).
Posiva requirement (TURVA 2012)	–
Feature contributing to safety	low release rate of radionuclides
Performance targets	low fuel matrix conversion rate corrosion rate of structural materials < 10^{-3}/year
Characteristics to be determined and verified for the fuel to be disposed	chemical composition of fuel pellets material composition of cladding and structural parts observed leaking fuel rods fission gas release (FGR)

Rationale of the feature contributing to safety and performance target

As long as the canister remains tight no radionuclides can be dispersed into the surroundings. If the containment is breached, the low radionuclide release rate from the fuel pellets in the repository environment is of major importance for the safety of a KBS-3 repository. For all other parts of the fuel assembly that have been exposed to neutron radiation in the reactor and where activation products have been formed, i.e. cladding and structural materials, the corrosion rate of the materials containing activation products will also impact safety.

The low radionuclide dissolution rate from the fuel pellets is taken credit for in the radionuclide release and transport calculations in the safety assessment. Also, the release rates of activation products from the cladding and structural materials are taken into account in the safety assessment. The low release rate from the fuel pellets is based on dissolution experiments on UO_2, and fuel leaching experiments which show that the fractional release rate lies in the range 10^{-6} to 10^{-8}/year (SKB 2010c). The corrosion rate of structural materials is justified based on documented material corrosion rates and the design of the fuel assemblies. In scenarios with breached canisters in SR-Site

and TURVA-2012, fractional release rates in the interval 10^{-6} to 10^{-8}/year and corrosion rates of structural materials $< 10^{-3}$/year were used to assess the fulfilment of the risk and dose constraints for the repository as a whole.

Conditions that impact the release rate of radionuclides from fuel pellets

The gap inventory, see Section 3.2, is not bound in the fuel pellets and is assumed to be released instantly should the containment in the canister be breached. With respect to this, it is important that the gap inventory is limited. The gap inventory is considered to be proportional to the fission gas release, FGR (SKB 2010a), which in turn is strongly correlated to the linear heat generation rate and burnup. Therefore, the FGR needs to be known in order to estimate the gap inventory.

If the canister is breached, and the fuel pellets are exposed to water, radionuclides will be released into the water. This is expected to occur in two different stages, the first occurring rapidly by release of the gap inventory, the second occurring slowly through continuous matrix dissolution. The fuel matrix dissolution is controlled primarily by the fuel composition and the chemical environment of the intruding water (SKB 2010c). It is also affected by the transport of uranium species out of the canister.

The fuel matrix dissolution is modelled conceptually by considering two processes. Chemical dissolution which is connected to the low solubility of the fuel matrix, and the oxidative dissolution which is connected to the oxidation of U(IV) to U(VI). Precipitation of secondary uranium phases on the fuel surfaces may also affect the radionuclide release rates. The combined effect causes a net release of radionuclides, referred to as "fuel conversion", and the fractional radionuclide release from the fuel matrix occurs at the fractional rate of fuel conversion. If there is no significant transport of uranium species out from the canister, the intruding water will reach the solubility limit of uranium. According to Ollila (1999), the solubility of uranium in anaerobic conditions is in the order of 10^{-8} mol/L (Eh −0.1 V) and typically even lower, in the order of 10^{-9} mol/L, under more reducing conditions (Eh −200 to −300 mV). Since the solubility of uranium in a reducing environment is very low, it will prevent a net chemical dissolution of the fuel matrix, although the fuel conversion will still be ongoing due to the radiolytic oxidation of the fuel surface. If, however, the transport rate out of the canister is significant, the chemical dissolution component will become more important (SKB 2010c, Section 3.3). In the post-closure safety assessment, both SKB and Posiva assign a fuel conversion rate to assess the release of radionuclides from the spent nuclear fuel matrix.

For high burnup (i.e. BU > 45 MWd/kgU), a change in the structure of the fuel matrix can be observed at the rim of the fuel pellet. It was initially assumed that a change in structure may affect the dissolution behaviour of the fuel matrix. Based on data available at the time, upper limits for the burnup were stated for the safety assessment SR-Site and TURVA-2012, these limits are 60 MWd/kgU for UOX fuel and 50 MWd/kgHM for MOX fuel, the latter is for SR-Site only. Investigations under varying redox conditions have concluded that high burnup does not increase the matrix dissolution rate (Zwicky et al. 2011, Fors et al. 2009). Consequently, there is no need to restrict the allowed burnup only on this basis. However, the gap inventory is related to the linear power rate and FGR, which to some degree are related to the burn-up. This implies that the possible increase of the gap inventory at high burn-up needs to be considered.

The dissolution behaviour of spent fuel pellets may be modified by chemical additives (e.g. Cr, Al). Such additives, or dopants, have in recent fuel types been used to enhance the performance of the fuel in the reactors. Thus, leaching tests of spent fuel with such additives should be performed to verify that they behave in the same way as non-doped fuel.

In case the fuel cladding is fractured or otherwise penetrated during operation or handling, the fuel pellets will be exposed to the surrounding fluids and gases. If the pellets are exposed to water or air, parts of the UO_2 matrix of the fuel pellets will be oxidised from U(IV) to U(VI). The extent of oxidation will depend on the prevailing temperature. U(VI) has a much higher solubility than U(IV) and can be expected to be released relatively quickly from the fuel pellet if it is exposed to water or moist air. Safety assessments have demonstrated that the amount of U(VI) formed in the reactor and during the handling of fuel assemblies with leaking fuel rods, and that remains in the fuel rod at encapsulation, is acceptable with respect to the safety of the repository (SKB 2011). However, the

presence of oxygen in the canister might lead to further oxidation and this oxygen content should therefore be limited. This is one of several reasons for limiting the content of water and moist air in the canister, see further Section 4.3.6. In order to limit the negative effects of failed cladding, fuel rods with observed leaking cladding should be removed and placed in specific casings.

Conditions that impact the release rate of radionuclides from the structural parts

The radionuclide inventory of the structural parts, e.g. cladding, spacers, plugs and springs, consists of activation products formed in the structural materials and in the crud disposed on their surfaces during the irradiation in the reactor. The radionuclide inventory in the crud is not bound in the fuel assembly and is assumed to be released instantly should the containment in the canister be breached. The radioactive substances in the structural materials are bound in the materials. In order to model the radionuclide release rate from structural parts, the structural materials are assigned a corrosion rate that can be shown to be valid for the material compositions to be used.

The structural parts of nuclear fuel for light water reactors mainly consist of steel, zirconium alloys and Inconel alloys. Their composition can vary slightly between different fuel types and the total amount of structural material varies between fuel types. The dimensions of the structural parts vary both within each assembly and between different types of nuclear fuel.

In the safety assessment, a release time over which the structural parts fully corrode and the activation products are released is assumed. This release time is based on assumed corrosion rates for the structural materials and a given thickness.

Cladding is manufactured from zirconium-based alloys with Zr as the predominant alloying component (> 98−99 wt-%). Data for the rates of general corrosion of these zirconium-based alloys are available in the literature. Shoesmith and Zagidulin (2010) have reviewed the available information on the corrosion rate of these alloys under repository conditions. The cladding thickness differs between the various designs of fuel assembly.

Zirconium alloys are examples of passive materials which are protected from corrosion by the formation of an adherent protective (or passive) film, in this case comprising ZrO_2. The ZrO_2 film is stable over a wide range of temperature, redox conditions and pH (Pourbaix 1974). Corrosion rates are of the order of nm/year, with Shoesmith and Zagidulin (2010) suggesting a best estimate of 5 nm/year, with a conservative upper limit of 20 nm/year and a lower limit of 1 nm/year. Based on the best estimate, the corrosion rate for 0.5 mm thick cladding (assuming corrosion from both sides) is $2.0 \cdot 10^{-5}$/year. The performance target for the corrosion rate of structural materials of 10^{-3}/year is therefore a factor of 50 higher than that estimated based on the best estimate of the corrosion rates recommended by Shoesmith and Zagidulin (2010) and a factor of 250 higher than that based on the lower limit of the recommended range of corrosion rates.

Components such as spacers, plugs and springs are fabricated from either stainless steel (generally AISI Type 304L), zirconium-based alloys similar to those used for the cladding, or by nickel-based alloys (either the Ni-Cr-Fe-Mo grade 718 or the Ni-Cr-Fe alloy X 750). The corrosion rates of stainless steels and nickel alloys in repository conditions have been reviewed by King and Watson (2010) and Kursten et al. (2004).

Both stainless steels and nickel-based alloys are examples of passive materials. In this case, the passive film is composed of Chromium (III) oxide/hydroxide. In comparison with ZrO_2, Cr(III) oxide/hydroxide exhibits a narrower range of stability (Pourbaix 1974), but nevertheless results in a highly passive film under repository conditions. There is a wide range of corrosion rates reported in the literature for these two classes of material, which partly reflects the wide range of environmental conditions that have been used in various studies. Stainless steels and nickel-based alloys tend to exhibit a greater sensitivity towards Cl (both in terms of their susceptibility to localised corrosion and the rate of general corrosion) than zirconium-based alloys (King and Watson 2010). Corrosion rates typically lie in the range 0.01−1 µm/year, with rates increasing with increasing temperature and salinity. For a component thickness of 2 mm, the fractional release rate would then be in the range 10^{-5} to 10^{-3} per year, assuming corrosion from both sides. In the performance target, the upper end of the range is used.

Both Posiva and SKB also intend to dispose of PWR control rod clusters. These consist of steel and a silver alloy. The activation products formed in these control rods are an additional source term for the radionuclide release and transport calculations and their radionuclide inventories have to be known. Additionally, their release rates should be assessed.

3.7 Fuel characteristics that impact safety, design or safety assessment to be determined for the fuel to be disposed

3.7.1 Fuel characteristics to be determined

As discussed in Section 3.1, the spent fuel has features that contribute to the safety of a KBS-3 repository. The spent fuel also has characteristics that impact the design of the barrier system, or that unless they are constrained may impact the safety functions of the barrier system. For these spent fuel characteristics, limiting values are stated based on the most recently performed safety assessment and the current design of the barrier system. During the handling of the spent fuel assemblies, these characteristics should be determined and verified to lie within the limits expressed by limiting values. In addition, there are fuel characteristics, most significantly the radionuclide inventory, that need to be known in order to assess safety, but that do not contribute to maintain safety or have any direct impact on the design, and consequently have no limiting values. These characteristics need to be determined with sufficient accuracy during the handling.

For Posiva and SKB to verify that the spent fuel assemblies can be safely encapsulated and disposed of in a KBS-3 repository, information about the nuclear fuel characteristics need to be provided and/or assessed:

- before irradiation in the reactor,
- at the discharge from the reactor and prior to delivery to SKB and Posiva,
- at encapsulation.

The nuclear power plant operators should provide the information in Table 3-1 for each type of nuclear fuel they intend to use in the reactors. The information is given in the fuel type specifications provided by the fuel manufacturers. The information shall be provided so that SKB and Posiva can confirm that spent fuel assemblies of this type can be finally disposed in a KBS-3 repository and that they can be handled within Posiva's and SKB's spent fuel management systems. For new fuels the information about the characteristics, or their values, shall be provided before any assembly of the associated type is loaded into the reactor. For old fuels the corresponding information shall be provided, so that SKB and Posiva can check and confirm, its safe management. Note that, with the exception of the fuel pellet chemical composition, the stated limiting values either depend on the design of the KBS-3 repository or constitute input to the post-closure safety assessment. This means that they can be altered if the design is altered, or if it is decided or required to alter them based on results of additional research or safety assessments. In addition, SKB and Posiva need sufficient data about the fuel type to check if the spent fuel assemblies can be handled and disposed with respect to criticality safety, or if demonstrating sub-criticality will require specific measures during handling and encapsulation or alteration of the canister or the fuel assemblies.

Before the spent fuel is delivery to SKB's or Posiva's spent fuel management facilities, the nuclear power plant operators shall provide the information in Table 3-2. At delivery to SKB and Posiva, the information in Table 3-1 and Table 3-2 needs to be provided per delivered assembly. As for the information to be provided prior to irradiation, SKB and Posiva need the information to confirm that the delivered spent fuel assemblies can be handled and finally disposed of as planned, and the limiting values will depend on the design or last performed safety assessment.

The fuel characteristics to be verified and documented prior to encapsulation or that are needed to assess the post-closure safety are presented in Table 3-3. For those characteristics for which limiting values are stated the related design issue or feature contributing to safety is given. Further, the analysis within the safety assessment where the information is used is stated in the table.

Table 3-1. Fuel characteristics to be provided by the nuclear power plant operators for the un-irradiated, fresh, nuclear fuel. The characteristics are stated in the fuel type specifications provided by the manufacturers.

Characteristic	Limiting value	Related feature contributing to safety or related design issue	Specification of data
enrichment	$U\text{-}235_{average}$ < 5 % (common) $Pu\text{-}fissionable_{average}$ < 4.5 % (SKB only)	maintain sub-criticality	nominal average, max average, max fuel rod, BA-zone. w% U-235 w% fissionable Pu-isotopes
burnable absorber*	programme and fuel type specific minimum content	maintain sub-criticality	type and w%, chemical composition
total length	programme and fuel type specific maximum length	canister dimensions	mm
induced length increase	maximum at maximum design burnup	canister dimensions	mm
cross section	programme and fuel type specific maximum	canister dimensions	mm
total weight	programme and fuel type specific maximum	design of canister and technical systems to handle the fuel assemblies	kg
chemical composition of fuel pellets	oxide form, UO_2 or (U,Pu) O_2 or other form with similar dissolution rate	low release rate of radionuclides	for all kinds of fuel pellets, best available knowledge on proportion of all elements, proportion of the impurities N and Cl and other detected impurities
material composition of cladding and structural parts	zirconium, steel, nickel or silver alloy or alloy with similar corrosion rate	low release rate of radionuclides	best available knowledge on kind of alloy and proportion of all elements it contains (or upper limits)

*) only SKB

Table 3-2. Fuel characteristics to be provided by the nuclear power plant operators prior to the delivery to SKB or Posiva.

Characteristic	Limiting value	Related feature contributing to safety or related design issue	Specification of data
total length after irradiation	programme and fuel type specific maximum	canister dimensions	mm, if deviating from fuel type specification.
cross section after irradiation	programme and fuel type specific maximum	canister dimensions	mm, if deviating from fuel type specification.
observed leaking cladding	no assemblies containing fuel rods with observed leaking cladding	low release rate of radionuclides	yes/no, documentation
fission gas release (FGR)	–	low release rate of radionuclides	calculated average in assembly, including distribution and standard deviation
average burnup of assembly at final discharge from the reactor	programme and fuel type specific minimum	maintain sub-criticality	kWd/kgU

Table 3-3. The fuel characteristics to be determined and documented for the encapsulated spent fuel. The fuel characteristics may be determined or documented per assembly or canister or both. Some characteristics need to be checked and verified to conform to limiting values.

Characteristic	Limiting value	Related feature contributing to safety or related design issue	Related analysis within safety assessment
total radionuclide inventory	–	–	radionuclide release and transport, doses and risks
radionuclide inventory in fuel pellets	–	–	radionuclide release and transport, doses and risks
gap inventory	calculated average FGR for the encapsulated assemblies < maximum to be determined	low release rate of radionuclides	radionuclide release and transport, doses and risks
radionuclide inventory in structural parts	–	–	radionuclide release and transport, doses and risks
crud inventory*	–	–	radionuclide release and transport, doses and risks
chemical composition of fuel pellets	oxide form, UO_2 or $(U,Pu)O_2$ with additives for which the solubility has been tested	low release rate of radionuclides	radionuclide release and transport, doses and risks
total length	maximum total length < minimum tested inner length of insert fuel channel	canister design	–
cross section	maximum cross section < minimum tested inner cross of insert fuel channel	canister design	–
decay power	total decay power in the canister < programme and fuel type specific maximum	repository design and layout	heat development
radiation dose rate at the surface of the canister	dose rate at the canister surface < 1 Gy/h	canister design	canister corrosion
reactivity (k_{eff})	loading curve (enrichment, burnup) or approved canister specific analysis satisfied	maintain sub-criticality	criticality safety
intactness of cladding.	fuel rods with observed leaking cladding encapsulated in specific casings	low release rate of radionuclides	radionuclide release and transport, doses and risk
water content.	total water content in sealed canister < 600 g	canister design	canister corrosion resistance, internal pressure in canister

*) SKB, but not Posiva, estimates the radionuclide inventory in the crud.

3.7.2 Justification of characteristics to be determined

Radionuclide inventory

It is the radionuclides in the spent fuel assemblies that may cause harm to people and the environment. Consequently, the radionuclide inventory needs to be determined in order to assess post-closure safety. With respect to the assessment of post-close safety, the radionuclides that are not bound in the fuel pellets or structural parts, and that can be considered to be released relatively fast if the canister is breached are of special interest. It is also important to know how the total inventory of

radionuclides in the spent fuel assemblies to be disposed of is distributed in the disposed canisters. With respect to this, the total radionuclide inventory to be disposed of and how it is distributed in the canisters, fuel pellets, structural materials, gap and crud needs to be determined in order to assess post-closure safety.

Enrichment, BA-content and burnup

Both the limits for maximum enrichment and minimum BA-content are set with respect to criticality safety. Both Posiva and SKB perform criticality safety assessments by applying qualified computer codes and according to general practices for the management of uncertainties (Agrenius 2010, Posiva 2013, Section 6.27). Both organisations use computer codes to determine the domains of enrichment, BA-content and burnup that fulfil the criteria for sub-criticality for the different fuel types to be encapsulated and finally disposed. The acceptable combinations will be programme specific and are not included in this report.

The maximum limit of 5 % set for the enrichment is the current limit generally applied within the nuclear power industry.

The limiting values for BA-content and burnup are determined from the performance target that k_{eff} shall be < 0.95 for the canister filled with water and geometry and materials verified at encapsulation. Also postulated post-closure cases when alterations acting to increase k_{eff} have taken place, and for which the criterion $k_{eff} < 0.98$ may be used, are assessed. Cases with altered materials and geometry can be defined based on processes that can occur, and a systematic investigation of which such changes will contribute to increase k_{eff} the most. Such an investigation of the evolution in a breached canister has been performed by Agrenius and Spahiu (2016). They identified magnetite, siderite and water and a small water-filled gap between the corrosion products and fuel rods as conceivably occurring alterations acting to increase the reactivity. A case, or a set of cases, with altered geometry and materials that shall be used to determine the acceptable combinations of enrichment, BA-content and burnup at encapsulation remains to be determined. The case, or cases, may be programme specific due to differences in the spent fuel to be disposed and regulatory contexts in Finland and Sweden. Also for which cases the criteria $k_{eff} < 0.95$ and $k_{eff} < 0.98$, respectively, shall be applied needs to be further investigated and justified in the light of the regulatory contexts in Finland and Sweden.

The acceptable combinations of enrichment, BA-content and burnup will depend on the canister design and the assessed conceivable alterations that may take place if the canister is breached. With respect to the requirement of a robust design, the canister design must be such that sub-criticality can be readily verified for the bulk of the fuel assemblies to be finally disposed. This implies that the differences between the actual and required BA-contents and burn-ups with respect to the involved uncertainties should be large enough to demonstrate sub-criticality for any combination of assemblies to be encapsulated, so that criticality will not unduly restrict the selection of assemblies for encapsulation. If the canister design is modified, the validity of the analyses must be checked and the acceptable combinations of enrichment, BA-content and burnup possibly altered.

Fission gas release (FGR)

The gap inventory can be determined from the fission gas release. If the fission gas release is large, this implies that a relatively large portion of the radionuclides formed in the fuel pellets have escaped from the fuel pellets and have been released to the gap. Since the gap inventory is assumed to be instantaneously released in the case of a canister breach, the low dissolution rate of radionuclides is not applicable to the gap inventory. This, in turn, implies that the gap inventory, and thus the FGR, needs to be restricted in order to claim that all other radionuclides formed in the fuel pellets are retained in the fuel matrix and their release retarded by the low dissolution rate of the fuel pellets. The limit for the calculated average FGR of the fuel assemblies in a canister is set so that the related portion of the radionuclides that is assumed to be instantaneously released in the case of a breach is acceptable with respect to the safety of the repository. Calculations to determine the limit for the average FGR of the assemblies in a canister remain to be performed.

Dimensions and weight

The limits for total length and cross section are set with respect to the dimensions of the canister insert, so that the fuel can be encapsulated.

The limits for thickness of the cladding and structural materials are set with respect to the validity of the performance targets for corrosion rates and release of the radionuclide inventory in the cladding and structural parts respectively. The release rates are based on corrosion rates from literature and a material thickness. The material thicknesses may alter during the irradiation or during interim storage. Since the corrosion rates are set very high and the material thicknesses in general are larger than the thicknesses used when setting the corrosion time for the structural parts, local deviations from the dimensions stated for the un-irradiated assembly will not have any significant impact on the corrosion rates stated as performance targets. Thus, it is justified to check the material thicknesses for the un-irradiated fuel. This thickness is provided by the fuel manufacturers in their specifications of the fuel.

The maximum weight is set with respect to the design of technical systems for handling of the spent nuclear fuel assemblies. The weight of the assemblies is also included in the total weight of the encapsulated spent fuel. This weight is required when assessing mechanical loads on the canister.

Material composition of cladding and structural materials

The materials need to be stated with respect to the validity of the performance targets for corrosion rates and release of radionuclides from the cladding and structural parts of the fuel assemblies. If new materials or alloys are used, it need to be checked that the assumed corrosion rates are justifiable also for them.

Material composition of fuel pellets

Unless the release rate of radionuclides from the fuel pellets is low the safety of a KBS-3 repository cannot be demonstrated. The fuel pellets shall be in oxide form or form with similar dissolution rate in the repository environment.

Occurrence of leaking fuel rods

If the fuel pellets are exposed to water or air, and depending on the prevailing temperature, the UO_2 matrix will be oxidised from U(IV) to U(VI) which has a much higher dissolution rate. If a large amount is oxidised to U(VI), a corresponding part of the fuel pellet radionuclide inventory will have to be assumed to be released instantly in the case that the containment is breached. This could result in unacceptable doses or risks. To avoid the pellets being exposed to liquid water or moisture, or rather oxygen, fuel rods with observed leakages shall be encapsulated in specific casings.

Decay power

The limit for the decay power needs to be set with respect to the thermal properties of the repository as a whole, and a valid assessment of the development of decay power, heat and temperatures as the deposition proceeds and after closure. Given the allowed decay power in the canisters the temperatures must stay below their acceptable values. If the limit for decay power in the canisters is exceeded unacceptable temperatures may occur, see Section 2.2.1.

3.7.3 Implications for handling and verification

Radionuclide inventory

The radionuclide inventory needs to be determined with sufficient accuracy for the assessment of post-closure safety. The required, or desirable, accuracy can be stated considering the results of the assessment. Currently, the accuracy has not been defined, partly due to there still being a large uncertainty regarding the future operation of the nuclear power plants and also regarding the available information about old spent fuel assemblies.

In general, the radionuclide inventory should be determined with as good an accuracy as is reasonably achievable. This is especially true for the part of the inventory that has the largest impact on the assessed doses and risks. If the inventory of radionuclides of major importance for doses and risks can be determined with high accuracy, this may relax the requirements on the barrier system. With respect to this, it is important that the nuclear power plant operators provide and quality assure the data required to calculate the radionuclide inventory and its distribution in fuel pellets, structural materials, gap and crud. If these data are not provided, the radionuclide inventory will need to be determined either based on conservative or worst case estimations, or methods to determine the radionuclide inventory by measurements need to be developed and qualified. Conservatism and worst cases will result in overestimations that may be hard to handle in the safety assessment and repository design. With respect to this, it is important to inspect the data available for historical spent fuel and to define the data required for calculating the radionuclide inventory. In addition, a strategy for how to combine calculations and measurements to determine the radionuclide inventory should be developed.

Enrichment, BA-content and burnup

Enrichment, BA-content and burnup are the most important fuel characteristics in criticality analyses. These are also the fuel characteristics that must be verified to conform to the limiting values before the fuel assemblies are placed in the canister and encapsulated. This implies that the values for each assembly need to be provided and quality assured by the nuclear power plant operators.

The burnup is the fuel characteristic with the largest impact on the radionuclide inventory and thus the decay power and dose rate of an assembly at a given time. This implies that the burnup needs to be determined with sufficient accuracy for the determination of radionuclide inventory, decay power and dose rate. The burnup can be determined from calculations provided that there is information about the irradiation history. The accuracy of the calculated burnup will depend on the available irradiation history data and on the applied computer code. The burnup can also be determined based on measurements. Strategies and plans for how calculations and measurements can be combined in order to determine the burnup with sufficient accuracy remain to be developed.

Fission gas release (FGR)

The FGR is related to the gap inventory. The gap inventory needs to be restricted with respec to post-closure safety. In order to determine the gap inventory the FGR should be estimated and reported to Posiva and SKB. At encapsulation, the average FGR of the fuel assemblies in each canister, i.e. the average of the calculated assembly averages, can be checked and possibly compared to a specified limit.

Dimensions and weight

The limiting values are based on the current design of the canister. If there should be longer fuel assemblies or their cross section increased the design of the canister can be modified. That implies that the design analysis for the canister must be redone and if the production is initiated possibly also the qualification of production procedures.

Material composition of cladding and structural materials

The material composition of cladding and structural components is set with respect to the validity of the performance targets for corrosion rates. If new materials or material compositions are used, the validity of the corrosion models needs to be checked.

Material composition of fuel pellets

SKB and Posiva verify the release rate of radionuclides from irradiated spent fuel in leach tests. If new additives that may impact the dissolution rate of the fuel pellets and the release of radionuclides are used, SKB and Posiva will need sufficient information to verify the slow release of radionuclides from the fuel matrix.

Occurrence of leaking fuel rods

The occurrence of leaking fuel rods is generally identified during the operation of the nuclear power plants. If a leaking fuel rod is observed it is removed from the fuel assembly, if reasonably achievable. The leaking fuel rods need to be dried and encapsulated in specific water and gas tight containers which then can be handled and encapsulated in a similar way to the spent fuel assemblies.

Decay power

The decay power in each canister needs to be known in order to verify that no unacceptable temperatures will occur in a KBS-3 repository. With respect to cost and efficiency, it will be important to determine the decay power to high accuracy. If the decay power can be determined with high accuracy, this means that the required margins for uncertainties can be relaxed. This will be important since compliance with the acceptable decay power in the canister will affect the possibility of utilizing the encapsulation rate that the management system is designed for and the possibility of filling all canisters. It will also impact the margin for uncertainties required when determining the distance between deposition holes, also see Sections 2.2.1, 8.2.2 and 8.3.2.

4 Canister

4.1 Design and safety functions in a KBS-3-repository

The canister is a gas and water leak tight container with a corrosion resistant shell of copper and a load-bearing insert in which spent nuclear fuel is placed to be disposed of in a KBS-3 repository.

The main safety functions of a KBS-3 repository are to, either directly or indirectly by protecting and preserving the safety functions of the barrier system, isolate the repository and the encapsulated spent nuclear fuel from the surface environment; contain radionuclides and to retain and retard their dispersion into the environment. In addition, sub-criticality shall be maintained in the canister and repository, see Section 1.2.2.

In a KBS-3 repository, the canister maintains the containment. Containment is achieved by making and keeping the canister leak-tight. As long as the copper shell is not breached, the containment is maintained. In a KBS-3 repository, the canister shall maintain the containment and contribute to the main safety functions of the repository by maintaining the safety functions to:

- withstand corrosion,
- withstand mechanical loads and
- maintain sub-criticality of the encapsulated spent nuclear fuel.

The canister must allow the spent nuclear fuel to be encapsulated, taking into account its reactivity, decay power and dimensions.

The materials and design of the canister must not adversely affect the safety functions of the engineered barriers or the rock, see Section 2.2.2. This has resulted in technical design requirements for the insert material composition.

The technical design requirements in this report are based on a design with a tight copper shell and a cast iron insert with steel channels for emplacement of the spent fuel assemblies and a steel lid.

4.2 Safety functions and performance targets

4.2.1 Withstand corrosion

SKB requirement (SR-Site)	The canister shall maintain the containment and withstand the corrosion loads that are expected to occur in the final repository (Requirement SSC8).
Posiva requirement (TURVA 2012)	The canister shall withstand corrosion in the expected repository conditions (Requirement L3-CAN-7).
Safety function	withstand corrosion
Performance target	copper thickness > 0
Characteristics to be designed and verified in the production	copper shell • material composition • dimensions (thickness) • defects conditions in the canister

Rationale of the safety function and performance target

As long as the canister remains tight, a KBS-3-repository will maintain the containment and no harmful effects of radiation can occur. Chemical resistance is required to maintain the containment as long as this is required with respect to the radiotoxicity of the spent fuel, see Section 2.2.1.

The performance target, copper thickness larger than zero, is set since it is the copper shell that maintains the containment and thus ensures that no radionuclides can escape unless its thickness, at least at some location, is zero.

The copper shell material shall be corrosion resistant and its thickness shall have an allowance or margin to withstand corrosion. For canisters that are disposed in deposition holes and surrounded by a buffer that fulfil their technical design requirements and maintain their performance targets, this margin shall be sufficient to exclude breaching of the copper shell due to corrosion. If the margin is not sufficient this could result in breaching the containment in several or all canisters which in turn would endanger the radiation safety of the repository as a whole.

Conditions to be considered and assessed

The different corrosion mechanisms taken into account are described in King et al. (2012). These include general corrosion under oxic and anoxic conditions, localised corrosion (pitting), microbially influenced corrosion and stress corrosion cracking. A range of studies over several decades (see e.g. King et al. 2001, 2012) have identified substances capable of corroding the copper canister material under repository conditions: oxygen, nitric acid formed by gamma-radiolysis of nitrogen compounds in moist air in the gap between the canister and the buffer, oxidants formed by radiolysis of water and sulphide transported in from the buffer, or from the backfill or rock via the buffer.

The most important corrosion agents are the oxidants oxygen and sulphide. Oxygen is introduced into the repository during operation and via the amount trapped in the pores of the buffer and the backfill. Sulphide is present in groundwater and can be produced via microbial activity in the groundwater and buffer and backfill. Methane and H_2 are of importance because they could support microbial activity. Corrosion is also affected by pH, chloride, sulphate and bicarbonate ions as well as stress corrosion cracking (SCC) enhancing agents, i.e. nitrogen-containing compounds (nitrite and ammonium) and acetates.

The oxygen introduced during operation is expected to be consumed when the repository is closed and sealed, and after that anoxic conditions are expected. In anoxic conditions, chloride corrosion can occur only if, simultaneously, pH is low (<4) and chloride concentration is high (>2 mol/L) according to SKB (2010a, Section 3.5.4). Salinities will vary during the expected evolution of the repository due to up-coning of saline waters and due to infiltration of non-saline and possibly oxygen-rich waters, e.g. glacial meltwaters, from the surface.

Stress corrosion cracking is not expected to occur in anoxic conditions (Posiva 2013, Section 6.14). Based on results by King et al. (2012, Chapter 6), it is unlikely that stress corrosion cracking would occur in the repository if the concentration of NO_2^-, NH_3 and acetate are less than 10^{-6}–10^{-5} mol/L. King et al. (2012, Chapter 6) further report experimental evidence that stress corrosion does not occur if the concentration of NO_2^- is less than 10^{-3} mol/L. Also in case of acetate, there is fewer experimental data available, but these suggest that the threshold can be higher 5×10^{-2} mol/L. According to Kinnunen (2006), stress corrosion cracking did not occur even when the acetate concentration was as high as 10^{-3} mol/L. Other factors like interfacial pH and chloride concentration at the copper surface, temperature and the tensile stress in the copper affect the potential for stress corrosion cracking. Exceeding the limits for concentration of nitrite, ammonia or acetate is not sufficient for stress corrosion cracking to occur.

The impact of sulphide corrosion depends primarily on the amount of sulphide. According to the TURVA-2012 performance assessment (Posiva 2012b), sulphide concentrations of up to 3 mg/L (corresponding to 10^{-4} mol/L) present for the entire assessment period of one million years, did not lead to an unacceptable number of canister failures with respect to regulatory criteria on releases or risk. Similar results were obtained in SR-Site (SKB 2011, Sections 12.6, 12.9 and 15.3), where sulphide levels in the range 0.03–0.3 mg/L were considered and the buffer was assumed to be lost in deposition holes with high groundwater flows.

These chemical conditions that impact the canister corrosion processes have been considered when stating performance targets for favourable conditions in the rock, see Sections 2.2.1 and 8.2.4. Canister corrosion and potential corrodants also impact the design of the engineered barriers and underground openings, see Sections 2.2.2, 5.3.6, 6.3.5, 6.5.2 and 8.3.7.

In the case of loss of buffer or rock safety functions, i.e. in the case of an eroded buffer, corrosion will be enhanced and potentially result in breaches of the copper canister. This may occur for single canisters and must not result in unacceptable harmful effects of radiation. The potential harmful effects will depend on the number of deposition holes where buffer erosion may occur and on the margin set for the corrosion of the copper canister.

Corrosion may also occur from the inside of the canister if corroding agents are trapped within the canister at the encapsulation of the spent nuclear fuel. With respect to this, the amount of water and air inside the canister must be limited.

4.2.2 Withstand mechanical loads

SKB requirement (SR-Site)	The canister shall maintain the containment and withstand the mechanical loads that are expected to occur in the final repository (Requirement SSC9).
Posiva requirement (TURVA 2012)	The canister shall withstand the expected mechanical loads in the repository (Requirement L3-CAN-9).
Safety function	withstand mechanical loads
Performance targets	withstand isostatic load ≤ 50 MPa withstand shear movement over deposition hole ≤ 5 cm at a velocity of 1 m/s for a buffer with the maximum allowed shear strength withstand asymmetric loads for buffer swelling pressures of 3–10 MPa
Characteristics to be designed and verified in the production	copper shell • material properties • material composition • dimensions • defects insert • material properties • material composition • dimensions • defects

Rationale of the safety function and performance target

To maintain the containment, the canister must be tight and withstand the mechanical loads in the repository.

The performance target for isostatic load is set considering the largest load that, based on the assessment of the post-closure evolution of the repository, may occur. The largest isostatic load is the sum of the largest buffer swelling pressure, see Section 5.2.5, and the largest groundwater pressure that may occur. The groundwater pressure will depend on the repository depth see Section 8.3.1. When the site is covered by an ice sheet the groundwater pressure will increase. The increase will depend on the thickness of the ice sheet, see Section 8.2.3. Based on this and the results and conclusions from the safety assessments SR-Site and TURVA-2012 it is reasonable to set a total isostatic pressure of 50 MPa as a performance target for the canister's ability to withstand isostatic loads. This is further discussed in Section 8.2.3.

Evaluations of isostatic load contributions from future ice sheet thicknesses, see Section 8.2.3, and from buffer swelling pressures, and of how the hydrostatic pressure and the swelling pressure should be added, suggest that there may be cases where the performance target for isostatic load on the canister is exceeded. Provided that the canister is dimensioned to withstand 50 MPa, the consequence if the performance target is not fulfilled would be that a more detailed evaluation would be required in the safety assessment. In the safety assessment, the actual design and characteristics of the disposed canisters should be considered. All canisters will be exposed to the isostatic load and the safety assessment should investigate whether a violation of the performance target would result in the containment being breached in several or all canisters.

The integrity of the canister can also be threatened due to shear-type rock movements, if the shear plane intersects the deposition hole and the shear movement and rate are large enough. The shear movements that may occur in fractured rock are discussed in Section 8.2.3. The deposition holes shall be placed with respect to the fractures of the rock so that the possibly of occurrence of shear movements can be constrained and justified to not exceed 5 cm at a rate of 1 m/s. The shear movement will be transferred to the canister via the buffer, and the shear properties of the buffer must be such that the canister withstands the load, see Section 5.2.4. Again, given that the canister is dimensioned to withstand this shear load, it would not necessarily imply that the canister is breached even if the performance target is not fulfilled, but that more elaborate analyses may be needed. In contrast to the isostatic load only individual, and not all, canisters will be exposed to the shear load.

If the buffer is installed so that there are large differences in the installed density in the buffer surrounding the canister, asymmetric loads on the canister may occur. The performance target for asymmetric loads is based on the lowest and highest swelling pressures that are acceptable for the buffer, see Section 5.3.1.

Asymmetric load may also arise due to uneven saturation and build-up of swelling pressure, a tilted canister or irregularities in the geometry of the deposition holes, see next section. The performance target for pressure difference over the canister is based also on feed-back from the design and damage tolerance analysis of the canister (Raiko et al. 2010) that cover these loads.

Both the isostatic and shear loads are the result of changes that are external to, and independent of the presence of, the repository. However, the quantitative values set for the performance targets will depend on the design of the buffer and acceptable placement of deposition holes, see Section 8.3.2. The asymmetric loads will depend on the design and emplacement of the buffer. Thus, all mechanical loads can be altered if the design is altered.

Conditions to be considered and assessed

The canister shall withstand the isostatic load on it being the sum of the maximum swelling pressure of the buffer and the maximum groundwater pressure. The maximum groundwater pressure occurs when the repository is covered with ice and the weight of the ice contributes to the groundwater pressure at repository depth. Since the site is expected to be covered by an ice sheet during several periods of the assessment period, and the pressures will increase and decrease when the ice sheet advances and retreats over the site, the canister shall withstand repeated exposure to an isostatic load of 50 MPa.

The copper corrosion barrier should remain intact after a specified shear movement at a specified velocity and for all locations and angles of the shearing fracture in the deposition hole. The shear movement shall be transferred by a Ca-bentonite buffer with maximum allowed swelling pressure, see Section 5.3.1 and shear strength see Section 5.3.3. The insert should, after the shear load, maintain its pressure-bearing properties to withstand the isostatic and asymmetric loads.

The canister may be subjected to asymmetric loads during different phases in the repository evolution. This could temporarily occur due to uneven saturation of the buffer. Permanent asymmetric loads may occur due to a slightly tilted canister in the deposition hole or uneven density distribution of the saturated buffer due to irregularities in the geometry of the deposition holes. The deposition hole and buffer shall be designed so that they will not expose the canister to unacceptable loads. This implies that asymmetric loads must not endanger the canister's capacity to withstand mechanical loads in the repository.

4.2.3 Maintain sub-criticality

SKB requirement (SR-Site)	The canister shall prevent criticality (Requirement SSC47).
Posiva requirement (TURVA 2012)	The canister shall be subcritical in all postulated operational and repository conditions including intrusion of water through a damaged canister wall (Requirement L3-CAN-14).
Recommended safety function	maintain sub-criticality
Performance targets	reactivity k_{eff} < 0.95 for the canister filled with water reactivity k_{eff} < 0.98 for altered geometries and materials acting to increase the reactivity*
Characteristics to be designed and verified in the production	dimensions material composition density defects between the fuel channels of the insert

*) May be based on low probability and/or low-consequence justification, subject to regulatory approval, see Sections 3.6.1 and 3.7.2.

Rationale of the safety function and performance target

The rational of the safety function and performance target is presented in the spent fuel chapter Section 3.6.1.

Conditions to be considered and assessed

The canister is primarily designed to maintain containment in the final repository. However, the purpose of the canister is to encapsulate the spent fuel, and the spent fuel must always be handled so that criticality is prevented. This requires that the canister design must allow verification of sub-criticality for the spent fuel assemblies to be finally disposed. It may be acceptable to alter the geometry of single assemblies if required with respect to the verification of sub-criticality, but the canister design must allow encapsulation based on acceptable values for burnup and contents of burnable absorbers that can be readily verified for the bulk of the assemblies to be finally disposed, see also Section 3.7.2.

Since the presence of water is a prerequisite for k_{eff} to increase from very low values, to preserve the canister tightness, is of most importance for maintaining sub-criticality. As long as there is no water in the canister, criticality cannot occur. If the canister is breached and filled with water, criticality can still not occur unless some alterations that significantly increase the propensity for criticality take place, e.g. the geometry or material properties affecting neutron reflection and moderation are altered, see also Sections 3.6.1 and 3.7.2.

Defects occurring between the channels tubes of the insert will act to increase the reactivity. Since defects also impact the mechanical properties of the canister and its ability to withstand mechanical loads, a set of hypothetical defects are assumed for the criticality safety assessment. These defects are further discussed in Section 4.3.3.

Changes of the geometry can occur due to the mechanical loads on the canister e.g. in the case of a significant rock shear movement, as well as due to corrosion of the insert in a breached canister which can lead to changes in the spacing of the fuel assemblies or even redistribution of the spent fuel pellets inside the canister. Further, corrosion may cause alteration in materials so that the propensity for criticality increases.

A realistically occurring alteration of the materials inside a breached canister acting to increase k_{eff} is corrosion of the insert and formation of magnetite. The presence of carbonate in the groundwater may cause formation of siderite ($FeCO_3$) as a corrosion product. In the presence of sulphide, various iron sulphide corrosion products may be formed. Formation of siderite will result in a further increase of k_{eff}. Conceivable and realistically occurring alterations within a breached canister acting to increase k_{eff} are systematically assessed in Agrenius and Spahiu (2016). To assess criticality, a specific geometry and specific materials must be defined, also see Section 3.7.2.

4.3 Technical design requirements

4.3.1 Canister material properties

Characteristic	Technical design requirement	Related safety function
material properties of cast iron insert, steel lid and copper shell	The copper shell shall remain leak tight and the canister maintain its ability to resist loads for an isostatic pressure of 50 MPa.	withstand mechanical load
	The copper shell shall remain tight and the canister maintain its ability to resist loads for – 5 cm rock displacements at all angles and a rate of 1 m/s, – exerted on the canister by a buffer with an unconfined compressive strength at failure lower than 4 MPa at a deformation rate of 0.8 %/min.	withstand mechanical load
	The copper shell shall remain tight and the canister maintain its ability to resist loads for bending of the canister resulting from asymmetric loads according to Figure 4-1.	withstand mechanical load
	The copper shell shall remain tight and the canister maintain its ability to resist loads for shearing of the canister resulting from asymmetric loads according to Figure 4-2.	withstand mechanical load
material properties of cast iron insert, steel lid and copper shell	The radiation attenuation over the canister components shall, given the encapsulated spent fuel assemblies and their radiation emission rate, yield a dose rate at the canister surface < 1 Gray/h.	withstand corrosion
material properties of cast iron insert, steel lid and copper shell	The canister material properties shall lie within the range for the validity of the criticality analyses.	maintain sub-criticality
material properties of cast iron insert, steel lid and copper shell	The thermal conductivity over the canister components and internal gaps shall, given the encapsulated spent fuel assemblies and their decay power, yield a temperature on the canister surface < 100 C°.	long-term stability (see Section 2.2.1)

Justification

The copper shell shall remain leak tight and the canister maintains its ability to resist isostatic loads for an isostatic pressure up to 50 MPa, see Section 4.2.2. The canister shall remain leak tight if exposed to this load on several occasions. This means that relevant characteristics of the canister shall not significantly be deteriorated after exposure to the maximum isostatic load.

The copper shell shall also remain tight for a 5 cm rock displacement at the rate of 1 m/s, due to earthquakes causing secondary movements on fractures intersecting deposition holes. The quantitative numbers of rock displacement and rate are based on assessment of the post-closure evolution of the repository and are justified in Section 8.2.3. The shear load applies for all locations and angles of the shearing fracture in the deposition hole.

In the deposition hole, the canister is surrounded by the buffer. Thus, the technical design requirement for the shear load must include the characteristics of the buffer that affect how the shear movements in the rock are transmitted via the buffer to the canister. The shear strength of the buffer is expressed as its unconfined compressive strength at failure at a deformation rate of 0.8 %/min, see Section 5.3.3. In the design and damage tolerance analyses, this strength must be recalculated to fit the shear rate 1 m/s and the models used in the analyses.

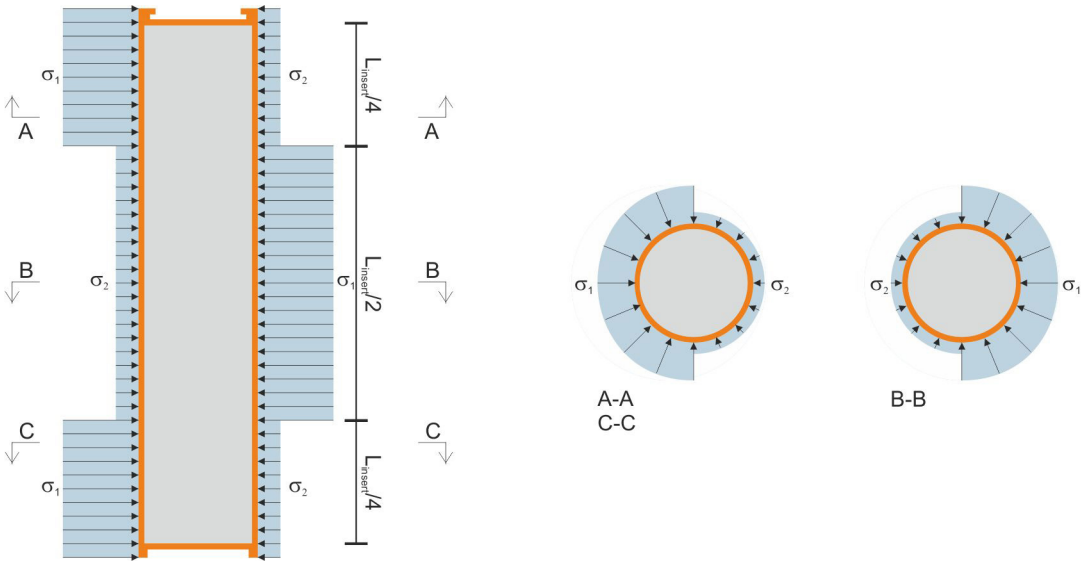

Figure 4-1. *Bending of the canister, σ_1 is the maximum swelling pressure and σ_2 the minimum swelling pressure of the buffer, i.e. 10 and 3 MPa respectively. To σ_1 and σ_2 the hydrostatic pressure at repository depth shall be added.*

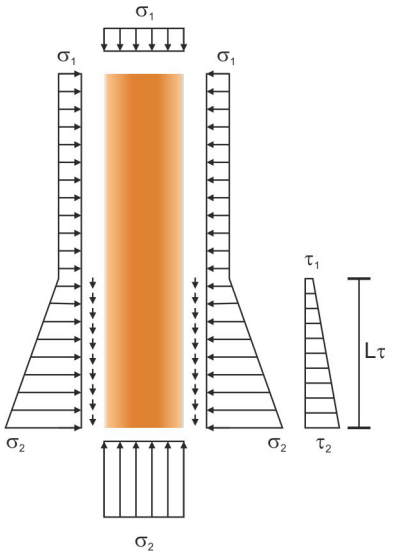

Figure 4-2. *Shearing of the copper canister induced by a buffer swelling pressure between 10 MPa (σ1) and 3 MPa (σ2). The hydrostatic pressure at repository depth shall be added to σ1 and σ2. The parameters τ1 and τ2 are the resulting shear stresses that act along the length Lτ of the surface of the canister.*

The canister may be subjected to asymmetric loads during different phases in the repository evolution. This could temporarily occur due to uneven water saturation in the buffer. Permanent asymmetric loads may occur due to an uneven density distribution of the saturated buffer due to irregularities in the geometry of the deposition holes or if the canister is slightly tilted or inclined in the hole within the buffer blocks.

The fracture toughness of the cast iron is a material characteristic that is important in the shear load case. At temperatures far below the freezing point of water, the cast iron will become more brittle and the fracture toughness will decrease to unacceptable values to withstand the mechanical loads. In general the material models used in the design and tolerance analysis are valid in the temperature interval 0–125 °C.

The canister shall remain leak tight and maintain its ability to resist loads after being exposed to the shear load. The canister shall also remain leak tight and maintain its ability to resist loads after exposure to the isostatic and asymmetric loads. This implies that relevant characteristics of the canister must not be significantly deteriorated after exposure to these loads. Both the copper shell and the insert contribute to the canister's ability to withstand mechanical loads. The main load bearing component of the canister is the cast iron insert. When the load from the groundwater pressure and the swelling of the bentonite develops, the copper shell will deform until it makes contact with the cast iron insert. The copper must possess sufficient ductility to allow this deformation and also to allow strain, either plastically or by creep when the insert deforms as a result of the loads defined in the technical design requirements (SKB 2010a, Raiko et al. 2010). The ductility of the canister will alter with temperature. as The highest acceptable temperature in the copper shell is set to 100 °C , since the temperature at the canister surface must not exceed 100 °C with respect to long-term stability of the buffer, see Section 5.2.6. The creep properties of the copper used in the design and tolerance analyses are valid for temperatures up to 100 °C.

The material properties of the canister will also affect its radiation attenuation and shielding. Further, some material properties constitute input to criticality safety analyses and some to the analysis of the temperature development within the canister. The radiation dose rate at the canister surface must be limited to avoid the formation of corrosive nitric acid or water radiolysis products, and critically must not occur in the canister, see Sections 3.4 and 3.6.1 respectively. The temperature at the canister surface must not exceed 100 °C with respect to long-term stability of the buffer, see Section 5.2.6. This means that the thermal conductivity and radiation attenuation over the canister components must not yield unacceptable temperatures or dose rates. Further, the canister material properties must lie within limits that are acceptable with respect to the validity of the assessments of criticality safety.

Implications for design and verification

The technical design requirements related to the safety function "withstand mechanical loads" concern, and shall be verified for, the canister as a whole, i.e. the insert and copper shell including their load-bearing parts. The verification of the mechanical loads shall comprise analyses, e.g. design and damage tolerance analyses that show that the strength and pressure-bearing ability of the canister are sufficient for the canister to withstand the mechanical loads specified in the technical design requirements. This includes verifying that the canister will not be affected or deformed in such a way that the copper shell is breached or the canister's ability to withstand future isostatic loads is lost. In addition, the design and damage tolerance analyses provide input to determine the design parameters i.e. yield- and rupture strengths, elongation, reduction of area and fracture toughness and their acceptable values. Further, input to determine the acceptable defects that need to be detected in the production is provided as a result of the design and damage tolerance analyses (Raiko et al. 2010, Raiko 2013).

In general, it is the requirement on the canister to withstand the mechanical loads in the repository that determines the required material properties. The material properties of the cast iron insert, with its steel cassette, that are most important for its ability to withstand the isostatic load, asymmetric loads and shear load are the yield strength, elongation at failure and fracture toughness.

The material properties of the steel lid and steel cassette of most importance for its ability to withstand the isostatic load, asymmetric loads and shear load are yield strength and elongation at failure.

The copper shell is not primarily a load-bearing component. It shall, however, have high enough ductility to withstand inelastic deformation to remain tight when the canister is exposed to the isostatic, asymmetric and shear loads. With respect to present knowledge, the average grain size in the copper material must not be too high to ensure the required creep ductility.

The canister is not actively designed to attenuate radiation, to decrease the propensity for criticality of the spent nuclear fuel or to conduct heat. However, in order to avoid radiolysis and demonstrate criticality safety the material properties need to be credited or considered. Further, the thermal properties of the canister are part of the temperature analysis. This implies that the material properties of relevance for radiation attenuation, criticality and temperatures in the repository shall be within the limits for the validity of the radiation shielding, criticality and thermal assessments. The

material properties considered in the attenuation and criticality analyses are the densities of the iron, steel and copper materials. These properties need to lie within an interval where the dose rates on the canister surface and the reactivity, k_{eff}, will yield acceptable values. The thermal properties of the canister materials are well known. Large defects in the insert will act to increase the reactivity and decrease the thermal conductivity. Defects in the insert will also impact the strength of the canister. The criticality and thermal analyses are based on a set of hypothetical defects that are considerably larger than those expected to occur in produced inserts.

4.3.2 Cast iron insert material composition

Characteristic	Technical design requirement	Related safety function
cast iron insert – material composition	The technical design requirements related to the safety function to withstand mechanical loads defined in Section 4.3.1.	withstand mechanical loads
	To limit gamma radiation caused hardness and brittleness in cast iron the Cu-content shall be < 0.05 %.	withstand mechanical loads
	The material composition shall be checked to lie within the limits for the validity of the criticality analyses.	maintain sub-criticality
	No organic materials in insert components.	compatibility and reliability of production (see Section 2.2.2)

Justification

The justification of the technical design requirements for the material composition is similar to the justification of the technical design requirements for the material properties, i.e. the technical design requirements state the mechanical loads for which the canister shall be verified to remain tight in the repository. In addition, the material composition must lie within the limits for the validity of the criticality safety analyses.

In the repository, the canister is exposed to radiation from the spent nuclear fuel. Consequently, as neutron and gamma radiation from the fuel can give rise to minor material changes in the cast iron insert and the copper canister, this must be considered in the technical design requirements. Precipitation of copper particles due to radiation is a well-known problem in reactor vessels. Calculations by (Brissonneau et al. 2004, pp 121–130) resulted in an upper limit for the copper content (< 0.05 %) in the insert cast iron to avoid precipitation embrittlement. This result is most probably pessimistic, as the damage flux was overestimated (Toijer 2014), but the limit is kept as no new limit has been determined yet.

In the case of breaching of the containment, organic materials in the canister and released radionuclides may form complex compounds that can be transported relatively fast through the repository. The formation of such compounds may also act to increase the release rate of radionuclides from the spent nuclear fuel. With respect to this, organic materials inside the canister shall be avoided, and no organic materials are allowed in canister components.

Implications for verification and design

The verification of the mechanical loads comprises analyses, e.g. design and damage tolerance analyses, that show that the strength and pressure-bearing ability of the canister are sufficient for the canister to withstand the mechanical loads, see Section 4.3.1. The material composition of the cast iron, the steel in cassette and lid shall be such that required material properties are obtained. The material composition shall be verified in production.

The material composition of the insert affects the reactivity and thus criticality. Several design parameters specifying the material composition of the cast iron insert, steel cassette and steel lid constitute input to the criticality safety analysis. If the specifications are altered the validity of the criticality analysis must be checked, see Section 3.7.2.

4.3.3 Insert dimensions

Characteristic	Technical design requirement	Related safety functions
dimension of cast iron insert and steel lid	The technical design requirements related to the safety function to withstand mechanical loads defined in Section 4.3.1.	withstand mechanical loads
	The insert dimensions shall be checked to lie within the limits for the validity of the criticality analyses.	maintain sub-criticality
defects in cast iron insert	Defects within limits to be determined within the design and damage tolerance, criticality and thermal analyses (out of scope of this report).	withstand mechanical loads maintain sub-criticality compatibility and reliability of production (see Section 2.2.2)

Justification

The justification of the technical design requirements for mechanical loads for the dimensions and acceptable defects is similar to the justification of the technical design requirements for the material properties, i.e. the technical design requirements that state the mechanical loads the canister shall be verified to withstand. In addition, the dimensions must lie within the limits for the validity of the criticality safety analyses.

Implications for verification and design

The dimensions of the insert will affect its strength and pressure-bearing ability and thus the canister's ability to withstand mechanical loads in the repository. They will also affect the reactivity and ability to maintain sub-criticality.

Dimensions of importance for the insert's ability to withstand mechanical load are outer diameter, thickness of the bottom, distance between channel tubes and outer surface (edge distance), corner radius of the channel tubes, distance between channels tubes, and channel tube thickness (Raiko et al. 2010, Raiko 2013).

The verification of the canister's resistance to mechanical loads is included in the design and damage tolerance analyses, see Section 4.3.1. The design and damage tolerance analyses provide input to determine the material properties and dimensions required to provide sufficient strength and pressure-bearing ability. The damage tolerance analyses also provide information on defects that are acceptable without unduly impairing the canister's ability to withstand mechanical loads. These calculations related to modelled defects are in turn used as input to define the defects that need to be detected in the production of the insert.

The dimensions of most importance for criticality are distances between channel tubes and the wall thicknesses between them. If the insert design is altered so that the channel tubes are placed closer to each other the reactivity will increase. Defects between the fuel channel tubes will also act to increase the reactivity, and for the criticality analyses a set of hypothetical defects is assumed. Further, the outer dimensions of the insert shall fit to the dimensions of the copper shell. The insert dimensions must also allow the different types of fuel assemblies to be encapsulated. The dimensions of the fuel assemblies will limit the possible insert dimensions, also see Section 3.5.1.

4.3.4 Copper shell material composition

Characteristic	Technical design requirement	Related safety function
copper shell material composition	The copper material shall be highly pure copper.	withstand corrosion
	To avoid grain boundary corrosion the oxygen contents shall be ≤ 5 wt-ppm.	withstand corrosion
	The technical design requirements related to the safety function to withstand the mechanical loads defined in Section 4.3.1.	withstand mechanical loads
	The material composition shall be checked to lie within the limits for the validity of the criticality analyses.	maintain sub-criticality

Justification

Copper is used as a corrosion barrier in a KBS-3 repository, since copper according to established knowledge and thermodynamic data has a sufficient corrosion resistance in the repository environment and in the granitic rock and groundwater occurring at repository depth. To withstand the potential corrosion mechanisms in the repository discussed in Section 4.2.1, the copper material shall be highly pure copper. In order to restrict corrosion coupled to grain boundaries, the oxygen content in the copper material must be limited (SKB 2010a, Raiko 2013). The set value for the maximum oxygen content, 5 wt-ppm, has, in safety assessments of the repository, been shown to be low enough to restrict corrosion at grain boundaries (SKB 2009, Gubner et al. 2006, Gubner and Andersson 2007). In addition, 5 wt-ppm has been used in the specification for test manufacturing of copper components. Consequently, the majority of time-consuming creep testing has been performed on copper components with this specification (Nolvi 2009, Raiko et al. 2012, p 16, Andersson-Östling and Sandström 2009).

The technical design requirements related to the ability of the canister to withstand mechanical loads are justified in Section 4.3.1. To remain tight, the copper must have sufficient ductility to allow inelastic straining strain?, either plastically or by creep when the loads specified in the technical design requirements stated in Section 4.3.1 are exerted on the canister. In addition, the material composition must be within the limits for the validity of the criticality safety analyses.

Implications for verification and design

The copper material composition will affect the ductility of the copper shell. The substances of most importance for the mechanical properties of the copper shell are phosphorous, sulphur, oxygen and hydrogen. Creep testing has been performed on oxygen-free copper material with different contents of alloyed phosphorous and sulphur (Andersson et al. 1999). Based on present knowledge, the composition of the highly pure copper shell includes specified contents of phosphorus and sulphur to obtain the required creep ductility (SKB 2009, Raiko et al. 2012).

In addition, the composition of the highly pure copper shell shall have a limited content of hydrogen to avoid embrittlement (Dies 1967, SKB 2009, Raiko et al. 2012) during the manufacturing process.

The material composition of the copper will have minor impact on the reactivity (k_{eff}), but needs to be included as input to the assessment of criticality safety.

4.3.5 Copper shell dimensions

Characteristic	Technical design requirement	Related safety function
copper shell dimensions	At deposition the copper thickness shall be ≥ 40 mm.	withstand corrosion
	Local reduction of the thickness is acceptable in some cases – *acceptance criteria to be determined*.	
copper shell dimensions	The technical design requirements related to the safety function to withstand mechanical loads defined in Section 4.3.1.	withstand mechanical loads

Justification

To withstand the potential corrosion mechanisms in the repository discussed in Section 4.2.1, a copper shell thickness of 5 mm has been shown to be sufficient (SKB 2010d, Werme 1998, Section 5.2.2). In case favourable and stable conditions for the engineered barriers are not maintained in some deposition holes, and the safety functions of the buffer are lost, a margin need to be added to the copper thickness. This margin needs to be sufficient to demonstrate the safety of the repository as a whole. Based on the results and conclusions in SR-Site and TURVA-2012, a copper thickness of 40 mm is considered to be sufficient to fulfil the criteria for radiation safety of final repositories stated by SSM and STUK, respectively.

The justification of the mechanical loads is the same as for all characteristics that impact the canister's ability to withstand mechanical loads, and stated in Section 4.3.1.

Implications for verification and design

At deposition, the copper thickness shall conform to the technical design requirement. This implies that defects reducing the thickness must be considered in the design of the copper components. Defects that may occur as the result of the manufacturing of the copper components and during welding, as well as during the handling and deposition of the sealed canister, must be considered when specifying the thickness of individual components.

Regarding dimensions that affect the mechanical strength of the canister, at deposition, these need to be sufficient to provide the creep and ductility required in the repository after deposition. In addition, thickness, tolerances and clearances with insert have to be such that they permit assembly of the canister. Further, the dimensions must be sufficient to withstand the mechanical loads occurring during the assembly of the canister and the handling and deposition of the sealed canister.

Dimensions of importance for the safe handling and lifting of the canister are the radius underneath the lifting shoulder and the dimensions of the lifting shoulder of the copper lid.

4.3.6 Conditions in the canister

Characteristic	Technical design requirement	Related safety functions
conditions in canister	The atmosphere in the insert shall consist of > 90 % argon.	withstand mechanical loads low release rate of radionuclides
	The maximum content of water in a sealed canister is 600 g.	
conditions in canister	The alterations of the canister materials in a breached canister, and their resulting corrosion products and substances acting to increase reactivity shall be predictable.	maintain sub-criticality

Justification

Nitric acid formed from radiolysis of nitrogen gas in moist air, can cause general corrosion and stress corrosion cracking of the cast iron. Water in the canister cavity and in the annulus between copper and cast iron will corrode the cast iron insert. Water trapped inside the canister may also result in increased pressure inside the canister caused by hydrogen gas produced as the water corrodes the insert. As a consequence of the corrosion processes, the integrity and mechanical strength of the cast iron insert may be jeopardised. Too high a pressure inside the canister may result in loads that can breach the containment. The quantitative limits for the technical design requirements given in the table above have been theoretically verified in analyses (SKB 2010a, pp 46–47).

If there should be fuel rods with leaks that have not been observed, the limitation of the amount of air and water inside the canister will set an upper limit on the extent of fuel pellet oxidation that may occur and result in an increased fuel dissolution rate, also see Section 3.6.2.

Both the materials surrounding the spent fuel assemblies and their geometrical arrangement will impact the reactivity. If water should enter the canister, it is reasonable to assume that corrosion will occur. Corrosion products that will act to increase the reactivity are magnetite and siderite (Agrenius and Spahiu 2016). It is reasonable to assume that the environment in a breached canister will consist of magnetite, siderite and water, see also Sections 3.6.1 and 3.7.2.

Implications for verification and design

The canister components shall be dry and the atmosphere in the insert shall be changed to argon before sealing of the canister. In addition, the fuel shall be sufficiently dried before encapsulation, also see Sections 3.5.2 and 3.6.2. The argon atmosphere inside the insert must be preserved until the copper shell is sealed.

In the selection of materials for the canister, and also in the geometrical arrangement of the spent fuel assemblies in the insert, the propensity for criticality must be considered.

5 Buffer

5.1 Design and safety functions in a KBS-3 repository

The buffer consists of natural clay containing swelling material. The buffer surrounds the canister and fills the space between the canister and the rock.

The main safety functions of a KBS-3 repository are to, either directly or indirectly by protecting and preserving the safety functions of the barrier system, isolate the repository and the encapsulated spent nuclear fuel from the surface environment; contain radionuclides and to retain and retard their dispersion into the environment, see Section 1.2.2. The buffer shall protect and preserve the containment of the radionuclides by limiting the transport and availability of corrodants at the canister surface. Further, to preserve the containment the buffer must be designed with respect to the mechanical integrity of the canister. If canisters are breached the buffer shall contribute to retain radionuclides and retard their dispersion into the environment. With respect to this the buffer is assigned the safety functions to:

- limit advective mass transfer,
- limit microbial activity,
- filter colloids,
- protect the canister from detrimental mechanical loads
  - rock shear load,
  - pressure load,
- resist transformation,
- keep the canister in position,
- retain sufficient mass over life cycle.

The choice of clay containing swelling material as a buffer between the canister and rock is made with respect to its ability to maintain these safety functions.

Clay materials have as an additional feature contributing to retaining radionuclides and retarding their dispersion, the capacity to sorb radionuclides if the containment should be breached, see Sections 1.2.5 and 2.2.3.

The materials and design of the buffer must be compatible with, and not unduly impair the safety functions of the engineered barriers or the rock, see Section 2.2.2. With respect to this, the materials used for the buffer must not jeopardise the:

- chemically favourable conditions in the repository.

This has resulted in technical design requirements for the content of impurities in the buffer. In addition, so as not to impair the safety functions of the engineered barriers or the rock there are technical design requirements for the gas transport properties of the buffer.

The technical design requirements for the buffer in this report are based on a design with blocks and pellets of swelling clay material installed in the deposition hole.

5.2 Safety functions and performance targets

5.2.1 Limit advective mass transfer

SKB requirement (SR-Site)	The buffer shall prevent the flow of water (advective transport) in the deposition hole (Requirement SSBU38).
Posiva requirement (TURVA 2012)	The buffer shall be impermeable enough to limit the transport of corroding substances from the rock into the canister surface (Requirement L3-BUF-13). The buffer shall be impermeable enough to limit the transport of radionuclides from the canisters into the bedrock (Requirement L3-BUF-12).
Safety function	limit advective mass transfer
Performance targets	hydraulic conductivity $< 10^{-12}$ m/s swelling pressure > 1 MPa
Characteristics to be designed and verified in the production	material-specific relation between hydraulic conductivity and dry density material-specific relation between swelling pressure and dry density installed buffer material mass

Rationale of the safety function and performance target

The need to limit advective mass transfer in the buffer arises firstly from the need to protect the canister from corroding substances in the groundwater and secondly from the need to retard radionuclide releases in case the containment of radionuclides in the canister is breached. The transport through the buffer is required to be limited and diffusion is to be the dominant transport mechanism. Diffusive transport and limited advective transport in the buffer is achieved by a low hydraulic conductivity and a high enough swelling pressure, that makes the buffer self-sealing if the potential for advective transport should occur.

Significant transport of species through the buffer by advection can be neglected compared with diffusion if the hydraulic conductivity in the saturated buffer is $< 10^{-12}$ m/s (SKB 2010b, Section 3.3.2).

To ensure diffusive transport, the swelling pressure in the buffer shall be such that it has capability to self-seal conductive features, e.g. remnants from the saturation process such as erosion channels and dead angle locations in the buffer blocks or in the pellet-filled space between the buffer and the rock. Unless such features are sealed, advective transport through or along the buffer may occur. The performance target for swelling pressure is >1 MPa and includes a safety margin (SKB 2010b, Section 3.3.2). In SR-Site (SKB 2011, Section 8.3.5), it is concluded that the margin for the hydraulic conductivity is related to the hydraulic gradient and the diffusivity of the substances in question, and that it is significant.

Conditions to be considered and assessed

Conditions that can increase the hydraulic conductivity are loss of buffer mass due to mechanical and chemical erosion. Loss of buffer mass will also reduce the self-sealing capacity in cases of the formation of cracks or pipes. Changes in ground water chemistry may also affect these properties.

Buffer mass may be lost due to e.g. piping and erosion during the water saturation phase. The contact between buffer and host rock, and between buffer and canister, are not initially tight along the length of the deposition hole due to spaces needed for installation. The pellet-filled gaps do not give so tight a contact that channel formation can be excluded (Pintado et al. 2013). The swelling of the buffer during saturation is required to be sufficient to self-seal the gaps to prevent preferential flow paths from forming. Different mass loss scenarios and related analyses have been presented by Åkesson et al. (2010).

The potential for, and the related consequences of, mass loss due to interactions of dilute groundwater with bentonite in a fracture intersecting deposition hole are required to be assessed.

5.2.2 Limit microbial activity

SKB requirement (SR-Site)	The buffer shall have the ability to limit microbial activity (Requirement SSBU9).
Posiva requirement (TURVA 2012)	The buffer shall limit microbial activity (Requirement L3-BUF-8).
Safety function	limit microbial activity
Performance target	swelling pressure > 2 MPa
Characteristics to be designed and verified in the production	material specific relation between swelling pressure and dry density installed buffer material mass

Rationale of the safety function and performance target

Microbial activity in the buffer can produce chemical species that may accelerate the corrosion of copper. The most important types of microbes are sulphate-reducing bacteria, which produce sulphide.

The prerequisites for significant viability of microbes are sufficient availability of free water, nutrients, and space for living cells to grow. Mechanical forces, low water activity and pore size will therefore affect the microbial activity in the buffer (Motamedi et al. 1996, Stroes-Gascoyne et al. 1997, Pedersen et al. 2000 a, b, Masurat et al. 2010b). The presence of sulphates-reducing bacteria (SRB) in commercial bentonite and their potential to be active after exposure to elevated temperature and salinity has been shown in Masurat et al. (2010a) and Svensson et al. (2011).

There is a correlation between swelling pressure and microbial activity. This correlation has not been sufficiently investigated and it is currently not clear which buffer characteristics limit microbial activity. In the SR-Can safety assessment, the limit for controlling microbial sulphide production was set as a saturated clay density of 1,800 kg/m^3 (SKB 2006, Table 2-2). This gives a pore space and swelling pressure that lie close to the low pore space and high swelling pressure reported to suppress microbes in Masurat (2006).

SKB and Posiva are currently working on a joint project to further investigate the viability of microbes in the conditions of buffer and backfill (Integrated sulphide project ISP, e.g. Bengtsson et al. 2015). For example, the lower limit of bentonite density and thereby the swelling pressure for which the microbial activity can be considered to be insignificant is being studied. Conclusions concerning the swelling pressure/dry density and potential additional constraints limiting microbial activity are, however, somewhat incomplete. There are however preliminary results that indicate that there is a sharp limit where microbial sulphate reduction ceases in MX-80 (Bengtsson et al. 2015). The performance target for limiting microbial activity is >2 MPa and applies to the entire buffer volume. The ISP is expected to give additional information to justify this value or for a future modification of the performance target (Bengtsson et al. 2016).

Conditions to be considered and assessed

The commercial bentonites contain a viable microbial population that is not easy to eliminate in industrial-scale mass production.

During the saturation of the buffer, the microbial activity may be enhanced before the swelling pressure is established.

Because of the high temperatures, and desiccation effects after deposition of the canister, initial microbial activity close to the canister is not likely. The water content in the buffer will decrease near the canister. The heat from the spent nuclear fuel will introduce a stress on microbial populations. However, many microorganisms can survive and be active at high temperatures, provided that they have access to water, space, electron acceptors, carbon sources and energy that can sustain metabolic processes for repair of unavoidable heat damage in the cells.

The radiation levels in the buffer are expected to have little effect on the cultivability of microbes in the buffer (e.g. Pitonzo et al. 1999a, b), although the number of microbes may decrease.

As a result of a loss of buffer density, sulphide can form due to microbial activity (SKB 2011, Section 10.3.13). The pellet-filled gap between the buffer and rock with a lower density, is the buffer volume that may have a more suitable environment for microbial activity. Wersin et al. (2014) considered this as the zone for potential sulphate-reducing activity.

5.2.3 Filter colloids

SKB requirement (SR-Site)	The buffer shall prevent colloids being transported through it (Requirement SSBU23).
Posiva requirement (TURVA 2012)	The buffer shall limit the transport of radiocolloids to the rock (Requirement L3-BUF-14).
Safety function	filter colloids
Performance target	dry density > 1 000 kg/m^3
Characteristics to be designed and verified in the production	installed buffer material mass

Rationale of the safety function and performance target

Colloids, i.e. particles with sizes of the order of 10^{-9} to 10^{-6} m, whose migration is not affected by gravity or inertial forces, can be relatively rapidly transported through the rock. Fuel colloids can form by dissolution of the fuel and due to oversaturation of uranium in the canister interior. Colloids are also formed in the clay-based buffer and backfill materials. These latter colloids can have available sorption sites for radionuclides. If radionuclides can be transported with colloids, the concept of solubility or concentration limits for fuel dissolution is invalid. In addition, colloid-facilitated radionuclide transport can result in faster radionuclide transport in the geosphere.

The relatively fast transport of radionuclides with colloids, is a concern in the safety assessment. The transport of fuel colloids from the interior of a damaged canister to the surrounding host rock and deposition tunnel is prevented if the buffer completely envelops the canister and has a density, expressed as dry density, of at least 1 000 kg/m^3 (SKB 2010b, Section 3.5.4, Posiva 2012b, Section 5.4.1), which will provide geometrical constraints. This is based on experimental results on gold colloids (Kurosawa et al. 1997, Holmboe et al. 2010).

Conditions to be considered and assessed

If fuel colloids inside a penetrated canister can be transported to the host rock, the concept of solubility or concentration limits for fuel dissolution is invalid. Colloids move mainly by advection in groundwater and by diffusion in pore waters of the host rock, buffer and backfill. These flows are affected by infiltration of less saline waters from the surface during deglaciations. The salinity of the groundwater in the near field of the repository changes during such processes and affects colloid stability.

5.2.4 Protect the canister from detrimental mechanical loads – rock shear load

SKB requirement (SR-Site)	–
Posiva requirement (TURVA 2012)	The buffer shall mitigate the impact of rock shear on the canister (Requirement L3-BUF-10).
Safety function	protect the canister from detrimental mechanical loads – rock shear load
Performance target	mitigate impact of 5 cm rock shear displacement at a rate of 1 m/s to a load acceptable for the canister
Characteristics to be designed and verified in the production	material-specific relation between shear strength and dry density installed buffer material mass

Rationale of the safety function and performance target

Rock shear movements may occur when stresses in the bedrock are released, see Section 8.2.3. Depending on the mechanical properties of the buffer, the rock shear movements may cause the insert to collapse or deform to such extent that the deformation of the copper shell will result in a breach and loss of containment. The less the buffer deforms in the deposition hole the higher the stresses that will be transmitted to the canister, i.e. the higher the shear strength of the buffer, the higher the stresses in the canister. To maintain containment, the shear strength of the buffer must not result in a load larger than the load the canister can withstand for the shear movements expected to occur in a deposition hole.

Conditions to be considered and assessed

The buffer shall be designed such that a shear movement in the deposition hole with 5 cm displacement at the rate of 1 m/s, will not cause excessive shear strain on the canister. This implies that the buffer must not be too stiff, and it must not be stiffer than in the canister design analyses (Raiko et al. 2010). The stiffness of the buffer and its shear strength relates to the swelling pressure, the rate of strain and the dominating cation in the bentonite, see Section 5.3.3. The largest shear strength will occur in a fully calcium-exchanged material at the dry density that corresponds to the upper limit for swelling pressure. Experimental results show that the strength increases slightly if the material is exposed to elevated temperatures in a saturated state (Dueck 2010). This needs need to be considered when determining the technical design requirement related to shear strength.

5.2.5 Protect the canister from detrimental mechanical loads – pressure load

SKB requirement (SR-Site)	–
Posiva requirement (TURVA 2012)	–
Safety function	protect the canister from detrimental mechanical loads – pressure load
Performance targets	swelling pressure < 10 MPa $T_{buffer} > -2.5$ °C
Characteristics to be designed and verified in the production	material-specific relation between swelling pressure and dry density installed buffer material mass

Rationale of the safety function and performance target

The swelling pressure of the buffer needs to be limited so that neither the canister nor the rock is exposed to loads they cannot withstand. High pressures on the canister may result in breach of the copper shell and loss of containment, and high pressures on the rock may cause cracking that in turn may result in increased transmissivity around the deposition hole. The maximum acceptable buffer swelling pressure in the deposition hole is restricted by the acceptable isostatic load on the canister.

A previous performance target (used in SR-Site and TURVA-2012) for the isostatic load on the canister was determined under the assumption that the buffer swelling pressure will not exceed 15 MPa. The now specified performance target (< 10 MPa) is selected based on feed-back from the design analyses of the mechanical loads on the canister (Raiko et al. 2010) and the need of tolerances in design and installation of the buffer.

If the groundwater in the rock around the buffer freezes, further cooling of the buffer decreases the swelling pressure. At a critical temperature T_c, the swelling pressure is completely lost. If the temperature falls below T_c, ice starts forming in the buffer. If the buffer freezes, development of damaging pressures due to expanding water cannot be ruled out. Therefore, to avoid pressure increase, the buffer temperature should not fall below T_c. T_c depends on the swelling pressure at 0 °C. For typical buffer materials T_c is in the interval −2.5 to −11 °C (Birgersson et al. 2010). The temperature of −2.5 °C is the performance target for the buffer's ability to limit the pressure on the canister as well as for favourable thermal conditions in the repository, see Section 2.2.1.

Conditions to be considered and assessed

Groundwater chemistry, salinity and ion-exchange will affect the swelling pressure. This is however already considered in the performance target.

The maximum acceptable buffer swelling pressure in the deposition hole is restricted by the acceptable isostatic load on the canister. The installed buffer density shall be chosen so that the swelling pressure of the saturated buffer will not exceed the limit set by the canister.

The temperature conditions to which the buffer and the canister are exposed need to be considered in setting the performance targets. After deposition of the canister, the buffer will experience a rise in the temperature. Experimental results show that the swelling pressure decreases slightly if the material is exposed to elevated temperatures in a saturated state (Dueck 2010).

In a long time perspective, cold climates and the development of permafrost will occur. If the temperature in the buffer falls below the critical temperature T_c, at which ice starts forming in the buffer, the pressure in the buffer will increase. T_c is the temperature at which freezing is initiated, whereas complete freezing occurs at much lower temperatures (Birgersson et al. 2010). The repository depth shall be selected such that there is sufficient confidence to exclude freezing of the buffer, see Sections 8.2.2 and 8.3.1. It has been shown that the freezing and thawing cycles do not significantly affect the characteristics of the buffer when unfrozen (see e.g. Schatz and Martikainen 2010, 2012).

5.2.6 Resist transformation

SKB requirement (SR-Site)	The buffer shall maintain its barrier functions and have long-term durability in the environment expected in the final repository (Requirement SSBU8).
Posiva requirement (TURVA 2012)	Unless otherwise stated, the buffer shall fulfil the requirements over hundreds of thousands of years in the expected repository conditions except for incidental deviations (Requirement L3-BUF-4).
Safety function	resist transformation
Performance target	withstand temperature < 100 °C
Characteristics to be designed and verified in the production	thermal conductivity

Rationale of the safety function and performance target

The buffer must resist transformation in order to maintain its safety functions in a long-term perspective, see Section 2.2.1. At elevated temperatures, chemical alterations of the swelling clay material acting to decrease the development of swelling pressure would occur (Leupin et al. 2014).

The highest temperatures in the repository occur due to the deposition of the spent fuel and the decay power it develops, see Section 3.3. The buffer must withstand the increase in temperature caused by the decay power developed in the encapsulated spent nuclear fuel. With respect to this, a temperature limit needs to be stated for which it can be demonstrated that the buffer resists transformation and that is acceptable with respect to the encapsulated spent nuclear fuel and the thermal properties of the barrier system. This acceptable temperature is the performance target for the buffer's ability to withstand transformation as well as for favourable thermal conditions in the repository, see Section 2.2.1. The alterations of swelling clay materials are also affected by the chemical conditions, and in addition the bedrock shall provide chemically favourable conditions.

With respect to the temperature increase resulting from the disposal of the spent nuclear fuel, the buffer shall retain its favourable characteristics at temperatures up to 100 °C. This implies that the transformation of its swelling minerals and mechanical properties shall be shown to be insignificant for temperatures up to 100 °C. If this performance target is upheld in the buffer, also the backfill and closure containing swelling clay will resist transformation, since their temperatures will be lower than in the buffer.

Conditions to be considered and assessed

The advantageous physical characteristics of the buffer, principally its swelling pressure and low hydraulic conductivity, are determined by the capacity for water uptake between the montmorillonite layers (swelling) in the bentonite. Montmorillonite can transform into other minerals (SKB 2010b, Figure 3-22) of the same principal atomic structure, but with less or no ability to swell in contact with groundwater. If montmorillonite transformation occurs, the buffer functions will alter. The transformation processes usually consist of several basic mechanisms (SKB 2010b, Section 3.5.9).

Both thermal and chemical conditions in the repository will impact the montmorillonite transformation processes. Two important transformation processes are illitisation and chloritisation.

The illitisation process is limited by a low concentration of potassium. According to Karnland and Birgersson (2006, Chapter 3.1), illitisation is unlikely if the concentration of potassium remains below 80 mM whereas the results by Leupin et al. (2014) indicate that the illitisation of MX-80 bentonite remains insignificant in potassium concentration of 0.1 mol/L. At low concentrations of Fe, chloritisation is insignificant.

Also the alkalinity will impact the buffer material. The effect of a hyperalkaline solution on a compacted mixture of argillite and MX-80 bentonite, investigated experimentally by Cuisinier et al. (2008), was manifested as microstructural changes in the material, which could be attributed to mineral dissolution. According to several studies, montmorillonite dissolution increases with increasing pH along with increased SiO_2 solubility (see e.g. Leupin et al. 2014, Arenius et al. 2008, Savage and Benbow 2007, Karnland and Birgersson 2006). According to Karnland and Birgersson (2006, Figure 3-3), a further silicate reaction increases the montmorillonite dissolution at pH > 11.

Montmorillonite transformation is not likely to occur, or will be limited, unless the temperature in the rock is elevated (see Leupin et al. 2014). Both thermal and chemical conditions that impact the montmorillonite transformation processes have been considered when stating performance targets for favourable conditions in the rock, see Sections 8.2.2 and 8.2.4.

5.2.7 Keep the canister in position

SKB requirement (SR-Site)	The buffer shall keep the canister in its centred position in the deposition hole as long as required with respect to the safety of the final repository (Requirement SSBU10).
Posiva requirement (TURVA 2012)	The buffer shall be able to keep the canister in the correct position (to prevent sinking and tilting) (Requirement L3-BUF-17).
Safety function	keep the canister in position
Performance target	swelling pressure > 0.2 MPa
Characteristics to be designed and verified in the production	material-specific relation between swelling pressure and dry density installed buffer material mass

Rationale of the safety function and performance target

The buffer's main role is to reduce the potential negative interactions between the canister and the host rock including the groundwater. If the buffer density is too low, it will deform under the weight of the canister and thus allowing the canister either to sink or to tilt so that the surrounding buffer thickness is reduced or the canister even touches the walls or bottom of the deposition hole. If so, the buffer will not surround the canister and the safety function regarding diffusive transport in the buffer, see Section 5.2.1, would no longer be maintained.

Analyses (Åkesson et al. 2010) of canister sinking in a deposition hole for a range of buffer densities and hence swelling pressures indicate that the total sinking will be less than 2 cm for swelling pressures of the buffer surrounding the canister down to 0.1 MPa (SKB 2010b, Section 3.4.1). A performance target > 0.2 MPa is selected based on this information. It can, however, be noted that this target will be automatically satisfied if the swelling pressure required to ensure diffusive transport, which is much higher, see Section 5.2.1, is upheld.

Conditions to be considered and assessed

The buffer needs to be able to support the weight of the canister containing the fuel, which in the Finnish case is 18.8 to 29.0 tons (Raiko 2013, Table 6). In the Swedish case, the maximum allowed weight of the canister with spent nuclear fuel is 28 tons. In addition to the swelling pressure, friction between the buffer and the canister and the host rock influence the sinking. The unevenness of the deposition hole may lead to variations in buffer density within the deposition hole, which may then lead to development of a non-uniform swelling pressure that could induce movement of the canister.

5.2.8 Retain sufficient mass over life cycle

SKB requirement (SR-Site)	–
Posiva requirement (TURVA 2012)	–
Safety function	retain sufficient mass over life cycle
Performance target	stable in contact with water with total charge equivalent of cations $\sum q[Mq^{+}] > 8 \times 10^{-3}$ mol/L
Characteristics to be designed and verified in the production	installed buffer material mass

Rationale of the safety function and performance target

To maintain the safety functions described in Sections 5.2.1, 5.2.2, 5.2.3 and 5.2.7 a certain minimum buffer density is needed. Mass loss would lead to decrease in density and thereby jeopardise these safety functions. The most critical process leading to mass loss over time is chemical erosion.

Chemical erosion of the buffer does not occur if the groundwater has sufficient ionic strength. It has been reported by SKB (SKB 2010b, Section 3.5.11 and Figure 3-29) and Birgersson et al. (2009) that a minimum cation concentration of 4 mM is required to avoid colloid formation. However, recent chemical erosion tests in horizontal and inclined artificial fractures have shown that if the charged cation concentration is 4 mM, at least pure Na- and Na/Ca-bentonites are still prone to erosion. However, erosion does not occur at a cation charge concentration of about 8 mM. Also, the pH of the groundwater will impact the chemical erosion, and the tests have been done at near-neutral pH conditions. This has been considered when stating performance targets for chemically favourable conditions in the rock, see Section 8.2.4.

Conditions to be considered and assessed

There is a large degree of uncertainty in the detailed salinity distribution around the repository. In addition, the salinities can become sufficiently low for not maintaining the performance target, and chemical erosion may occur during some periods, and in some parts of the repository volume. The calculated distributions of salinity obtained from the modelling of the future evolution of the repository site are used in the analysis of buffer evolution.

5.3 Technical design requirements

5.3.1 Material-specific relation between dry density and swelling pressure

Characteristic	Technical design requirement	Related safety functions
material specific relation between dry density and swelling pressure	The minimum dry density yielding a swelling pressure > 3 MPa when determined with a specific laboratory test procedure.	limit advective mass transfer limit microbial activity keep the canister in position
	The maximum dry density yielding a swelling pressure < 10 MPa when determined with a specific laboratory test procedure.	limit pressure on the canister

Justification

There is a relation between the swelling pressure at saturation and the (dry) density of bentonite. The swelling pressure also depends on the material composition, especially the content of swelling clay minerals in the bentonite, and on the chemistry of the saturating ground water. These relations and representative bentonites were the basis for the specified density interval in the design premises for SR-Site (SKB 2009) and the design basis in TURVA-2012 (Posiva 2012a). When determining the density interval, the relationship between swelling pressure and the montmorillonite content in investigated candidate bentonites (MX-80, Deponit-Can), as reported in Karnland et al. (2006), were used by both SKB and Posiva.

However, recent results show that for bentonites from different sources the same montmorillonite content may yield different swelling pressures. With respect to this, the technical design requirements state the material-specific dry density required to yield the required swelling pressure at saturation. The lower limit for the swelling pressure, i.e. 3 MPa, is based on the swelling pressure stated as performance target and includes a margin for loss of material. The upper limit for the swelling pressure, i.e.10 MPa, is equal to the swelling pressures stated as performance target. The material-specific relation between dry density and swelling pressure shall be measured in a laboratory test according to a procedure qualified for this purpose. Development of such a test and procedure is being carried out by SKB and Posiva.

Implications for verification and design

The development of a test and test procedure need to consider the dominating cation, salinity of the water and also temperature since the relation between dry density and swelling pressure will depend on these parameters. The swelling pressure decreases with increasing salinity, with the effect of salinity being more pronounced at lower dry densities of the bentonite (MX-80 and Deponit-Ca-N, see SKB 2010b, Section 3.4.1). According to these results and the tests on MX-80 and IBECO bentonites reported by Martikainen and Schatz (2011), swelling pressures of 10 MPa or even higher can be reached even at salinities up to 70 g/L in the case of a saturated density of around 2000 kg/m^3. The hydraulic conductivity, at such a salinity and density, is 10^{-13} m/s or lower, see SKB (SKB 2010b, Figures 3-5 and 3-6) and Martikainen and Schatz (2011, Figure 4-2). The water chemistry used in the tests shall consider these and the conditions at the site, see Section 8.2.4.

The determination of swelling pressure is a rather time consuming test procedure. The swelling pressure tests are, therefore, primarily intended to be used in the qualifications of materials and material suppliers, whereas less time-consuming tests are intended to be used for the delivered qualified material. In order to verify that the characteristics of the qualified material measured with these methods can be correctly correlated to the swelling pressure, the homogeneity of the material needs to be quantified. For this purpose, testing of the montmorillonite content is a suitable procedure. Frequent testing of montmorillonite content can be made by e.g. x-ray diffraction and CEC, as described in SKB (2010e). To assure the quality of the delivered material, routine testing of e.g. montmorillonite content can be combined with less frequent tests of the swelling pressure. The tests as well as the test frequencies and sampling need to be selected and qualified considering the observed variability of the material, so that the quality of the installed buffer can be assured.

5.3.2 Material-specific relation between dry density and hydraulic conductivity

Characteristic	Technical design requirement	Related safety function
material specific relation dry density – hydraulic conductivity	The minimum dry density yielding a hydraulic conductivity in saturated state < 10^{-12} m/s when determined with a specific laboratory test procedure.	limit advective mass transfer

Justification

The hydraulic conductivity in saturated state is a crucial parameter for buffer performance. The performance target for ensuring diffusive transport is a hydraulic conductivity < 10^{-12} m/s. The performance target includes a margin relative to the hydraulic conductivity at which diffusive trans-

port cannot be guaranteed. There is a material-specific relationship between hydraulic conductivity at saturation and the dry density of bentonite. With respect to this, the technical design requirement states the material-specific dry density required to yield the required hydraulic conductivity at saturation. The limit for the hydraulic conductivity is generally fulfilled if the lower limit for swelling pressure, 3 MPa, see Section 5.3.1, is fulfilled.

As for the swelling pressure, the material specific relation between hydraulic conductivity and dry density shall be measured in a laboratory test according to a procedure qualified for this purpose. Development of such a test and procedure is being carried out by SKB and Posiva in a similar way as for the swelling pressure.

Implications for verification and design

The implications for the design are similar to those for the swelling pressure, i.e. determination of the relation between dry density and saturated hydraulic conductivity is primarily used in the qualifications of materials and material suppliers, whereas the quality of the delivered material is verified by testing its homogeneity in the same way as for the swelling pressure, see Section 5.3.1.

5.3.3 Material-specific relation between dry density and shear strength

Characteristic	Technical design requirement	Related safety function
material specific relation between dry density and shear strength	The maximum dry density yielding an unconfined compressive strength at failure < 4 MPa at a deformation rate of 0.8 %/min when determined with a specific laboratory test procedure, and for material specimens in contact with waters with less favourable characteristics than site-specific groundwater.	mitigate the impact of rock shear on the canister

Justification

Rock shear movements may occur when stresses in the bedrock are released, see Section 8.2.3. Depending on the mechanical properties of the buffer, the rock shear movements may cause the insert to collapse or deform to such an extent that the deformation of the copper shell will result in a breach and loss of the containment.

There is a correlation between the swelling pressure and the shear strength of swelling clay materials. The shear strength will increase with increasing swelling pressure. In addition to the swelling pressure, the shear strength of the buffer will depend on the rate of strain and the dominating cation in the bentonite. High shear strength, as well as too high a swelling pressure, are undesired characteristics of the buffer, since they will result in high stresses in the canister in the case of rock shear.

The shear strength in the technical design requirement is expressed as the unconfined compressive strength at failure, since it is this strength that is measured in the test. Since the shear strength will also depend on the rate of strain, this also needs to be considered in the technical design requirement. The rate of 0.8 %/min is selected based on generally applied experimental practices. The test shall be performed with material in contact with water that has a less favourable composition than the site specific waters. It has been shown that the shear strength is as highest in fully calcium-exchanged materials.

For the swelling pressure, an upper limit is set with respect to the canister's ability to withstand isostatic loads, see Section 4.2.2. Since the shear strength increases with swelling pressure, the technical design requirement for shear strength should for most materials be fulfilled for the dry density yielding a swelling pressure of 10 MPa. The aim is to verify this by testing that the technical design requirement for shear strength is fulfilled at the dry density that corresponds to a swelling pressure of 10 MPa. If the tested unconfined compressive strength at failure exceeds 4 MPa at a swelling pressure of 10 MPa and a deformation rate of 0.8 %/min when determined for fully Ca-exchanged material specimens, the dry density, and thus the swelling pressure, that fulfils the unconfined compressive strength technical design requirement shall be determined.

Implications for verification and design

As for the swelling pressure, the test for determining the shear strength shall be qualified for the purpose. Development of such a test and procedure is being carried out by SKB and Posiva.

The implications for the design are similar to those for the swelling pressure and hydraulic conductivity, i.e. the control of the shear strength is primarily used in the qualifications of materials and material suppliers, whereas the quality of the delivered material is verified by testing its homogeneity, see Section 5.3.1.

The technical design requirement for maximum shear strength can be verified by the specific test. However, the unconfined compressive strength at failure, i.e. 4 MPa at a deformation rate of 0.8 %/min, cannot be used to express the shear load that will impact the canister. This load must be defined as part of the design and damage tolerance analysis of the canister, see Section 4.3.1.

5.3.4 Installed buffer material mass

Characteristic	Technical design requirement	Related safety functions
installed buffer material mass	The installed buffer material mass shall in average in the buffer volume (Figure 5-1) result in a dry density ≥ the least required dry density determined for the specific buffer material.	limit advective mass transfer limit microbial activity filter radiocolloids keep the canister in position retain sufficient mass over life cycle
installed buffer material mass	The installed buffer material mass shall in average in the buffer volume (Figure 5-1) result in a dry density ≤ the highest allowed dry density determined for the specific buffer material.	mitigate rock shear limit pressure on the canister

Justification

For the buffer to maintain its safety functions, the installed buffer dry density shall lie within the material-specific limits specified for swelling pressure, hydraulic conductivity and shear strength, as described in Sections 5.3.1, 5.3.2 and 5.3.3. This implies that the mass of buffer material, with allowance for respect taken to the water content at installation and the dimensions of the deposition hole, shall result in an average dry density within these limits. The requirement on average buffer density in a deposition hole is based on the optimistic assumption of complete homogenization. SKB currently believes that this is justified for the given design. This however, remains to be verified.

Implications for verification and design

The installed buffer material mass has been chosen since the dry density cannot be directly measured during production. The installed mass of blocks and pellets, together with their water contents and the deposition hole dimensions, can be used to calculate the average installed dry density of the buffer.

In order to determine the average dry density, the dimensions of the deposition hole must be known. The buffer will thus impose limits on acceptable dimensions of the deposition hole, see Section 8.7.6. The part of the deposition hole for which acceptable limits need to be stated is defined by the buffer volume of the deposition hole illustrated in Figure 5-1.

The nominal, or target, installed dry density should be selected as the mean value of the densities yielding 3 respectively 10 MPa swelling pressure for a given saturated material.

The mass shall be distributed so that the variations of density within the deposition hole are as small as possible. However, there will inevitably be an uneven density within the hole. This is caused by:

- different initial density of the materials (installed blocks and pellets),
- unevenness in the walls of the deposition hole and variation of the deposition holes within the acceptable tolerances,

- expansion of the buffer up into the backfill,
- rock fallout in the wall of the deposition hole,
- un-centred installation of buffer blocks or deposition of the canister.

The unevenness will to some respect extent be homogenized by the swelling of the bentonite. There will, however, always be persisting density gradients, even in a very long time frame. The variability in swelling pressure will lie well within the limits of 3–10 MPa. The mass and water content of the buffer components, the positions of the buffer blocks and the dimensions of the deposition holes will be determined during the production so that the variation in installed density can be determined.

5.3.5 Buffer thickness and volume

Characteristic	Technical design requirement	Related safety function
thickness	The buffer thickness, i.e. the distance between the canister and the deposition hole wall, shall be at least 30 cm. The thickness of the buffer below the canister bottom shall be at least 50 cm. The thickness of the buffer above the canister shall be at least 50 cm.	overall functions of the buffer
volume	The buffer volume shall be cylindrical and determined from its cross section area in the deposition hole and its height, i.e. the sum of its thickness above and below the canister and the distance between the surface of the canister lid and bottom, minus the canister volume (Figure 5-1).	

Justification

A buffer thickness of at least 30 cm around the canister and a thickness of at least 50 cm below and above the canister, has, in previous post-closure assessments, been shown to be sufficient for assuring safety (SKB 2011, Posiva 2012a). The thicknesses around, above and below the canister will together with the dimensions of the canister determine the buffer volume.

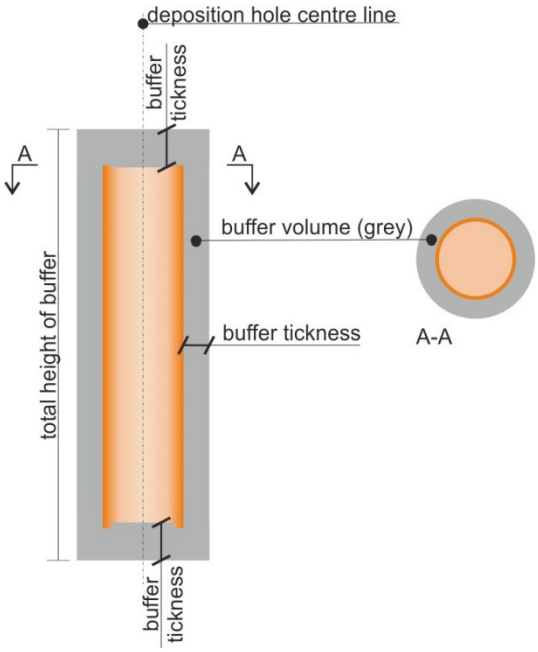

Figure 5-1. *The buffer thickness and volume.*

A thicker buffer may lead to more effective limitation of advection and more effective damping of rock shear, but will also give slower re-saturation, increased temperature and a higher probability for the deposition hole to intersect a water-conductive fracture. A thicker buffer and hence a larger deposition hole diameter, would, to a limited extent, mitigate the effects of buffer erosion, since an increased buffer mass would allow more buffer to be lost without advective conditions arising (SKB 2011, Section 14.3.2). This is, however, counteracted by the increased deposition hole diameter, which to some extent would increase the erosion rate (Moreno et al. 2010) and also increase the probability of having a water-conducting fracture intersecting the deposition hole. A thicker buffer, i.e. larger buffer material mass, is not seen as a practical means of mitigating the effects of buffer erosion. The quantitative values in the technical design requirements are specified as a feedback from the buffer design assessed in previous post-closure assessment (SKB 2011, Posiva 2012b) where the canister is surrounded by 30 cm thick bentonite blocks and a 5 cm thick pellet-filled slot.

Implications for verification and design

The buffer components and their geometrical configuration in the deposition hole as well as the dimensions of the deposition hole shall, in addition to the required installed density, be determined with respect to the required thickness. This basically sets a requirement on the dimensions of the blocks. The required thickness sets a limit on the volume within which the average dry density must lie within the specified limits, also see Figure 5-1.

5.3.6 Content of impurities

Characteristic	Technical design requirement	Related safety function
material composition	The content of organic carbon shall be less than 1 wt-%.	compatibility and reliability of production (chemically favourable conditions, see Section 2.2.2)
	The sulphide content shall not exceed 0.5 wt-% of the total mass, corresponding to approximately 1 wt-% of pyrite.	
	The total sulphur content (including the sulphide) shall not exceed 1 wt-%.	

Justification

The clay materials used for the buffer should not include substances or impurities that may impair the safety functions of the repository, see Section 2.2.2. Carbon, sulphide and sulphur are impurities occurring in clay materials that may adversely affect the favourable chemical conditions in the repository. The chemical composition of the buffer should be such that it has limited potential to act as a source of sulphides, which may corrode the copper canister. In Posiva (2012a), Posiva set limits for the chemical composition of the buffer focusing on organics, oxidising compounds, sulphur and nitrogen compounds.

The specified allowed contents of carbon, sulphide and sulphur in the buffer were assessed in the safety assessments SR-Site (SKB 2010d, Sections 5.3.1 and 5.3.2, Posiva 2012a, Section 6.5.7). It was shown that copper corrosion caused by impurities in the buffer does not pose a threat to canister integrity if the contents are below the specified levels. Conditions in which the buffer may lose part of its swelling pressure and thus foster microbial activity were considered in the formulation of this requirement and assessed in the long-term safety assessment. Uncertainties in the understanding of the processes leading to sulphide production in the buffer due to microbial activity were highlighted as an issue for further research (Hellä et al. 2014, Section 10.3.3). The joint Posiva-SKB Integrated Sulphide Project will provide additional understanding on the processes leading to the production of, and sinks for, sulphide in the buffer. Results from this project will be used to re-assess the technical design requirements for the buffer.

Implications for verification and design

The buffer consists of natural materials and the chemical composition is variable depending on the supplier but also within the same bentonite quarry. The content of organic carbon, sulphide and total sulphur will be determined as part of the approval of buffer materials and qualification of buffer material suppliers. The approval and qualification include characterisation of sulphur-containing minerals or sources of microbial nutrients that could enhance production of sulphides during the long-term evolution of the buffer. At delivery the material must be inspected to verify that delivered material conforms to specification.

5.3.7 Thermal conductivity

Characteristic	Additional technical design requirement	Related safety function
thermal conductivity	The thermal conductivity over the installed buffer shall, given the allowed decay power in the canister, the thermal properties of the canister and the rock and the canister spacing, yield a buffer temperature < 100 °C.	long term stability (see Section 2.2.2) resist transformation

Justification

The thermal evolution of the near field is of importance for the safety functions of the engineered barriers. As a performance target for the buffer to resist transformation and for providing favourable thermal conditions in the repository, the peak buffer temperature must not exceed 100 °C. This temperature is pessimistically chosen in order to, with a margin to safety, avoid mineral transformations of the buffer, see Section 5.2.6.

The thermal evolution of the repository depends on the allowed decay power in the canister, see Section 3.3, the thermal properties of the canister, rock and buffer and on the canister spacing, see Section 2.2.1. In order to analyse the temperature development in the repository, the thermal conductivity over the installed buffer must be known. For a given decay power in the canister and temperature on the deposition hole wall the thermal properties of the buffer must lie within the limits set in the analyses of the temperature development, also see Section 8.3.2.

The thermal conductivity of the installed buffer strongly depends on buffer design with blocks and pellets and on the degree of saturation. A saturated buffer has 2–3 times higher thermal conductivity than a dry buffer. For the installed buffer, the thermal conductivity will depend on the occurrence and thermal properties of air-filled gaps, and the thermal properties of the buffer blocks and pellet- filled slots. For the calculated peak temperature in the buffer, which shall not exceed 100 °C, to be valid, the thermal properties of the installed buffer must not result in a lower thermal conductivity than that assigned to the installed buffer in the thermal analysis.

Implications for verification and design

The temperature condition of 100 °C is determined with respect to post-closure safety. However, to determine the allowed decay power in the canister, the thermal properties and distances between deposition holes are required. This is an integrated design issue, and thus out of scope of this report. The integrated analyses must be made with respect to the allowed decay power in the canister, the thermal properties of the canister and the rock and the canister spacing, also see Section 2.2.1. It is thus separately specific for Posiva and SKB, and also between alternative design options. The thermal conductivity assigned to the installed buffer should be based on the conductivities that have been measured in the laboratory and in full-scale tests. Values measured in full-scale tests should be correlated with those measured in the laboratory.

5.3.8 Gas transport properties

Corrosion processes in the near field, or in a breached canister, will result in the production of hydrogen gas. If the gas production exceeds the ability of the surrounding groundwater to take it into solution and transport it away from the canister, a pressure will build up. Unless the evolved gas can escape via the buffer and the fractures in the rock, there will be a further build-up of gas pressure to levels that may impair the safety functions of the canister or rock, see Section 2.2.2.

The buffer and rock must have sufficient capability to transport gas. Gas can escape through the fractures of the rock. The gas transport properties of the buffer are related to its swelling pressure where a lower swelling pressure is an advantage. Based on experimental evidence (Harrington and Horseman 2003), the bentonite is assumed to ultimately open by fracturing if the pressure increase is large enough. The produced gas can then escape through the buffer and the fractures in the rock. The outflow through the buffer is expected to proceed until the pressure falls to levels at which the swelling pressure of the buffer would act to seal the formed passage.

6 Backfill and plug in deposition tunnels

6.1 Design and safety functions in a KBS-3 repository

The backfill is the material installed in deposition tunnels to fill them. The backfill consists of clay containing swelling material.

The plug is the construction closing deposition tunnels during the operational phase until the adjacent main or connecting tunnel is closed. In SKB's and Posiva's current conceptual design, the plug consists of a concrete plug, a swelling clay seal and a filter.

The backfill and plug in deposition tunnels can be regarded as an integrated system.

The main safety functions of a KBS-3 repository are to, either directly or indirectly by protecting and preserving the safety functions of the barrier system, isolate the repository and the encapsulated spent nuclear fuel from the surface environment; contain radionuclides and to retain and retard their dispersion into the environment, see Section 1.2.2. The backfill and plug system shall contribute to these main safety functions of a KBS-3 repository by maintaining the safety functions to:

- keep the buffer in place and
- limit advective mass transfer.

The choice of clay containing swelling material as backfill in deposition tunnels is made with respect to its ability to maintain these safety functions.

Clay materials have as an additional feature contributing to retaining and retarding the dispersion of radionuclides, the capacity to sorb radionuclides if the containment should be breached, see Section 2.2.3.

The materials and design of the backfill and the plugs in deposition tunnels must be compatible with, and not unduly impair, the safety functions of the engineered barriers or the rock, see Section 2.2.2. With respect to this, the materials used for backfill and plug must be chosen to preserve:

- chemically favourable conditions in the repository.

This has resulted in technical design requirements for the content of impurities in the backfill and for the material composition of the plug.

The role of the plug in the backfill-plug system is to support the overall function of the backfill in the closed deposition tunnel during the operational phase of the repository. With respect to this, it must have sufficient strength and tightness. The plug can be regarded as a component that contributes to the reliable and robust production of a KBS-3 repository with the required safety functions and characteristics, also see Section 2.2.2. After closure, the plug has no function in a KBS-3 repository, but it will remain in the repository and must not impair the post-closure safety of the repository. The role of the plug and its functions are further discussed in Section 6.4.

The technical design requirements for the backfill and plug in this report are based on a backfill design with blocks and pellets of swelling clay material installed in the deposition tunnel and a plug with a concrete body, a swelling clay seal and a filter.

6.2 Safety functions of the backfill

6.2.1 Keep the buffer in place

SKB requirement (SR-Site)	The backfill shall restrict upward buffer swelling/expansion in the deposition holes (Requirement SSBF8).
Posiva requirement (TURVA 2012)	The backfill shall keep the buffer in place (Requirement L3-BAC-16*)*.
Safety function	keep the buffer in place
Performance target	backfill deformation shall be sufficiently limited to keep the buffer swelling pressure > 2 MPa in average over the buffer volume
Characteristics to be designed and verified in the production	installed backfill mass installed backfill geometry (configuration of blocks and pellets) material- specific relation dry density – swelling pressure deformation properties at dry state

Rationale of the safety function and performance target

In order for the backfill to protect and preserve the safety functions of the buffer, the deformation of the backfill must not result in a volume change giving rise to in an unacceptable loss of buffer density. The density loss of the buffer is unacceptable if the result is that its technical design requirements are not upheld. The lowest acceptable swelling pressure for the buffer is 2 MPa and this swelling pressure shall be maintained in average over the buffer volume, see Section 5.3.5.

Conditions to be considered and assessed

At the interface between the buffer and the backfill, the buffer exerts a swelling pressure against the backfill and vice versa, depending on the evolution of the saturation process in the buffer and backfill (SKB 2010b, Posiva 2012c). If the backfill is dry and the buffer is in a saturated state, the buffer swelling would be counteracted solely by the stiffness and the weight of the backfill. This is an extreme case with a low probability, since the backfill tunnel is expected to be intersected by more water- conductive fractures than a single deposition hole. This case has nonetheless been modelled by SKB (SKB 2010b, Börgesson and Hernelind 2009) and Posiva (Posiva 2012c, Leoni 2013) and it has been simulated in Äspö through a buffer swelling test (Sandén et al. 2017). Since a backfill consisting of blocks and pellets is initially heterogeneous, the deformation of the backfill is affected not only by the deformation properties of the materials used, but also by the configuration of different backfill components. In order to assess the deformation of the backfill, a number of analytical calculations and numerical modelling cases were performed (considering the unsaturated backfill case) by Johannesson and Nilsson (2006), Johannesson (2008), Börgesson and Hernelind (2009), Korkiala-Tanttu (2009) summarized in SKB (SKB 2010b) and Posiva (Posiva 2012c) and later by Leoni (2013), and Börgesson and Hernelind (2014). The basic assumption made in these studies was that the saturated buffer density should remain above 1950 kg/m^3 at the level of the canister lid. The buffer swelling test has provided data for the validation of this assumption through numerical modelling. The validation of the numerical models is presented in reports by Börgesson and Hernelind (2017) and Leoni et al. (2017).

Considering the case in which both buffer and backfill are in saturated state, a net pressure arises against the backfill when the buffer swells upward and compresses the backfill material. The saturated backfill case has been modelled as part of the THM evolution assessment of buffer and backfill (SKB 2010b, Pintado and Rautioaho 2013). The displacement of the buffer-backfill interface depends on the difference between the swelling pressures of buffer and backfill (in saturated state) and structural stiffness of the backfill (considering a case with dry backfill and fully saturated buffer). The net pressure difference depends on the backfill material. If the difference is significant, the swelling pressure from the buffer decreases as its density decreases. At the same time, the counter-pressure from the backfill increases as it is compressed and its density increases. The upheave of the buffer and compression of the backfill are counteracted mostly by the stiffness of the backfill and because frictional forces at the deposition hole rock wall are much reduced by

mobilisation of the pellets. When the force of the swelling pressure in the buffer is equal to the sum of the force of the counter-pressure in the backfill (and the friction against the rock), the buffer upheave ceases (SKB 2010b, p 90). If the stiffness of the backfill or its density and swelling pressure are not large enough, the swelling pressure of the buffer may decrease below its target range.

6.2.2 Limit advective mass transfer

SKB requirement (SR-Site)	The backfill shall limit the flow of water (advective transport) in deposition tunnels (Requirement SSBF7).
Posiva requirement (TURVA 2012)	The backfill shall limit advective flow along the deposition tunnels (Requirement L3-BAC-8).
Safety function	limit advective mass transfer
Performance targets	average hydraulic conductivity between two deposition holes < 10^{-10} m/s swelling pressure at all points in the deposition tunnel > 0.1 MPa
Characteristics to be designed and verified in the production	material- specific relation between dry density and hydraulic conductivity material- specific relation between dry density and swelling pressure installed backfill mass

Rationale of the safety function and performance targets

The need to limit advective mass transfer in the backfill primarily arises from the need to protect the buffer and canister from potentially harmful substances in the groundwater and secondly from the need to retard radionuclide releases in case the containment of radionuclides in the canister is breached and the radionuclides have been migrated through the buffer (SKB 2010b, Posiva 2012c). A hydraulic conductivity target $K < 10^{-10}$ m/s is a limit that will ensure limited advective transport trough the backfill. A swelling pressure target of 0.1 MPa is required to be satisfied at all points in the deposition tunnel, ensuring the self-sealing ability of piping channels in conditions prevailing after closure and saturation of the repository when the hydraulic gradient is estimated to be small.

These performance targets apply to the post-closure and saturated state of the repository. In order to reach these values in the initially heterogeneous backfill, an average swelling pressure of 1 MPa is set as the technical design requirement for the backfill, see Sections 6.3.1 and 6.3.2.

Conditions to be considered and assessed

Since the persistence and continuity of flow paths cannot be verified in the long term, it is important to select and install the backfill material in a way that assures a predictable long-term evolution and the fulfilment of its performance targets.

During the saturation process, the homogeneity in density of the backfill affects the hydraulic properties of the system. As seen in various field tests in the Äspö HRL (e.g. SKB 2010b, Dixon et al. 2008a, b; 2011), the water flows and erosion/material re-distribution in the backfilled tunnel in the very early saturation phase are concentrated in the pellet-filled zone, which has lower initial density than the backfill blocks. Therefore, a sufficient homogenisation of the backfill blocks and pellets in density is needed during the saturation of the system.

One of the most probable places where preferential flow path(s) could develop is at the interface between the backfill and the rock. Advective mass transfer in the backfill is most likely to manifest during the saturation period and its significance diminishes after the deposition tunnel has been plugged and once the swelling pressure from the backfill rises against the rock. Eventually, the rock-bolts installed in the tunnel roof will fail and some rock fall out cannot be ruled out despite of the swelling pressure generated by the backfill and, even if the backfill were to generate locally higher swelling pressure due to uneven distribution of material. This could locally form a more conductive region between the backfill and the rock, known as the “crown effect”, and this is taken into account in the groundwater flow and transport models by both Posiva and SKB.

6.3 Technical design requirements for the backfill

6.3.1 Material-specific relation between dry density and swelling pressure

Characteristic	Technical design requirement	Related safety function
material-specific relation between dry density and swelling pressure	An acceptable dry density is one giving a swelling pressure > 1 MPa when determined with a specific laboratory test.	limit advective mass transfer

Justification

There is a relation between the swelling pressure and the (dry) density in swelling clay. The swelling pressure also depends on the material composition and the content of swelling clay minerals.

Swelling pressure is essential for lowering the density difference between the low density pellet-filled zone and the backfill blocks. Otherwise the pellet-filled zone would remain at its initial dry density (900–1100 kg/m^3, Keto et al. 2013), at which where the hydraulic conductivity requirement ($K < 1 \cdot 10^{-10}$ m/s) for limiting advective flows is not upheld. In addition, swelling pressure is needed for self-sealing of piping channels and to fill local defects where the density is low due to erosion that may take place during the early saturation phase of the backfill. The installed backfill mass and the swelling pressure should be enough to withstand the loss of material due to erosion in the early saturation phase (SKB 2010b, Posiva 2012c).

The homogenisation of the backfill block and pellet system (in density) has been studied inwith small-scale laboratory tests by Sandén et al. (2008) and Schatz and Martikainen (2012). In addition, numerical modelling with the aim of studying the phenomena seen in laboratory scale homogenisation tests with buffer materials (Dueck et al. 2014) is ongoing as part of the engineered barrier system (EBS) task force work. In order to study homogenisation further, the scale effect needs to be studied with larger scale laboratory tests and eventually with field tests combined with modelling. The field-tests performed so far, e.g. the Prototype repository test (Svemar et al. 2016) and the Engineered Barrier (EB) Experiment (García-Siñeriz et al. 2008, 2015) performed at the Mont Terri Rock Laboratory show that mass redistribution as a consequence of water saturation took place resulting in at least partial homogenization with respect to density. However, the results from these tests are not directly comparable due to significantly smaller amount of swelling minerals in the backfill (Prototype repository) and significantly smaller amount of blocks in the EB experiment compared with to the current Posiva/SKB backfill design (Keto et al. 2013).

However, for a “bentonite-like” material, the homogenisation and self-sealing abilities are assumed to be directly related to the swelling pressure. The performance target of 0.1 MPa concerns the maintenance of the safety function of limiting advective mass transfer during the long-term evolution of the backfill. The technical design requirement of 1 MPa concerns the conditions after installation and initial saturation.

Implications for verification and design

The material-specific minimum dry density to yield a swelling pressure of 1 MPa shall be determined in the same way as described for the buffer in Section 5.3.1. The water chemistry used in the tests shall consider the conditions at the site, see Section 5.3.1 and 8.2.4.

The minimum dry density determined in the specific laboratory test and its related swelling pressure shall be achieved within the volume between two deposition holes, i.e. considering the total installed dry mass and the tunnel volume in the tunnel section as well as the loss of material during saturation. The potential loss of material will depend on the inflow to the deposition tunnel during the installation of the backfill. Both the total inflow and its distribution need to be controlled. Determining the acceptable levels of mass loss is out of scope of this report, but the amount of mass loss for each deposition tunnel will be compensated by specifying as extra mass to be placed in the tunnel. In the design phase, when the exact volume of the tunnel is not yet known, the density is calculated assuming the average dry density of the backfill components and the average tunnel volume, see Section 8.3.6. This is correct as an arithmetic mean estimate if case the distribution of the density of backfill components and of tunnel volume follows a symmetric distribution around the

mean value. Therefore, the robustness of the design is shall also to be checked for, considering also the extreme case of with a maximum tunnel volume and a low installed backfill mass.

The material-specific relation between dry density and swelling pressure shall be measured in the laboratory according to a standardised test procedure qualified for this purpose. The development of such a test and procedure is being carried out by SKB and Posiva, see also see Section 5.3.1.

6.3.2 Material-specific relation between dry density and hydraulic conductivity

Characteristic	Technical design requirement	Related safety function
material-specific relation between dry density and hydraulic conductivity	The minimum dry density yielding a hydraulic conductivity < 10^{-10} m/s when determined with a specific laboratory test.	limit advective mass transfer

Justification

The hydraulic conductivity is the most relevant characteristic for the backfill performance. There is a material-specific relationship between hydraulic conductivity and dry density of swelling clay materials. As discussed in Section 6.2.2, a hydraulic conductivity $k < 1 \times 10^{-10}$ m/s is a limit that will ensure limited advective transport trough the backfill. The technical design requirement for swelling pressure (1 MPa) adds some safety margin, since the dry density required to yield this swelling pressure is higher than that required to yield the target k-value. This value can be used to derive a material-specific minimum dry density for the backfill. The water chemistry used in the tests shall be less favourable than the groundwater conditions expected at the site.

Implications for verification and design

The minimum dry density is defined as the total mass placed in the tunnel volume between two deposition holes. In the design phase when the exact volume of the tunnel is not yet known, the density is calculated assuming the average dry density of the backfill components and the average volume of the tunnel. This is correct if the distribution of the density of backfill components and tunnel volume follows a symmetric distribution about the mean values. Therefore, the robustness of the design shall also be checked considering also the extreme case of a maximum tunnel volume and low installed backfill mass.

The material- specific relation between dry density and swelling pressure shall be measured in the laboratory according to a standardised test procedure qualified for this purpose, see also see Section 5.3.1. The development of such a test and procedure is being carried out by SKB and Posiva. Since the relation between dry density and swelling pressure will depend on the dominating cation, the salinity of the water and the temperature, these parameters need to be considered when determining the test procedure. The tests should be run using less favourable water chemistry than those expected at each respective site.

6.3.3 Installed backfill mass

Characteristic	Technical design requirement	Related safety functions
installed backfill material mass	The installed backfill material mass shall, in average in the tunnel volume between two deposition holes, result in a dry density ≥ the least required material-specific dry density determined for the specific backfill material.	keep the buffer in place limit advective mass transfer

Justification

A sufficient amount of backfill material mass should be installed to meet the dry density target. The volume of the deposition tunnel and the water content of the backfill material components need to be considered. The requirement for the average density is set for the volume between two deposition

holes. Since the requirement meaning is to limit advective transport to and from athe deposition hole (in a case of containment breach), the distance between two deposition holes was selected as a basis for determining compliance.

Implications for verification and design

For design purposes, it is convenient to use only an average value for the minimum dry density. The minimum dry density is defined as the dry density needed to achieve the swelling pressure and hydraulic conductivity targets in the average tunnel volume between two deposition holes. The average dry density is calculated as the total installed dry mass/total volume in this tunnel section.

In order to determine the mass that needs to be installed the loss of material during saturation needs to be considered. There are methods available to determine the deposition tunnel volume with sufficient accuracy. The water content of the backfill components also needs to be considered.

6.3.4 Deformation properties

Characteristic	Technical design requirement	Related safety function
deformation properties	The overall deformation of the installed backfill both in dry and saturated state shall resist the swelling pressure from the buffer and maintain the buffer swelling pressure > 2 MPa in average over the buffer volume.	keep the buffer in place

Justification

As stated in Section 6.2.1, a key aspect of the backfill is the ability to restrict upward swelling of the buffer. The deformation properties of the backfill components when they are installed in the deposition tunnel and the configuration of the open spaces, e.g. gaps, porosity, voids, are used to model the maximum displacement of the buffer into the backfill during the saturation phase. The dry backfill case is considered as the worst case scenario concerning swelling of the buffer into the backfill.

The performance target for keeping the buffer in place is that the swelling pressure of the buffer shall remain above 2 MPa in average in the buffer volume, see Section 6.2.1. The buffer density decrease due to the volume increase caused by its expansion and compression of the backfill must not result in a buffer density that cannot maintain at least this swelling pressure.

If the backfill components have the water content they had at installation and the backfill is not saturated while the buffer is fully saturated, the buffer will exert a pressure up to 10 MPa. Considering the backfill at installation with no swelling pressure, its mechanical properties should withstand the load from the buffer with limited deformation. This is not a realistic scenario, but it is the largest pressure the unsaturated backfill may be exposed to. In the saturated state, the process is analysed with THM modelling including both buffer and backfill (Pintado and Rautioaho 2013).

Implications for verification and design

The factors affecting the ability of the unsaturated backfill to restrict buffer upheave are:

- configuration of blocks and pellets in the tunnel, including block size, block layout, thickness of the foundation layer and the pellet fill between the blocks and the rock,
- strength of the backfill blocks,
- compressibility of the pellets,
- compressibility of the blocks,
- distance between the top of the canister and the theoretical tunnel floor level,
- friction between rock and clay,
- internal friction of the clay,
- swelling pressure of the backfill, and
- design of the top of the deposition hole.

In dry conditions, the mass itself is not sufficient to keep the buffer in place, compressibility, friction and strength of the blocks are the key factors. The deformation of the backfill and the effect on the swelling pressure of the buffer is a process that needs to be evaluated by computer simulations. Setting the specifications for the backfill components is thus an iterative process, where the effect of the block configuration and material properties are evaluated by laboratory tests and computer analyses . The further development of the numerical models used by Börgesson and Hernelind (2009) and Leoni (2013) is ongoing based on the data gained in the full-scale buffer swelling test performed at Äspö HRL (Sandén et al. 2017). In this test, the swelling of the buffer into dry backfill was simulated with a hydraulic jack. The results of the tests are under evaluation to determine how they will affect the design in practice, e.g. strength requirements for the manufactured blocks.

In addition to showing by modelling that the design fulfils the requirement, it is important that the backfill components are installed in the deposition tunnel according to the design, i.e. the geometry and density of the components is within specifications. This will be verified in manufacturing of the blocks by measuring and weighing. In emplacement, compliance will be achieved by controlling the amount and volume of blocks placed in the tunnel, and by controlling the density of the pellet fill and foundation layer during installation. Finally, in determining the overall deformation allowance for the backfill, the design of the top of the deposition hole is also important as it includes an additional volume (chamfer) allowing installation of the canister and the buffer into the deposition hole.

6.3.5 Content of impurities

Characteristic	Technical design requirement	Related safety function
material composition	Impurities in the backfill shall not provide a significant source of sulphide, as this may corrode the copper canister.	compatibility and reliability of production (chemically favourable conditions, see Section 2.2.2)

Justification

In order to not impair the safety functions of the barrier system, the backfill material composition, more specifically its content of impurities, shall have limited potential to act as copper corroding agents. This is required to maintain the chemically favourable conditions in the repository (SKB 2010b, Posiva 2012c). In the repository, sulphide may corrode the canister, consequently the backfill material composition should be such that it has a limited potential to act as a source of sulphides. The limits preliminarily set by Posiva (Posiva 2012a) for the chemical composition of the backfill were the same as those for the buffer (organics, sulphur and sulphide). This, however, lacks a scientific basis and needs to be re-assessed. A more precise requirement will be provided when ongoing research on sulphide production in the backfill has been be concluded. It was also shown in SR-Site that, as long as the buffer is intact, copper corrosion caused by sulphide-generating contaminants in the buffer, backfill or groundwater does not pose a threat to canister integrity even over one million years.

Based on current- day knowledge, it is not yet possible to specify the limits on the chemical and mineralogical composition of the materials selected for the backfill. The joint Posiva-SKB Integrated Sulphide Project will provide additional understanding on the processes leading to the production and consumption of sulphide in the buffer and the backfill. This will be used to re-assess the technical design requirements for the backfill.

Implications for verification and design

Once the potential of accessory minerals and impurities that can be transformed into sulphide have been understood, the availability of these components has to be measured as part of the selection of backfill material.

The backfill consists of natural materials and the chemical composition is variable depending on the supplier but also within the same bentonite quarry. The material selection is based, among other factors concerning production and installation, on restrictions on sulphur-containing minerals and sources of microbial nutrients that could enhance production of sulphides during the long-term evolution of the backfill and facilitate their diffusion to the surface of the canister.

In addition to impurities in the backfill, the introduction of auxiliary equipment (e.g. water- handling materials such as geotextiles and temporary plugs) necessary to install the backfill may include materials that can impact the chemically favourable conditions in the repository. Such equipment can be considered to belong to the category engineered and residual materials and their amount, composition and location need to be checked and shown to not impair the safety functions, see Section 8.3.7.

6.4 The role of the plug

When constructing a KBS-3 repository, the deposition tunnels and holes are first excavated, then the buffer is installed, the encapsulated spent fuel disposed and the deposition tunnels backfilled (SKB 2010f, Keto et al. 2013). The deposition tunnels are connected to main or central tunnels used for transport. Given that the central tunnels will stay open longer than the deposition tunnels, a plug must be installed at the deposition tunnel mouth in order to prevent the backfill in the deposition tunnels from swelling and expanding out into the connecting tunnel. The plug is required to protect and preserve the safety functions of the disposed canisters, buffer and backfill during the operational phase until the main or central tunnel is closed, but it is not a barrier that is assigned safety functions in the finished and closed KBS-3 repository (SKB 2010f, Keto et al. 2013). By resisting the pressure from the backfilled deposition tunnel and restricting the flow of water past the deposition tunnel mouth, the plug contributes to the reliable implementation of the repository, see also see Section 2.2.2. In order to maintain its functions during the operational phase, the plug must have sufficient mechanical strength and water-tightness. In order not to impair the safety functions of the barrier system, it must stay in place and not decrease too much in volume and not contain materials that impact the chemically favourable conditions in the repository.

The plug does not have any safety functions after a KBS-3 repository is closed and is thus not assigned any long-term performance targets. However, both SKB and Posiva have formulated requirements on the functions that the plug part of the backfill and plug system shall satisfy during the operational phase. Therefore, the plug does not have any long-term safety function or performance targets. The functions of the plug during the operational period and until the saturation of the repository are presented in Sections 6.4.1 and 6.4.2 as a background to the technical requirements for the plug. The presentation is similar to the presentation of safety functions and performance targets for the barriers in the barrier system of a KBS-3 repository.

6.4.1 Resist the pressure from the backfilled deposition tunnel

SKB requirement (SR-Site)	The plug in a deposition tunnel shall withstand the hydrostatic pressure at repository depth and the swelling pressure of the backfill until the main tunnel is filled (Requirement SSPD15).
Posiva requirement (TURVA 2012)	The plugs shall keep the backfill in place during the operational phase (Requirement L3-BAC-18).
Plug function	resist pressure from the backfilled deposition tunnel
Characteristics to be designed and verified in the production	concrete plug strength

Rationale of the plug function

The plug shall provide a physical restraint to material transport and keep the backfill in place during its saturation and homogenisation while forces and counterforces at the opposing sides of the plug are not the same. This means that it shall prevent the backfill from swelling and expanding out from the plugged deposition tunnel, and also that it shall prevent material from being transported out from the deposition tunnels by flows of water, see Section 6.4.2.

In order for the backfill to maintain its safety functions, it must stay in the deposition tunnel and not loose density. A loss of backfill density would result in an increase of its hydraulic conductivity and decrease of its swelling pressure, and thus reduce its capability to limit advective transport. A loss of

swelling pressure may also impact the backfill's capability to keep the buffer in place. Thus, from the time the plug has been installed until the main or central tunnel connecting to the deposition tunnel has been closed, the plug in the deposition tunnel shall keep the backfill in place.

When the central tunnel is filled and closed, it will provide a counter pressure for the backfill swelling and expansion. This counter pressure will be fully developed after the saturation of the connecting tunnel. The plug has then fulfilled its function to keep the backfill in place. However, in order not to impair the safety function of the backfill by leaving an empty volume for the backfill to expand into, the plug must not decrease too much in volume even after the saturation of the repository and in a long time perspective.

Conditions to be considered and assessed

In order for the plug to prevent the backfill from swelling and expanding out to the connecting main or central tunnel, it must resist the pressure difference between the plugged deposition tunnel and the connecting tunnel without deforming. If the backfill is saturated while the connecting tunnel is still open, this pressure difference is the sum of the hydrostatic pressure at repository depth and the swelling pressure of the backfill. The groundwater flow during the operational phase and the saturation of the backfill must be considered in order to describe the evolution of the pressure on the plug. Also, the bearing capacity of the rock need to be considered, see Section 8.3.2.

Concrete structures have a finite lifetime in repository conditions due to concrete degradation. Degradation processes that need to be considered are dissolution of cement and additives and the material resulting from that, transport of materials from the plug into the rock and the compression of the remaining materials. The plug must include components that remain in place so that the density of the backfill will be sufficiently high to fulfil the performance targets in a long time perspective.

6.4.2 Restrict flow of water past the deposition tunnel mouth

SKB requirement (SR-Site)	The plug in deposition tunnels shall limit water flow until the adjacent main tunnel is filled and saturated (Requirement SSPD33).
Posiva requirement (TURVA 2012)	The plugs shall isolate the deposition tunnels hydraulically during the operational phase of the repository (Requirement L3-BAC-9).
Plug function	restrict flow of water past the deposition tunnel mouth
Characteristics to be designed and verified in the production	plug tightness

Rationale of the plug function

The plug shall provide a physical restraint to material transport into and out from the deposition tunnel. From the moment the buffer and backfill have been installed, clay material may be transported out from the deposition tunnels as long as there are i) open channels in the backfill or buffer, ii) a pressure gradient resulting in a water movement sufficient to erode clay particles and iii) a downstream location to accommodate the removed eroded material. When the clay is saturating, the material at the surface of channel will take up water and swell to decrease the channel size; eventually, the swelling pressure will build up and seal the open channels if the water flow and the amount of eroded material are not too high. It is, therefore, important to stop the potential water outflow from the deposition tunnel as soon as possible and to equalise the pressure difference between the fractures in the rock and the open channels. If a tight plug is installed close to the entrance of the deposition tunnel, the volume of water that can transport clay will not be larger than the air void volume in the deposition holes and deposition tunnel (SKB 2010f, Section 2.5.2). The role of fracture connectivity (potentially connecting a closed deposition tunnel to the central tunnel) in the overall process remains to be assessed.

The plug must also prevent water vapour from escaping from the deposition tunnels, since this may dry out the clay materials. If the backfill is dried out, moisture may be transported from the buffer and this could affect the thermal properties of the buffer.

Conditions to be considered and assessed

When determining the required tightness of the plug, the inflow to the deposition tunnels and holes and its distribution between deposition holes and tunnel, and along the deposition tunnel and to the void volumes in the buffer and backfill must be considered. The same total inflow to a deposition tunnel can result in different amounts and patterns of material transport depending on how it is distributed. As previously stated, if a tight plug is installed in the end of the deposition tunnel, the volume of water that can transport clay out from the tunnel will not be larger than the air void volume in the deposition holes and deposition tunnel. This volume together with the period the plug must restrict flow of water out from the plugged deposition tunnel will determine the acceptable flow rate over and through the plug.

The plug also needs to be reasonably gas tight to stop convection of air during the operational phase. The need for a requirement on gas tightness is currently being assessed as part of the plug design work.

6.5 Technical design requirements for the plug

6.5.1 Strength of the concrete plug

Characteristic	Technical design requirement	Related function
strength	The plug shall withstand the sum of the swelling pressure from the backfill and the hydrostatic pressure at repository level.	resist pressure from the back-filled deposition tunnel

Justification

The main function of the plug is to keep the backfill in place during the operational phase until the main tunnel is sealed. The concrete plug shall withstand the swelling pressure of backfill and the hydrostatic pressure at repository level. A loss of mechanical support would result in a loss of backfill swelling pressure in the deposition tunnel, and jeopardise the performance of the backfill and buffer.

After closure, mechanical strength of the plug is no longer needed, since the closure materials in the central tunnel will support the backfill in the deposition tunnel.

Since the backfill material has not yet been selected, the swelling pressures and design tolerances are not known yet. Therefore, the strength of the plug will need to be checked again once the backfill material is selected. In Posiva's case, the design basis load carrying capacity for the plug is 7.5 MPa, derived from the sum of the swelling pressure of the backfill (3 MPa, used as design basis swelling pressure load after homogenisation) and the hydrostatic pressure (4.5 MPa). The load from the swelling pressure is the average pressure in the deposition tunnel, but it can be locally higher.

Implications for verification and design

The design of the reference plug, common to SKB and Posiva, includes the following components: a concrete dome, a watertight seal, a filter layer or transition zone, delimiters made of concrete. The shape of the plug and its materials affect the mechanical strength of the final structure. A wedge plug is a design solution and the measurements are related to that shape and the way that the loads are distributed along the surface.

The mechanical function of the plug ends when the closure in the connecting tunnel provides sufficient support to keep the backfill material in the deposition tunnel in place. The design of the backfill therefore affects that of the closure, as the closure material outside the deposition tunnels should be able to withstand the long-term swelling pressure from the backfill in the deposition tunnels after the plug has mechanically degraded.

6.5.2 Material composition of the concrete plug

Characteristic	Technical design requirement	Related functions
concrete plug material composition	calcium/silica ratio – *level to be determined*	compatibility and reliability of production (chemically favourable conditions, see Section 2.2.2) resist pressure from the backfilled deposition tunnel restrict flow of water past the deposition tunnel mouth
	chemical composition of the plug – *to be determined*	compatibility and reliability of production (chemically favourable conditions, see Section 2.2.2) resist pressure from the backfilled deposition tunnel restrict flow of water past the deposition tunnel mouth
	filler material wt% – *to be determined*	compatibility and reliability of production (chemically favourable conditions, see Section 2.2.2) restrict flow of water past the deposition tunnel mouth

Justification

The deposition tunnel plug consists mostly of concrete. The major risk for the other EBS components is the high pH leachates from the concrete, which could be harmful to bentonite. Similar material restrictions as for the backfill material selection, i.e. provide limited potential for copper corrosion, see Section 6.3.5, apply also to the aggregate material in the concrete and possible additives needed although the diffusion distance from the plug to the surface of the canister is much larger.

The calcium/silica ratio affects the pH of the leaching waters. The current ratio of <1 has not yet been established as a requirement. The cement leachate load from the plug onto the clay components in the near field can be minimized if the transport capacity of the fractures surrounding the plug remains limited. The transport capacity depends on the extent, size and connectivity of fractures at and around the location of the plug and needs to be determined for each specific location.

The plug should not impair the safety functions of the backfill in the long term when the hydraulic isolation capacity has been lost (i.e. the concrete binder has been degraded or lost). Therefore, the plug shall consist of sufficient amount of filler material that remains in place between the backfill in the deposition tunnel and the closure in the adjacent main or central tunnel. However, the more filler (fines) used, the more binder will be needed to maintain the high tightness of the plug. The optimal ratio of aggregates (e.g. sand, stones), binders (e.g. cement, silica and fly ash) and water required to achieve a good quality concrete needs to be taken into account in the design of the plug.

The chemical and mineralogical composition of the materials selected for the plug shall be characterised and assessed from the long-term safety point of view as part of the material selection process. The maximum contents of sulphide-generating materials in the plug was been preliminarily set by Posiva in its Design Basis (Posiva 2012a) based on the corresponding limit in the backfill and buffer materials. However, this is now being reassessed as it lacks a scientific basis.

Implications for verification and design

These technical design requirements affect the selection of material for the backfill plug. The calcium/silica ratio should be such that the cement leachates from the plug do not affect the performance of the backfill. This means that the overall dilution and transport of the cement leachates should be assessed along with the impact on the performance of the backfill.

The inclusion of aggregate material in the plug design (in the filter and sealing layer) allows maintaining the hydraulic conductivity and swelling pressure in the backfill within the targets in the long term.

6.5.3 Tightness of the plug

Characteristic	Technical design requirement	Related safety function
tightness	200 m^3 of total outflow flow before the backfill is saturated (no assumption about operating time). (*The rate requirement remains to be developed*.)	restrict flow of water past the deposition tunnel mouth

Justification

The plug shall restrict flow of water from deposition tunnels during operation to enable the self-sealing properties of the backfill to be deployed. Advective flows are possible in the backfill after installation before the deposition tunnel backfill reaches saturation (Keto et al. 2009). Piping and erosion processes can transport buffer and backfill materials, and could lead to unacceptable losses of buffer or backfill material before saturation of the backfill if the plug is not hydraulically tight. The plug also needs to be hydraulically tight to provide favourable conditions for the saturation of the backfill and buffer. The hydraulic isolation provided by the deposition tunnel plug is not of major importance after the closure of the repository, because the closure of the central tunnels also inhibits groundwater flows since pressure gradients will decrease after closure.

After this, the closure materials in the central tunnel, together with the remaining aggregate material from the plug after cement dissolution, are required to maintain the backfill density at an acceptable value so that the safety functions of the backfill are maintained.

The leakage design requirement is based on SKB's requirement on the maximum allowed leakage total of 200 m^3 through the plug to prevent loss of bentonite due to piping erosion from the buffer and backfill (SKB 2011). The POPLU and DOMPLU tests in Finland and Sweden, respectively, will provide additional information concerning this requirement and a possible update within the next few years.

The plug also needs to be reasonably gas tight to stop convection of air during the operational period. A plug design that is fulfils the outflow requirement can also be considered sufficient to stop air convection during the operational phase. The need for an additional requirement on gas tightness is currently being assessed as part of the plug design work.

Implications for verification and design

This requirement affects the design of the plug through the selection of materials. The following considerations should be taken into account in the design:

- hydraulic conductivity of the concrete used in the plug,
- composition of the concrete for the plug,
- bond between the plug and the rock,
- allowed leakage around the plug (i.e. concrete/rock interface),
- watertight seal material, material-specific relation between dry density and hydraulic conductivity,
- installed watertight seal material mass,
- location of the plug with respect to water- conducting fractures.

This requirement has also implications on the requirements on the rock for the location of the plug, see Section 8.3.2, as the hydraulic tightness of the rock around the plug should be comparable to that of the plug.

The design solutions to fulfil this requirement and its verification could ultimately differ between Posiva and SKB. In the current plug design (common to both SKB and Posiva), a reasonable gas tightness of the plug is achieved by the sealing materials placed between the plug and the backfill.

The transport of gas past the plug will depend on whether there are channels or spaces for the gas to flow through. SKB defines gas tight as a situation where there is no continuous gas phase through the plug in the axial direction. The concrete in the concrete part can also be considered to be gastight, but in order to consider the concrete plug as a whole to be gastight, also the space between the concrete and the rock including the fractures in it must be taken into account.

The circulation of air during an operational time of up to 100 years in the deposition tunnel should be assessed taking into account the overall oxygen sources and sinks, for the presence of accessory minerals reacting with oxygen or aerobic bacteria, the potential air pathways through the rock around the plug and through fractures intersecting the deposition tunnels that could be connected to open spaces.

The amount of gas or oxygen that could be transported past the plug into the deposition tunnel can be estimated from the open volume inside the deposition tunnel in unsaturated conditions and the pressure gradient. The corrosion of the canisters nearest the plugs should be assessed taking into account the reactions in the backfill material (e.g. microbial respiration, pyrite oxydation) that will consume the oxygen before it reaches the first canisters.

A similar assessment could be carried out for the overall flux of water vapour and condensation inside the deposition tunnel, considering the conditions inside and outside the tunnel, e.g. the temperatures, relative humidity, pressure, tightness of the rock around the plug, tightness of the plug seal.

7 Closure

7.1 Design and safety functions

Closure is the materials installed in investigation boreholes, rock caverns, shafts and ramp and tunnels that are not deposition tunnels, in order to fill and close them.

The main safety functions of a KBS-3 repository are to, either directly or indirectly by protecting and preserving the safety functions of the barrier system, isolate the repository from the surface environment; contain radionuclides and to retain and retard their dispersion into the environment, see Section 1.2.2. The closure shall contribute to these main safety functions of a KBS-3 repository by maintaining the safety functions to:

- reduce the risk of unintentional intrusion,
- avoid the formation of new preferential flow paths,
- keep the deposition tunnel backfill in place.

The choice of materials and design of the closure is made with respect to its ability to maintain these safety functions.

Some of the closure materials have as an additional feature contributing to retaining radionuclides and retarding their dispersion, the capacity to sorb radionuclides if the containment should be breached, see Section 2.2.3.

The materials and design of the closure must not unduly impair the safety functions of the engineered barriers or the rock, see Section 2.2.2. With respect to this, the materials used for the closure must not jeopardise the:

- chemically favourable conditions in the repository.

This will result in requirements on the chemical compositions of the materials used for the closure and plugs in the closed underground openings and specifically on their content of chemical species that can disturb the favourable chemical conditions.

The closure in the different underground openings of a KBS-3 repository facility, will have different functions and thus different designs. Unintentional intrusion shall be obstructed in the ramp, shafts and in investigation boreholes connected to the surface in their parts at or close to the surface. Groundwater flow shall be restricted in investigation boreholes, central tunnels, ramp and shafts that connect the deposition areas to the surface in their parts at or close to the repository depth.

The closure will contain different kinds of plugs. *Mechanical plugs* shall separate filled and closed underground openings from underground openings that remain to be closed. They shall keep the closure material in the closed parts in place until the underground opening on the other side of the plug is filled and the material saturated. In tunnels and shafts where groundwater flow needs to be restricted *hydraulic plugs* shall separate sections that run through transmissive zones of the rock so that the formation of transport routes is avoided and the function of the closure can be preserved in a long-term perspective. *Borehole plugs* with similar functions to the hydraulic plugs are to be used in investigation boreholes. There are also plugs that contribute to a safe and secure installation of the closure.

The designs of the closure and plugs in a specific underground opening will to some extent be site specific. An example of closure design used in Olkiluoto in TURVA-2012 (Sievänen et al. 2012) is illustrated in Figure 7-1. The design at the Forsmark site is presented in SKB (2010g).

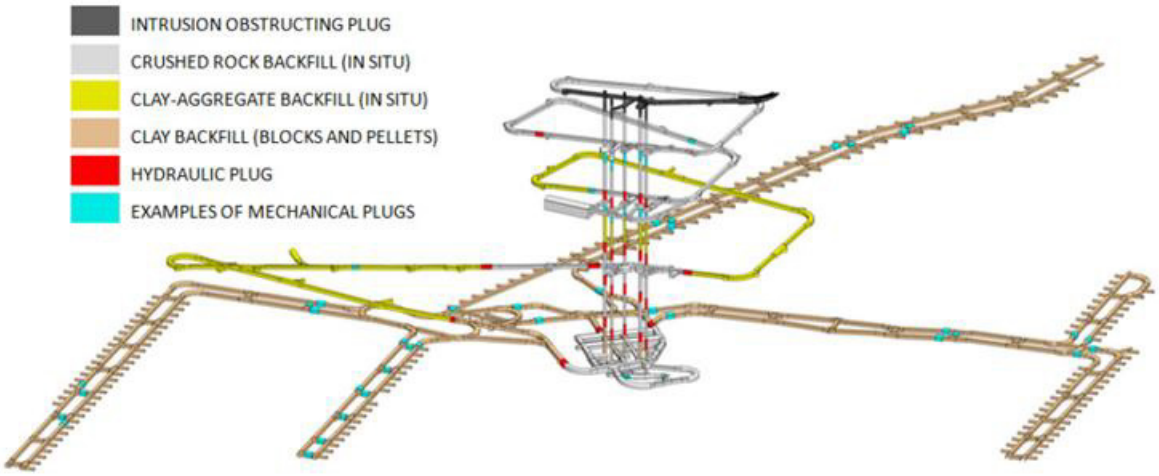

***Figure 7-1**. An example of closure system (from Sievänen et al. 2012). The number and location of mechanical and hydraulic plugs shown are only illustrative examples. Deposition tunnels not shown in the figure.*

7.2 Safety functions and performance targets

7.2.1 Reduce the risk of unintentional intrusion

SKB requirement (SR-Site)	The closure in the upper part of the ramp, shafts and boreholes shall considerably obstruct inadvertent intrusion into the repository (Requirement SSCL26).
Posiva requirement (TURVA 2012)	Closure shall complete the isolation of the spent nuclear fuel by reducing the likelihood of unintentional human intrusion through the closed volumes (Requirement L3-CLO-5).
Safety function	reduce the risk of unintentional intrusion
Performance target	–
Characteristics to be designed and verified in the production	thickness and materials of the intrusion preventing layer external appearance of the repository granule size distribution

Rationale of the safety function and performance target

The intent of a KBS-3 repository is to contain and isolate the spent nuclear fuel from man and the environment for as long as it poses a threat to human health and the environment. The potential exposure to large quantities of the radiotoxic material in the spent fuel is an inescapable consequence of its deposition in one final repository. Consequently, in addition to natural processes, human intrusion needs to be considered in the repository design and safety assessment. Future generations shall be able to utilize the site without unintentionally, or easily, intruding into the repository and being exposed to harmful effects of radiation.

Conditions to be considered and assessed

According to internationally accepted principles, the society that receive the benefits of nuclear power, or more specifically the nuclear power producers, shall bear the responsibility for the safe disposal of spent nuclear fuel and radioactive waste. However, current generations cannot be required to prevent future societies from their own intentional and planned activities. Based on this consideration, it is concluded that only inadvertent human actions need to be considered in the design and safety assessment of final repositories.

Since we cannot predict future human knowledge or behaviour, or the future technology, the list of means for possible future inadvertent intrusion into the repository can never be complete. To limit speculations as to scenarios involving intrusion into the repository, the current level of knowledge, technology development and the human practices at the repository site or similar locations elsewhere are assumed.

Natural changes, such as glaciations, are expected to take place during the long-term evolution of the repository and are also to be considered. The structures used in the closure of the upper parts of the disposal facility will freeze and thaw several times and be subjected to the mechanical loads from ice sheets. The upper part of closure should withstand these loads in order to preserve its ability to minimise the risk of inadvertent human intrusion into the repository.

7.2.2 Avoid the formation of new preferential flow paths

SKB requirement (SR-Site)	The closure in boreholes, shafts and tunnels that are not deposition tunnels shall prevent that conductive channels, that could jeopardise the rock's barrier function, are formed between the repository and the surface (Requirement SSCL18).
Posiva requirement (TURVA 2012)	Closure shall restore the favourable, natural conditions of the bedrock as well as possible (Requirement L3-CLO-6). Closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes (Requirement L3-CLO-7).
Safety function	avoid the formation of new preferential flow paths
Performance target	the hydraulic conductivity of closure as a whole should not significantly change the natural groundwater flow
Characteristics to be designed and verified in the production	average hydraulic conductivity of the rock mass at various depth levels depth of the upper part of closure location of hydraulic plugs material-specific relation between dry density and hydraulic conductivity installed closure mass

Rationale of the safety function and performance target

As part of the KBS-3 method, the cavities in the rock that are required for the deposition of canisters are backfilled and closed. The intention is to restore conditions similar to those in the unexcavated host rock so that its safety functions are preserved. A prerequisite for this is that the investigation boreholes, tunnels and shafts of a KBS-3 repository facility should not short-circuit hydraulically important zones in the rock and thus create new preferential flow paths, which could also contribute to changes in the geochemical conditions of the host rock.

In order to prevent formation of preferential flow paths and transport routes, the hydraulic conductivity of the closure in different facility sections needs to be sufficiently low to allow the natural host rock hydraulic conditions to be restored after closure. Further, to avoid the formation of flow routes in the closed underground openings, large fracture zones with high transmissivity need to be sealed and separated from the closure material.

Posiva's previous requirement (Requirement L3-CLO-6) on the restoration of the favourable, natural conditions of the host rock cannot be formulated through a quantitative performance target, so it has been replaced by a hydraulic conductivity performance target, and by requirements on the durability and chemical composition of closure materials so as to not impair the barriers' safety functions of the barriers, see Section 2.2.2.

Conditions to be considered and assessed

One of the most probable places where preferential flow paths could develop is at the interface between the closure materials and the rock. Advective flows in the closure are most likely to form during the installation period and their significance diminishes after the KBS-3 repository facility has been closed and once the swelling closure materials become saturated.

The hydraulic conductivity of the materials and structures used in closure should be such that closure does not create lower resistance flow paths than the natural groundwater flow paths. The overall hydraulic conductivity of the different parts of the host rock, including closure, can be modelled taking into account the natural features of the rock adjacent to the closure structures, such as the transport resistance and flow of the natural fractures and the flow rates through closure. SKB conducted such studies (Luterkort et al. 2012) for the Forsmark site and showed that the tight (clay

filled) closure backfilling only needs to be installed within the first 100 m above repository level. Posiva is conducting a similar study, still ongoing.

The shafts and access tunnel will intersect with some major hydraulically conducting fractures. The sealing of the access routes at these zones needs special consideration to ensure that new fast flow paths are not formed. If they do, they should be represented considered in the flow and transport modelling as well.

The effect of the annual freezing and thawing cycles on the hydraulic conductivity of the upper parts of closure needs to be taken into account in the design requirements, for example through the selection of materials for the upper parts of closure. Changing conditions are also expected during the long-term evolution of the repository and the site. According to the latest modelling results, during periods of cold climate, permafrost is expected to reach depths down to nearly 300 m at most both in Olkiluoto (Hartikainen 2013) and Forsmark (Brandefelt et al. 2013). The permafrost depth is variable throughout the site evolution, and the structures used in the closure of the upper parts of the disposal facility will thus freeze and thaw several times. The performance of the plugs and backfill at these levels should not be completely lost as a consequence of these processes in order to avoid the formation of preferential flow paths.

Furthermore, groundwater chemistry might become more diluted and the flow might be higher during in connection to a glacial meltwater stage of the climatic evolution. Hence, materials less prone to being adversely affected by freezing and thawing and dilute waters (e.g. rock) are considered in the design of closure areas where such processes are expected.

7.2.3 Keep the deposition tunnel backfill in place

SKB requirement (SR-Site)	The closure in main tunnels shall prevent the backfill from swelling/expanding or being transported out of the deposition tunnels (Requirement SSCL43). The closure shall keep the closure in adjacent or underlying underground openings in place (Requirement SSCL49).
Posiva requirement (TURVA 2012)	Closure shall not endanger the favourable conditions for the other parts of the EBS and the host rock (Requirement L3-CLO-8). The closure components shall keep the backfill and plugs of the deposition tunnels in place.” (Requirement L4-CLO-21).
Safety function	keep the deposition tunnel backfill in place
Performance targets	closure deformation should be limited to keep the deposition tunnel backfill in place
Characteristics to be designed and verified in the production	installed closure masses and volumes at repository level compressibility of the closure structures closure backfill materials: composition and properties deposition tunnel backfill materials: composition and properties closure plugs material: composition and properties duration of ”open volume” conditions

Rationale of the safety function and performance target

In order for the deposition tunnel backfill to maintain its safety functions, its density should not decrease significantly after the deposition tunnel plug has lost its mechanical strength. This function thus applies to the long-term evolution of closure. The backfill in deposition tunnels consists of a swelling clay material that will expand in contact with water and, unless there is something counteracting the expansion, it will expand out of the deposition tunnel. In the long-term, when the function of the plugs in deposition tunnels cannot be guaranteed, the closure in the tunnels adjacent to deposition tunnels needs to keep the backfill in deposition tunnels in place so that it will not lose density to such an extent that its safety functions are compromised. This implies that a design requirement on the compressibility of the closure materials is needed.

Closure as a whole should retain its configuration in order to maintain its safety functions. This is a complex goal as closure is composed of several structures and materials. This implies that closure structures adjacent to other structures containing swelling clay should function in the same way as closure in tunnels adjacent to the backfilled deposition tunnels.

Conditions to be considered and assessed

The closure should withstand the mechanical loads from the deposition tunnel backfill. The load to take into account corresponds to the swelling pressure of the deposition tunnel backfill and groundwater pressure. Both these values are site specific as they depend on the depth of the repository and the design of the deposition tunnel backfill, including the plug. Furthermore, expected changes in the hydrogeochemistry are also need to be taken into account, because they may cause changes in the swelling pressures of clay-based materials at repository depth, on both sides of the deposition tunnel plug.

7.3 Technical design requirements for the closure

The technical design requirements of the different closure components will be included in the country-specific requirements reports. Preliminary closure designs will be presented by Posiva and SKB in the next licensing step and assessed against the long-term performance of the whole repository. Such assessment will provide further feedback on the design and requirements for closure.

8 Host rock and underground openings

8.1 Design and safety functions in a KBS-3-repository

The underground openings are the man-made spaces (tunnels, shafts, holes, etc.) in the host rock that are required for a KBS-3 repository, and the irreversible alterations, constructions and materials that remain at the excavated rock surfaces or in the surrounding rock after deposition, backfill or closure respectively.

The host rock is the rock hosting the repository. Safety functions and their related performance targets are assigned to the host rock. The maintenance of safety functions and fulfilment of the performance targets depend on how the underground openings are located and constructed with respect to local host rock conditions.

The main safety functions of a KBS-3 repository are to, either directly or indirectly by protecting and preserving the safety functions of the barrier system, isolate the repository from the surface environment; contain radionuclides and to retain and retard their dispersion into the environment, see Section 1.2.2. The host rock and underground openings shall contribute to these main safety functions of a KBS-3 repository by providing

- isolation from the surface environment

and by maintaining:

- favourable thermal conditions,
- mechanically stable conditions,
- chemically favourable conditions,
- favourable hydrogeological conditions to limit the transport of solutes.

The rock has an additional quality contributing to retaining the radionuclides and retarding the dispersion of radionuclides, the capacity to sorb radionuclides if the containment should be breached, see Sections 1.2.5 and 2.2.3.

The construction of the underground openings shall not unduly disturb or alter the characteristics of the host rock that are important for performance of the host rock as a barrier. Further, the engineered barriers and their reliable installation impose requirements on the construction of the underground openings.

8.2 Safety functions and performance targets

8.2.1 Isolation from the surface environment

SKB requirement (SR-Site)	The underground openings of the repository shall be isolated from the human actions which, based on present living habits and technical prerequisites, may occur at the repository site (Requirement SSUO50).
Posiva requirement (TURVA 2012)	The host rock shall isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface (Posiva 2012a, Table 5-1).
Safety function	isolation from surface environment
Performance target	repository depth: several hundreds of meters
Characteristics to be designed and verified in the production	repository depth

Rationale of the safety function and performance target

The general aim of isolation is to protect the humans, plants and animals that in the future may live and utilise the repository site from exposure to radiation. This safety function also arises from the need to reduce the impacts of human activities at the site on the repository and the likelihood of the humans unintentionally intruding into the repository. Further, isolation from the surface environment contributes to maintaining the favourable and stable host rock conditions by reducing the influence of the changing conditions at the ground surface caused e.g. by climate evolution, see Sections 8.2.2 to 8.2.5.

Conditions to be considered and assessed

In order to protect the humans, plants and animals at the site from any harmful effects of radiation, the depth and location of the deposition areas comprising the deposition tunnels and deposition holes are to be adjusted to local host rock conditions. Depth and location of the deposition areas are selected so that the host rock conditions, taking into account both human actions and naturally occurring changes at the surface, will contribute to the containment of the radionuclides and to limitation and retardation of the transport of radionuclides if the containment is breached.

The likelihood of inadvertent human intrusion to the repository is restricted at the site selection phase by selecting a site that has a low potential for extractable natural resources. Thus, the likelihood of deep drillings for ore exploration is low. Human intrusion can be further restricted by selecting the repository depth so that it is unlikely that human activities, e.g. drilling of water wells, will reach the repository depth.

Natural changes in the surface conditions, e.g. erosion and other processes related to changes in climate conditions including permafrost and glaciation that affect the safety functions of a KBS-3 repository, are discussed in Sections 8.2.2 to 8.2.5.

8.2.2 Favourable thermal conditions

SKB requirement (SR-Site)	The layout of the underground openings shall be adapted to the repository rock so that thermally favourable conditions are provided and the containment of radioactive substances can be sustained over a long period of time (Requirement SSUO10).
Posiva requirement (TURVA 2012)	–
Safety function	favourable thermal conditions
Performance targets	$T_{\text{deposition hole}} \geq$ temperature yielding $T_{\text{buffer}} > -2.5$ °C $T_{\text{deposition hole}} \leq$ temperature yielding $T_{\text{buffer}} \leq 100$ °C
Characteristics to be designed and verified in the production	repository depth distances between deposition holes

Rationale of the safety function and performance target

Favourable thermal conditions are required to maintain the safety functions of the engineered barriers in a long time perspective, see Section 2.2.1.

Freezing of swelling clay materials in the buffer would cause an increase in pressure that could damage the canister or rock. It has been shown that the buffer does not freeze at temperatures above −2.5 °C. With respect to the temperatures acceptable for the buffer, the temperature in the deposition hole must stay above −2.5 °C. This temperature is the performance target for the ability of the buffer to limit the pressure on the canister, see Section 5.2.5.

Also, high temperatures resulting from the decay power of the disposed spent nuclear fuel may impact the safety functions of the engineered barriers. With respect to the transformation of the minerals of the swelling clay materials, the temperature in the buffer shall stay below 100 °C, see Section 5.2.6. The highest occurring temperature in the buffer will depend on the decay power of the spent nuclear fuel, the thermal properties of the host rock and buffer and the distances between deposition holes.

Conditions to be considered and assessed

During the extended periods of cold climate, permafrost may develop as a consequence of low ground temperatures. The lowest temperatures at the repository depth occur during the permafrost periods. The depth the permafrost reaches depends on the assumed climate conditions and the thermal properties of the host rock at the site. Permafrost modelling carried out for the Forsmark and Olkiluoto sites has shown that it is extremely unlikely that permafrost would reach the repository at either of the sites (for results of Forsmark, see Hartikainen et al. (2010), and for Olkiluoto, Hartikainen (2013)).

The highest temperatures in the buffer are affected by the decay power of the spent fuel in each canister, the thermal properties and dimensions of the buffer and canister, the temperature and thermal properties of the host rock, and the distances between the deposition holes and deposition tunnels. The canister spacing shall be selected so that unacceptable temperatures in the buffer will not occur, see Section 2.2.1.

In order to assess the lowest and highest temperatures in the repository, the ambient temperature in the repository host rock and the thermal properties of the host rock need to be known. However, no requirements on these properties are set, as in the design of the underground openings and with the known thermal properties of the rock, the lowest temperature in the repository is essentially controlled by the selection of the repository depth and the highest temperatures are controlled by the canister spacing.

8.2.3 Mechanically stable conditions

SKB requirement (SR-Site)	The layout of the underground openings shall be adapted to the repository rock so that mechanically stable conditions are provided and the containment of radioactive substances can be sustained over a long period of time (Requirement SSUO9).
Posiva requirement (TURVA 2012)	The host rock shall provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers (Posiva 2012a, Table 5-1).
Safety function	mechanically stable conditions
Performance targets	groundwater pressure at the repository depth, including the load from an ice sheet during glaciation, such that isostatic load on canisters < 50 MPa shear movements at deposition holes < 5 cm, and with a maximum velocity of 1 m/s
Characteristics to be designed and verified in the production	repository depth placement of deposition areas with respect to critical structures and volumes placement of deposition holes with respect to critical structures and volumes

Rationale of the safety function and performance target

The host rock shall provide mechanically stable conditions, so that the canister will not break under mechanical loads over a long period of time. The groundwater pressure at the repository depth and the increase in the groundwater pressure due to the presence of an ice sheet at the site, in addition to the swelling pressure of the buffer contribute to the isostatic load on the canisters. A performance target for the canister is that it shall withstand an isostatic load of 50 MPa, see Section 4.2.2, which sets the upper limit for the groundwater pressure.

The shear displacement in fractures intersecting the deposition holes shall be limited to avoid shear failures of the canisters. The shear load on the canister depends on the displacement, shear rate and shear plane orientation, and on the shear properties of the buffer. The shear properties of the buffer are discussed in Sections 5.2.4 and 5.3.3. The ability of the canister to withstand shear loads due to rock displacements is discussed in Sections 4.2.2 and 4.3.1. There are uncertainties related to shear displacements in fractures intersecting the canister in association with earthquakes related to stress conditions, strain rate, impact of the location of the hypocentre and heterogeneous properties of the zones. However, based on the correlation of the shear displacements and fracture sizes and on analyses carried out (see e.g. Fälth et al. 2010), means to avoid fractures where shear displacements of over 5 cm could occur have been found. In practice, this means considering the size of the structures among other things in classification of the structures as critical and to be avoided by the

different parts of the repository, see Section 8.3. Further, the analysis of the canister-buffer-system assuming characteristics according to Sections 4.3.1 and 5.3.3, have shown that the canister can withstand such shear displacements given that the shear velocity does not exceed 1 m/s. The low probability of shear displacements in deposition holes that would lead to canister failures and the limited impact of radionuclide releases due to such failures (see SKB 2011, Sections 10.4.5 and 12.8, Posiva 2012a, Section 7.2 and Posiva 2012d, Sections 11.2 and 11.3), gives the basis for maximum shear displacement of 5 cm and maximum shear velocity of 1 m/s as performance targets.

Conditions to be considered and assessed

The canister is designed to withstand an isostatic load up to 50 MPa, see Section 4.2.2. The loads contributing to the overall isostatic load consist of the swelling pressure of the buffer, 10 MPa at maximum, see Section 5.2.5, the groundwater pressure at the repository depth, 4–5 MPa corresponding to repository depth of 400–500 m, see Sections 8.2.1 and 8.3.1, and the increase in the groundwater pressure due to presence of an ice sheet at the site. Recent modelling of climate and ice sheet development (Quiquet et al. 2016) is primarily interpreted by SKB and Posiva such that a maximum ice sheet thickness of 4 000 m, corresponding to an isostatic pressure contribution of 36 MPa, may have to be considered at the Forsmark and Olkiluoto sites. Such a maximum thickness could possibly occur only after the first 120 000 year glacial cycle. A 4 000 m thick ice sheet yields, for a repository at 500 m depth, a slightly higher upper bound on the maximum isostatic load (10 + 5 + 36 MPa = 51 MPa) than the established technical design requirement of 50 MPa. This suggests that, in coming safety assessments at the Forsmark and Olkiluoto sites, the residual probability of canister failures when the isostatic load slightly exceeds that of the technical design requirement may have to be considered, in accordance with the discussion in Section 1.2.5. In such a case, also a distribution of maximum buffer swelling pressures could be considered when estimating the likelihood of canister failures in the repository.

Static and dynamic stress redistributions might trigger fractures to shear as an effect of nearby earthquakes. As both of the sites, Forsmark and Olkiluoto, are located in tectonically stable environments, the magnitudes of the earthquakes and thereby the shear movements they cause can be expected to remain limited during temperate climate periods. However, in connection with the advance or retreat of an ice sheet, changes in the rock stresses can lead to a decrease in the stability of some of the fault zones, which become more prone to host earthquakes that can potentially induce secondary shear displacements in fractures (see e.g. Hökmark and Fälth 2014).

The potential for shear failures can be mitigated by locating the deposition areas, deposition tunnels and deposition holes away from faults and other geological features such as fractures having potential to host critical slip. According to several studies and modelling (e.g. Munier and Hökmark 2004, Fälth and Hökmark 2006, 2011 and 2012, Fälth et al. 2010), no induced shear displacement exceeding 5 cm in deposition holes will take place, if deposition holes are not located within the faults and not intersected by fractures having more than a critical diameter. Thus a key task is to assess is the properties of the faults and fractures, especially their size and identify the critical ones to be able to avoid them in the deposition holes, see further discussion in Section 8.3.2.

Rationale of the safety function and performance target

Chemically favourable conditions are required for the performance of the engineered barrier system and for limiting the release of radionuclides from the spent fuel and radionuclide transport in case the containment is breached. Although the aim has been to give quantitative limits to all performance targets, it is not possible at the current stage for all the parameters. It is expected that e.g. the ongoing joint Posiva-SKB sulphide project can give further information e.g. on some of these parameters, but it may not be possible to give well-justified limits for all these parameters even after continued studies. Including these parameters as performance targets is however considered justified in that sense that these parameters have an impact on post-closure safety and should be considered in the safety assessment as well as e.g. in selection and acceptance of the materials to be used in construction. The impacts of the site-specific concentrations of substances for which no quantitative limits are given are analysed as part of the post-closure safety assessment by considering also the evolution of these concentrations with time.

8.2.4 Chemically favourable conditions

SKB requirement (SR-Site)	The layout of the underground openings shall be adapted to the repository bedrock so that a chemically favourable environment is provided and the containment and the prevention or retention of dispersion of radioactive substances can be sustained over a long period of time (Requirement SSUO7).
Posiva requirement (TURVA 2012)	The host rock shall provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers (Posiva 2012a, Table 5-1).
Safety function	chemically favourable conditions
Performance targets	favourable conditions for the canister: – anoxic conditions after the initially entrapped oxygen in the near field is consumed – pH > 4 and concentration of Cl^- < 2 mol/L – concentration of NO_2^- < 10^{-3} mol/L, low concentration of NH_4^+ and acetate – concentration of HS^- < 3 mg/L, higher short-term transients can be accepted favourable conditions for the buffer and backfill: – salinity; TDS < 35 g/L, short-term transients up to 70 g/L accepted – concentration of K^+ < 0.1 mol/L – total charge equivalent of cations $\sum q[M^{q+}] > 8 \times 10^{-3}$ mol/L, where q = charge number of ion and $[M^{q+}]$ = molar concentration of cation – pH 5–11 low release rate of radionuclides and limited radionuclide transport: – anoxic conditions – low organic content of the groundwater – high ionic strength
Characteristics to be designed and verified in the production	repository depth placement of deposition areas use, location and composition of engineered and residual materials total inflow to the final repository facility

Favourable conditions for the canister

Favourable groundwater composition contributes to an environment where the canister can withstand corrosion. The groundwater reacts with the buffer or also with the backfill before coming into contact with the canister. However, the groundwater should have favourable properties with respect to canister corrosion to account for e.g. cases when the buffer performance might be reduced. The various corrosion processes and the chemical conditions that impact them are discussed in Section 4.2.1 and the following is concluded:

- Anoxic conditions are required to avoid general corrosion.
- High enough pH and low enough chloride concentration are required to avoid chloride- induced corrosion.
- Low concentrations of nitrogen compounds and acetate limit stress corrosion cracking in aerobic conditions, which may occur soon after canister emplacement.
- A low concentration of sulphide reduces sulphide-induced corrosion.

Oxygen is present in the tunnels and deposition holes at the time of operation and installation. However, after the tunnel is closed, the remaining oxygen is consumed by microbial activity and reactions with reducing minerals in the buffer, in the backfill and present in the rock interface e.g. in the remaining rock bolts. The oxygen consumption is a rapid process and is assumed to take place within months after the saturation of the backfill (SKB 2011, p. 314) or within few years after deposition taking into account the non-saturated and partially saturated conditions and uncertainties in the pyrite oxidation rate (see Posiva 2012b, Section 5.5.2).

In anoxic conditions, sulphide is the most important corrosion agent, see Section 4.2.1. Figure 8-1 shows sulphide concentration and flow rate values, which would lead to no corrosion failures within 100 000 years and 1 million years assuming advective conditions in the buffer. According to the Figure 8-1, if flow rate is less than 1 L/year and sulfide concentration 10^{-4} mol/L (3 mg/L) or less, canister failures within the time periods considered would not occur.

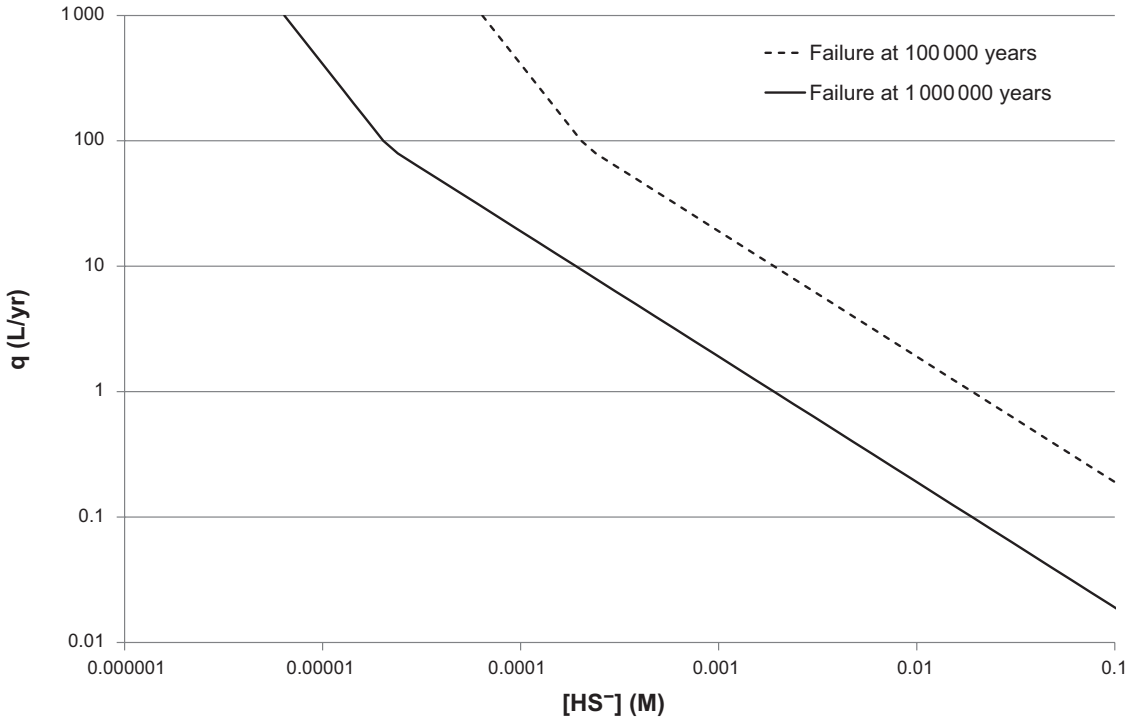

Figure 8-1. *Flow through buffer void volume in a deposition hole required to cause canister failures after 100 000 years and 1 000 000 years as functions of sulphide concentration. Advective conditions are assumed in the deposition hole. The buffer void volume and exposed canister surface area are as in (SKB 2011). The steeper slope at the low sulphide concentrations (high flow rates) is caused by flow being too high for all sulphide to have time to react while in the deposition hole; corrosion rate then varies as $q^{½}$, otherwise as q.*

Favourable conditions for the buffer and backfill

Favourable groundwater composition contributes to maintaining the performance targets of the buffer and backfill.

The capability to swell is essential for buffer and backfill materials and swelling pressure is a performance target for several of the safety functions of the buffer and backfill. For a given density, the salinity impacts the swelling pressure, see Sections 5.3.1 and 6.3.1. The groundwater at the repository depth at Olkiluoto and Forsmark has a salinity of around 10 g/L (TDS, see Posiva 2012b, Figure 3-6 and SKB 2008, Figure 8-46). Higher salinities may occur due to sea water infiltration during periods when the sites are submerged or due to upconing of the more saline waters in deeper parts of the rock as a response to the disturbed conditions caused by the repository construction and operation. Such disturbed conditions stabilise once the repository is closed and the buffer, backfill and closure become saturated. During the operational phase, the groundwater salinities (TDS) at the repository depth in Olkiluoto may rise to values slightly above 30 g/L (Hellä et al. 2014, Figure 4-1), but remain below 20 g/l in Forsmark (SKB 2011, Figure 10-39). With respect to this and the salinity of sea water the performance target is set to 35 g/L and the buffer and backfill are required to perform in salinities (TDS) of up to 35 g/L.

To enhance montmorillonite stability, conditions at the repository shall be such that major montmorillonite transformation processes occur only to a limited extent. With respect to this, the concentrations of potassium and possibly also iron need to be limited, see Section 5.2.6. On the other hand, iron can also contribute to maintaining favourable conditions by precipitating sulphide and thus reducing the sulphide concentrations. It is noted that iron in elementary form as used in construction (e.g. rock bolts) should also be limited until its impact on the montmorillonite transformation processes in the repository have been further investigated. Chemical erosion does not occur if the groundwater has sufficient ionic strength. Resent results from tests performed at near neutral pH conditions have shown that a charged cation concentration of about 8×10^{-3} mol/L is required to rule out loss of buffer mass, see Section 5.2.8. Also pH will impact the montmorillonite stability.

According to the modelling done for Forsmark (see SR-Site, page 518), the pH is expected to be in the range of 6.5 to 8.5, but also higher pH, of about 9.5, is possible in some of the deposition holes, at the times that an ice sheet advances and retreats, when dilute water leading to erosion can occur. In TURVA-2012, Posiva considered a bounding water based on the Grimsel meltwater with pH 9.6 for time periods with dilute conditions (Hellä et al. 2014, p 69). Chemical degradation of cementitious materials used in the repository, e.g. for grouting and in plugs, may produce a highly alkaline leachate. If this fluid comes into contact with the bentonite, chemical instability of montmorillonite will inherently result and montmorillonite can start to dissolve, see Section 5.2.6. In order for the buffer to resist transformation and retain sufficient mass over its life cycle, the pH should lie in the interval 5–11.

Low release rate of radionuclides and limited radionuclide transport

If the canister is breached, anoxic conditions at repository depth contribute to the stability of the fuel matrix, see Section 3.6.2, and to retarding the transport of radionuclides. The canister insert provides an abundant source of iron, which means that the conditions inside the canister are even more reducing than in the groundwater.

Sufficient ionic strength of groundwater suppresses the formation and stability of colloids. Colloids may contribute to relatively fast transport of radionuclides through the rock. According to Posiva (2012a, Figure 3-16), destabilisation of natural inorganic colloids is expected in ionic strengths above 0.1 mol/L. Compared with the natural colloids in the water, colloid formation at the buffer/rock interface in connection of chemical erosion is a more significant source of colloids. Chemical erosion requires an even lower ionic strength of the water to occur, a charge concentration of cations above 8×10^{-3} mol/L will prevent it, see discussion in Section 5.2.8.

Low organic content limits the formation of organic complexes, thus favouring the retardation of the radionuclides. The organic complexes increase solubility and decrease sorption, especially of trivalent actinides and lanthanides. No quantitative limit for the organic contents in groundwater can be given, since the main source of organics is expected to be the materials used for the buffer and the backfill.

Conditions to be considered and assessed

The safety function and the performance targets concern the groundwater composition in the rock surrounding the deposition holes and deposition tunnels. A key factor for favourable groundwater chemistry conditions in the host rock is the site selection. At the given site, the selection of the repository depth and placement of the deposition areas is also of importance. Further, the groundwater composition is affected by the construction and operation of the repository facility and the engineered and residual materials in the underground openings. In order to assess, whether the favourable hydrogeochemical conditions prevail at the site, the properties of the groundwater considered as performance targets need to be known. These properties are assessed as part of the site characterisation and monitoring during the construction and their future evolution is modelled to assess the impact of the repository construction and operation and the natural evolution at the site.

The repository depth – and the sites - have been selected so that they have favourable groundwater conditions. With increasing depth, the groundwater conditions become more stable, because of the reduced influence of the infiltration of surface water and lower groundwater flow rates at larger depths. Also, the impacts of glaciation reduce with increasing depth.

During the post-closure assessment period, the groundwater composition at the repository depth changes as result of the groundwater circulation at the site, see also Section 8.2.5. Relevant considerations are infiltration of surface waters, mixing of the infiltrating waters with existing groundwater, water-rock interactions and microbial reactions, the latter occurring mainly in the overburden and in the upper part of the rock, at interfaces with mixing of certain water types and also at the buffer/rock and backfill/rock interfaces. Microbially mediated aerobic oxidation in the overburden and in the shallow bedrock as well as methane oxidation consume oxygen in infiltrating waters, whereas pH is buffered mainly by calcites (Posiva 2012, pp 55–56, Salas et al. 2010). According to the expected natural evolution of the sites, Forsmark and Olkiluoto will experience land uplift, which, coupled to evolution of the surface environment, will lead to changes in the

composition of the infiltrating waters. As the shoreline retreats, the marine component of the infiltrating waters will be reduced. Periods of permafrost and glaciation, followed by the melting phase with infiltration of dilute glacial meltwaters and submerged periods, need also to be taken into account. The composition of the infiltrating water and the duration of the time periods with specific infiltration and flow conditions will affect groundwater conditions in the host rock.

The construction of the repository and the presence of the open underground spaces temporarily increase the groundwater flow circulation at the site, thereby increasing also the changes in the groundwater composition due to mixing of different water types. Disturbances caused by the construction and operation of the facility e.g. include an increase in salinity due to upconing and introduction of oxygen at repository depth. Further, leachates from the materials used in construction e.g. for grouting or in the engineered barriers, will affect the groundwater composition. The main concerns related to the use of cement is the increase of the pH of the groundwater. Construction materials with organic additives should be avoided, as their leachates might increase the concentration of organics, which in the natural groundwaters are low. Examples of other substances that need to be considered are iron and nitrogen.

8.2.5 Favourable hydrogeological conditions with limited transport of solutes

SKB requirement (SR-Site)	The layout of the underground openings shall be adapted to the repository rock so that favourable hydrological and transport conditions are provided and the containment, prevention or retardation of dispersion of radioactive substance can be sustained over a long period of time (Requirement SSUO8).
Posiva requirement (TURVA 2012)	The host rock shall provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers (Posiva 2012a, Table 5-1). The host rock shall limit the transport and retard the migration of harmful substances that could be released from the repository (Posiva 2012a, Table 5-1).
Safety function	favourable hydrogeological conditions to limit the transport of solutes
Performance targets	transport resistance in fractures intersecting the deposition hole > 10 000 year/m flow rate in fractures intersecting the deposition holes (per one metre of fracture width) < 1 L/m per year
Characteristics to be designed and verified in the production	repository depth placement of deposition holes properties of the excavation damage zone around the underground openings other than deposition tunnels and deposition holes properties of the excavation damage zone around deposition tunnels properties of the excavation damage zone around deposition holes

Rationale of the safety function and performance target

Favourable hydrogeological conditions with limited transport of solutes are required to support the performance of the engineered barrier system and to limit radionuclide transport in the case of release from a breached canister. Limitation of the flow rate around the deposition holes contributes to limit changes in the groundwater chemistry in the vicinity of the deposition holes and restricts the mass transfer between the groundwater and the buffer. Thereby, the risk of erosion and loss of the safety functions of the buffer is reduced. Further, low groundwater flow rates in the vicinity of the deposition holes and the high transport resistance along the transport routes limit the transport of radionuclides in the case of radionuclide release.

The post-closure flow rates (or the corresponding Darcy fluxes defined as the volumetric flow rate per unit area, L/m^2 per year) and the transport resistance for the transport paths from a single deposition hole in the post-closure period are addressed through discrete fracture network (DFN) based groundwater flow modelling. The earlier safety assessments by both Posiva and SKB have shown that transport resistances higher than 10 000 years/m and flow rates in the fractures (per one metre of fracture width) lower than 1 L/m per year can be considered favourable. Therefore, the number of deposition holes having such properties should be high, although adverse values in some of the deposition holes are unlikely to lead to violation of the release, dose or risk criteria for the repository as a whole.

In addition to the transport resistance, the non-flow related retention properties of the near-field rock affect the transport of radionuclides in the case of a release. The non-flow related retention properties (solubility, speciation, sorption, porosity and diffusivity) of many radionuclides are affected by the chemical environment, including salinity, pH, dissolved carbonate content and redox conditions, see Section 8.2.4. The non-flow related retention properties need to be known for the assessment of post-closure safety, see also discussion in Section 2.2.3. However, the flow-related transport resistance discussed above is typically more significant for geosphere retention than the non-flow related retention properties. The transport resistance practically determines geosphere retention for the non-sorbing nuclides. In the case of sorbing nuclides, high transport resistance contributes significantly to the geosphere retention. However, high values of sorption coefficients (K_d) are also important for the retention of radionuclides with long half-lives since higher K_d-values significantly contribute to reduce the activity release from the geosphere to the biosphere. Further, although there are differences in the retention properties of the different fracture and rock types, the degree of variation is such that, it is not meaningful to use these parameters to guide the location of the deposition holes or tunnels, given the variation of chemical conditions. Therefore, no performance targets related to the non-flow related retention parameters are stated.

Conditions to be considered and assessed

The groundwater flow at the site is dependent on the network of conductive fractures and fault zones and the density variation of the groundwater. The groundwater flow is affected by changes in the surface environment resulting from the ongoing land uplift, permafrost conditions and glaciations, which change the boundary conditions in the groundwater flow modelling. These are to be taken into account according to the lines of climate evolution that are adopted.

The construction of the repository and the presence of the underground openings increase the groundwater flow circulation at the site. During the construction, grouting is used to control the inflows to the open tunnels in order to limit the hydraulic disturbances at the site. The grouting materials may on the other hand affect the groundwater chemistry as discussed in Section 8.2.4. Rock damage can be excavation-induced, stress-induced or thermally induced. The damaged rock around the underground openings, and specifically, below the tunnel floor and around the deposition holes, may affect the flow routes and rates around the deposition holes. The flow through the damaged zone is, however, controlled by the water supplied by the natural fractures.

The post-closure flow rate in fractures and the transport resistance in the vicinity of the deposition holes can only be assessed by modelling. For the assessment, a model of the fracture network describing the hydraulic properties of the fractures and their connectivity is needed. Most important for the flow conditions around a deposition holes are the fractures intersecting the deposition hole and the connections of these fractures to fault zones with high conductivity. So, in the repository design, the deposition holes are placed so that such fractures do not intersect the deposition holes. The selected repository depth also contributes to the favourable hydrogeological conditions, since the groundwater flow is limited at that depth.

8.3 Technical design requirements

The technical design requirements concern the repository depth, the placement of the deposition areas, deposition tunnels and the deposition holes, inflows to the underground openings, properties of the excavation damage zone, location of the underground openings with respect to each other, geometry of the underground openings and use of engineered and residual materials. The technical design requirements are assigned to characteristics to be designed and verified in production as defined for the specific safety functions and performance targets in Sections 8.2.1 to 8.2.5.

Some of the technical design requirements are site specific, as they depend on the site characteristics, whereas some depend on the spent fuel to be disposed. Therefore, it is not always possible to state common quantitative technical design requirements, but rather to state the factors for which quantitative requirements for the repository design at a specific site and for the methods applied need to be set.

The location of the deposition areas, deposition tunnel and deposition holes need to be adjusted to local host rock conditions, so that it can provide mechanically, chemically and hydrogeologically stable and favourable conditions according to discussion in Section 8.2.3 to 8.2.5. For this purpose, the *critical structures (CS)* and *critical volumes (CV)* are introduced. The critical structures and critical volumes are geological structures or rock volumes in their vicinity with properties such that they can negatively impact the post-closure safety of a KBS-3 repository. For example, deformation zones that form main groundwater flow routes or that can transmit movements generated by earthquakes large enough to induce canister-breaching secondary displacements, are considered as critical structures. Critical structures and volumes are decisive for the layout of a KBS-3 repository. By considering the potential impact of the rock structures or the rock volumes on the post-closure safety, the critical structures and volumes are classified with respect to their impact on the repository layout. The following classes apply to the structures and volumes respectively:

CS1/CV1 are structures/volumes with properties such that they cannot be accepted within the repository footprint i.e. shall not intersect any tunnels or shafts belonging to the repository system. Thus they steer the location of the repository and set boundary limits for the repository.

CS2/CV2 are structures/volumes with properties such that they cannot be accepted within deposition tunnels. Thus they influence the layout of the repository and steer the locations of deposition tunnels.

CS3/CV3 are structures/volumes with properties such that they cannot be accepted to intersect deposition holes. Thus they steer the location of deposition holes.

As an example of the classification of the structures, Figure 8-2 shows the procedure to assess whether a deformation zone will impact the location of the deposition tunnel i.e. whether it belongs to Class 2. The key topics, mechanical stability and importance for groundwater flow are assessed first. The size of the zone is considered as an indicator for earthquake potential. Also, other factors such as orientation with respect to current and anticipated stress fields need to be considered when judging mechanical stability. Judging the importance from the hydrogeological point of view needs to be based on modelling. A similar approach with relevant classification parameters for the specific class is also applied to Class 1 structures not allowed to intersect the repository footprint and Class 3 structures not allowed to intersect deposition holes. Work is ongoing to develop details of the classification procedure.

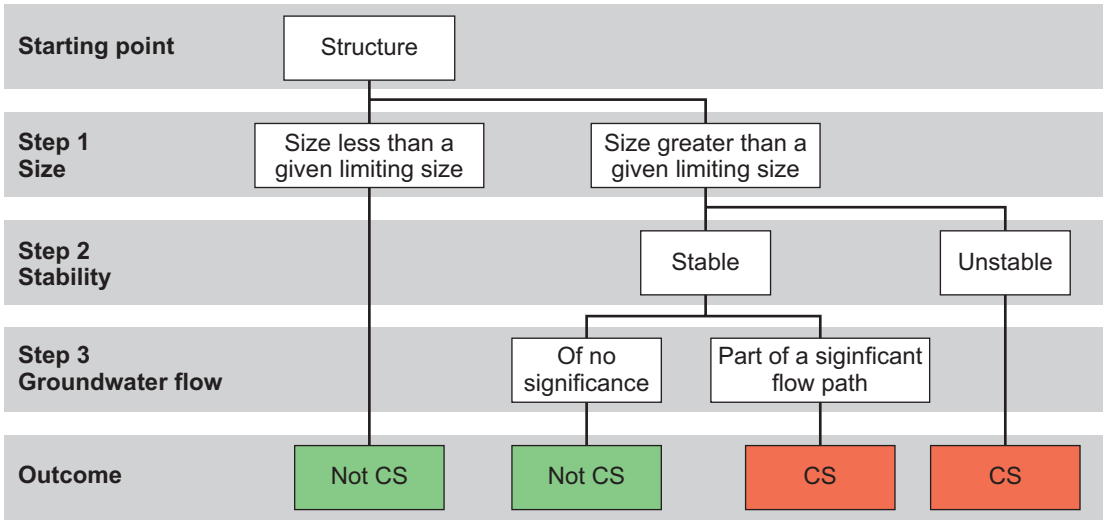

Figure 8-2. *Process chart for defining critical structures or volumes, an example for classification of CS2 structures. The starting point of the classification is a modelled structure based on the mapping in tunnels, boreholes and other investigation data. In the first step, the size of the zone is considered (Step 1). For the zones having size greater than the limiting size, the stability of the zone (Step 2) and the impact on the groundwater flow (Step 3) are assessed. The outcome of the process is classification of the zone as not critical (green boxes) or as a critical structure (red boxes).*

8.3.1 Repository depth

Characteristic	Technical design requirement	Related safety functions
repository depth	400 m < repository depth < 700 m	Iisolation from the surface environment favourable thermal conditions mechanically stable conditions chemically favourable conditions favourable hydrogeological conditions to limit the transport of solutes

Justification

The repository shall be placed at the depth of several hundreds of meters to isolate it from the surface environment, see Section 8.2.1. The repository depth shall provide favourable and stable conditions for the engineered barriers as discussed in Sections 8.2.2 to 8.2.5. The repository depth of >400 m is set based on the safety assessments that have been performed and considering both potential human intrusion and naturally occurring changes at the surface. At the repository sites considered, smaller depth would result in a potentially larger impact from the changes on the surface or close to the surface, e.g. occurrence of the permafrost and otherwise less favourable rock properties.

Considering the favourable thermal properties, the permafrost, i.e. the level of the 0 °C isotherm, is not expected to reach 400 m depth at the Forsmark and Olkiluoto sites (Hartikainen et al. 2010 and Hartikainen 2013, respectively). The fracturing and transmissivities of the fractures reduces notably with depth. At the depth of about 400 to 500 m i.e. at the proposed repository depth, the groundwater flow is concentrated on a few zones with high conductivity and a sparse network of fractures with lower transmissivity between them. With increasing depth, the hydrogeochemical conditions become more stable and groundwater flow is reduced, which limit the impact of the infiltrating surface waters and mixing of the different water types. Low groundwater flow at depth is a key factor in maintaining these favourable conditions.

On the other hand, rock stresses, mechanical properties of the rock, increase of temperature, potentially more adverse groundwater composition, e.g. increase in salinity, and demanding investigation and construction techniques are constraints on specifying a deeper location of the repository. To provide mechanically stable conditions for the canister it must not be exposed to too large isostatic load. The isostatic load is the sum of the swelling pressure from the buffer, the groundwater pressure at repository depth and the load from an ice sheet during glaciation, see Section 4.2.2. Therefore, the selection of the repository depth at the given site and the requirement on the isostatic load on the canister need to be consistent.

Implications for verification and design

As the repository depth depends on the local rock properties and on the expected glacial conditions, which may also vary between the sites, the selection of the exact repository depth is a site-specific issue. Considering the thermal, mechanical, chemical and hydrogeological conditions at the Olkiluoto and Forsmark sites, a repository depth between 400–500 m has, in the assessments of the post-closure safety, been demonstrated to be suitable.

The repository depth is adjusted according to the information gained during the site characterisation phase. The repository depth needs to be decided in a relatively early phase as it affects the design and construction of the access routes. Further adjustments to the repository depth, at least for parts of the deposition areas, can be done based on further site characterisation data including data gained from the underground facilities.

8.3.2 Location of deposition tunnels, deposition holes and deposition tunnel plugs

Characteristic	Technical design requirement	Related safety functions
placement of deposition areas	Deposition areas must not be placed within critical volumes of class 1.	isolation from the surface environment mechanically stable conditions chemically favourable conditions favourable hydrogeological conditions to limit the transport of solutes
	The deposition areas should be placed so that the salinity (TDS), pH and sulphide content of the groundwater are within the limits of their performance targets.	chemically favourable conditions
placement of deposition tunnels	Deposition tunnels must not be placed within critical volumes of class 1 and 2.	mechanically stable conditions favourable hydrogeological conditions to limit the transport of solutes
placement of deposition tunnel plugs	The deposition tunnel plugs shall not be placed within critical volumes of class 1, 2 or 3.	compatibility and reliability of production (see Section 2.2.2)
alignment of deposition tunnels	The deposition tunnels should be aligned according to the site-specific rock stresses to limit damaged rock volume around the tunnel.	compatibility and reliability of production (see Section 2.2.2)
placement of deposition holes	Deposition holes must not be placed within critical volumes of class 1, 2 or 3.	mechanically stable conditions favourable hydrogeological conditions to limit the transport of solutes
	Deposition holes shall be placed where the transmissivity of the pilot hole drilled in deposition hole position is less than *limit under development*.	favourable hydrogeological conditions to limit the transport of solutes
distance between deposition tunnels	The distance between the deposition tunnels shall be at least *site specific distance to* avoid mechanical influence between tunnels.	compatibility and reliability of production (see Section 2.2.2)
distance between deposition holes	The minimum distance between deposition holes within a deposition tunnel and to holes in adjacent tunnels shall be such that the temperature in the buffer < 100 °C.	favourable thermal conditions
	The distance between the deposition holes shall be at least *site-specific distance to* avoid mechanical influence between holes.	compatibility and reliability of production (see Section 2.2.2)

Justification

Placement of deposition areas

The deposition areas shall not be placed within critical volumes of class 1. Adjusting the location of the deposition areas with respect to the deformation zones being the main groundwater flow routes and potentially also mechanically unstable further contributes to the mechanically stable conditions, favourable hydrogeological conditions with limited transport of solutes as well as favourable chemical conditions.

Further, the groundwater composition in the deposition areas shall fulfil the requirements concerning salinity (TDS), pH and sulphide content given in Section 8.2.4.

Placement and alignment of deposition tunnels

The deposition tunnels shall not be placed within rock volumes of class 1 or 2. This is required in order to provide stable mechanical and favourable hydraulic and chemical conditions for the deposition tunnels and the backfill and further to the canister and buffer, in the long term. In practice,

this means that deposition tunnels shall not intersect larger deformation zones or main conduits of the groundwater flow. Avoiding such features means that inflows and the post closure-flow rates are such that no unacceptable amount of backfill mass is lost and the backfill will not be exposed to such chemical conditions that the properties of the backfill will change so that processes e.g. microbially induced, occur that can lead to production of harmful substances to buffer and canister performance or enhance transport through the backfill Avoiding these structures in the deposition tunnels contributes also to mechanically stable conditions in the deposition holes. Further, too high inflows may make the installation of the backfill difficult, see also Section 8.3.4.

The distance between the deposition tunnels needs to be adjusted according to the distance between the deposition holes within a single tunnel to limit the maximum temperatures in the deposition holes to an acceptable level. The distance between the tunnels needs to be at least such that the adjacent tunnel is not within the rock volume influenced by the tunnel. As the influence distance of the tunnel is two to three times the radius of the tunnel from the centre of tunnel, the distance between the centrelines of the two adjacent tunnels needs to be at least four to six times the tunnel radius, so that there is no significant mechanical interaction between the tunnels. Further, the orientation, as well as the shape of the tunnels have to be adjusted to local stress conditions and rock properties of the site in order to support the stability of the tunnels and to minimise the excavation damage.

The deposition tunnel plugs are not allowed to be located within critical volumes of class 1, 2 or 3. This is in order to ensure that the rock is good enough that a sufficiently tight plug can be constructed that supports the performance of the backfill during the operational period.

Placement and distances between deposition holes

The deposition holes shall not be placed within rock volumes of class 1, 2 or 3 in order to provide stable mechanical and favourable hydraulic and chemical conditions for the buffer and canister in the long term. If deposition holes are placed within critical volumes of rock, the buffer may erode and the canister may be exposed to unacceptable corrosion. In such rock volumes, there may be potentially fast flow paths to the surface or rock displacements generating unacceptable shearing of the canister. Further, if deposition holes are placed within such rock volumes it may make the installation of the buffer and deposition of the canister difficult.

To identify locations for deposition holes that can be expected to fulfil the performance targets related to favourable hydrological conditions to limit the transport of solutes, a criterion related to the transmissivity of the fractures intersecting the deposition holes is being developed as a joint effort by SKB and Posiva. A criterion based on transmissivity is considered to be a better predictor of the post-closure flow and transport conditions around the deposition holes than the inflow-based criterion used so far. However, a limitation on inflow is also needed for proper installation of the buffer.

Favourable thermal conditions for the engineered barriers mean that the temperature increase due to the disposal of the encapsulated spent fuel must not result in temperatures above 100 °C in the buffer, see Section 5.2.6. Given the decay power in the canisters, constraints on the thermal properties of the buffer and canister, thermal properties of the host rock and the highest acceptable temperature in the buffer, thermal analyses can be used to determine the required distances between the deposition holes, both within a deposition tunnel and the distances between the deposition tunnels, also see Sections 4.3.1 and 5.3.7. The distance between the holes needs to be at least such that the adjacent hole is not within the rock volume influenced by the hole. This distance is four to six times the radius of the hole from the centre of hole.

Implications for verification and design

Detailed characterisation and modelling of the observations from and the results of the investigations in the pilot holes for any tunnels and deposition holes as well in the excavated rooms has to be carried out to detect, characterise and model any features that may affect the location of the deposition areas, deposition tunnels or holes. During the detailed characterisation, more detailed information on their geometry and properties and the critical volume surrounding them are gained. That information is to be taken into account in the following design steps.

Monitoring during the construction phase will also give information on the rock properties and especially those of the groundwater composition within the deposition areas and at the repository depth in general. Short-term disturbances may occur, but a programme for evaluation of their causes, durations and impacts on the post-closure safety needs to be developed.

SKB and Posiva have developed both on their own and jointly similar investigation techniques as well as investigation and evaluation procedures to define and assess the locations for deposition tunnels and deposition holes. For the construction phase, a formal procedure covering the investigations, assessment of the rock volumes acceptable for locating deposition tunnels and deposition holes, and providing the information to the design in a structured manner needs to be developed. As the construction of the ONKALO is already ongoing, in Posiva such a formal procedure, the RSC-procedure, has been developed. Posiva is currently developing a manual describing the investigations to be carried out to support the RSC-classification in detail. Also, SKB is developing an equivalent procedure to be used for construction of a repository at Forsmark. The joint requirement basis described in this report also forms a good basis for any joint development projects on further development of the requirements, investigation techniques and evaluation process.

A site-specific rock mechanics analysis is needed to assess the potential for rock damage, be it excavation, stress or thermally induced, and ways to mitigate it. The tunnel design must be adapted accordingly. This may involve decisions about orientation, in particular, of the deposition tunnels, and tunnel geometry with respect to the maximum horizontal stress. The need, and possibility, to align tunnels with respect to the stress orientation is site and design specific.

The thermal properties of the rock need to be characterised for the thermal analyses to determine the canister spacing (e.g. see Hökmark et al. 2009 and Ikonen and Raiko 2012). Further, information on the thermal properties is to be gathered during construction in order to ensure that the properties lie within the assumptions used in the thermal analyses as discussed above.

The deposition holes shall be located so that the major part of the transport resistance is likely to be gained within the first tens of metres in the vicinity of the deposition holes when the transport path has not yet reached any highly conductive zone. There is a large uncertainty related to the transport routes from a single deposition hole, but the transport routes have the tendency to be directed towards fractures and deformation zones with higher hydraulic conductivity and smaller transport resistance. Therefore, the properties in the rock surrounding the deposition holes are important.

The results by Joyce et al. (2013) and Hartley et al. (2014), show that although there is a correlation of the inflows to the deposition holes in open repository conditions and the post-closure flow rates, there is sufficient variation as to leave uncertainty in identification of the deposition holes with post closure flow rates higher than the limit value. According to the results by Joyce et al. (2013), a potentially better indicator of the post-closure flow rates is the specific capacity (outflow/head change) observed in injection tests and further, there is also a reasonable correlation of the specific capacity with the sum of transmissivities of the fractures intersecting the injection hole. This suggests that injection test results could be used for defining technical design requirements for deposition hole positions. The results also contain mapped hydraulic connectivity in the simulated system. Currently, a Posiva-SKB joint project is ongoing to develop transmissivity related criteria for predicting post-closure flows in fractures intersecting the repository. In this project, hydraulic data from the experimental holes and pilot holes for these holes in ONKALO Demonstration tunnel 2 (DT2) is being used. The experiments are supported by model simulations at open and saturated conditions within the underground openings for a) quantifying inflow to pilot holes and deposition holes b) simulating hydraulic injection test results pertaining to pilot holes and deposition holes and c) simulating Darcy fluxes (and transport resistances) associated with deposition hole positions at saturated conditions. Simulations are being made both using an unconditioned model and with a model locally conditioned on information from the ONKALO Demonstration area. The results and statistical relationships derived between the various entities are expected to provide basis for giving guidance as to how to establish acceptance of a given deposition hole position. Results of this project are expected during 2017.

8.3.3 Location with respect to other underground openings

Characteristic	Technical design requirement	Related safety function
location of the underground openings with respect to investigation holes	The distance between investigation holes connected to the surface and shafts or tunnels other than deposition tunnels shall be at least *site-specific distance to be determined in the design*. The distance between investigation holes connected to the surface and deposition tunnels shall be at least *site-specific distance to be determined in the design.* The distance between investigation holes connected to the surface and deposition holes shall be at least *site-specific distance in the design.*	compatibility and reliability of production (see Section 2.2.2)
location of the deposition tunnels with respect to other underground openings	The distance between deposition tunnels where canisters have been emplaced and other underground openings shall be at least *site-specific distance to be determined in the design.*	compatibility and reliability of production (see Section 2.2.2)
distance between deposition tunnels and rock construction	The distance between deposition tunnels where canisters have been emplaced and rock construction shall be at least *site-specific distance to be determined in the design*.	compatibility and reliability of production (see Section 2.2.2)
distance between central or main tunnel and plug in deposition tunnels	Larger than *site-specific limit to be determined in the design* to avoid mechanical influence.	compatibility and reliability of production (see Section 2.2.2)

Justification

The construction of the underground openings must not impair the safety functions of the host rock, see Section 2.2.2. The excavation works will generate mechanical disturbances such as vibrations. In addition, depending on the rock strength with respect to prevailing rock stresses, spalling may occur in the underground openings. Increased fracturing around the underground openings will affect the groundwater flow and transport of solutes.

In order to avoid creating hydraulic connections between the surface and the underground openings, there needs to be a distance between existing investigation holes connected to the surface and underground openings where the hydraulic conductivity must be limited after closure of the repository. This required distance depends on the kind of underground opening, e.g. deposition hole, deposition tunnel, other tunnel or shaft, and on the properties of the host rock. Investigation holes in this connection mean boreholes and drill holes made either for investigation or construction purposes.

Construction works shall not disturb the canisters and buffer already emplaced in the deposition holes and the backfill and plugs already installed. In order to avoid mechanical disturbances caused by the excavation and the potential hydraulic and hydrogeochemical disturbances caused by the adjacent underground openings, there must be a sufficient distance between the backfilled deposition tunnels and other underground openings and construction work. Further, the heat produced by the emplaced canisters may induce spalling and mechanical instability and therefore there needs to sufficient distance between the emplaced canisters and open tunnels. These distances depend on the properties of the host rock at the site and to some extent on the time for which specific tunnels remain open and needs to be assessed considering the site-specific conditions and disposal schedule. It is noted that at Olkiluoto, no deposition tunnels are planned to be placed below the access tunnels.

The plug shall be placed in a location that allows it to perform as specified. This means that the quality of the rock shall be good and, therefore, plugs shall not be constructed within critical volumes of class 1, 2 or 3, see Section 8.3.2. There needs to be a sufficient distance between the plug and the intersection of the deposition tunnel and central, or main, tunnel in order to limit rock damage caused the redistribution of stresses around the excavated tunnels and to ensure the tightness of the plug. Further requirements, e.g. on the inflows, on the plug location may arise based on the ongoing plug tests.

Implications for verification and design

The required distance between investigation holes connected to the surface and deposition holes, deposition tunnels, other tunnels or shafts need to be determined so that conductive channels between the underground openings and investigation holes are not formed or can be shown to be insignificant for post-closure safety. In determining the distance, hydrogeological and mechanical properties as well as thermally induced stresses in the host rock need to be considered, as well as the accuracy of locating the investigation holes. Potentially, tools to locate the investigation holes from the tunnels are to be used.

The distances between deposition tunnels and other underground openings need to be determined so that mechanical disturbances and hydraulic and hydrogeochemical alterations that significantly impair the favourable conditions in the host rock are avoided. In determining these distances, the conditions in the host rock as well as the planned development of the deposition areas, the rock excavation methods to be applied and the thermal conditions resulting from the deposition of the spent fuel shall be considered. Also, the time before the underground openings are backfilled affects the potential disturbances and must be taken into account.

8.3.4 Inflow to underground to ensure proper initial state

Characteristic	Technical design requirement	Related safety functions
total inflow to the underground openings	Total groundwater inflow to the underground openings shall be less than *site specific limit*.	chemically favourable conditions compatibility and reliability of production (see Section 2.2.2)
inflow to deposition tunnel	Less than *limit to be determined in the design* to allow installation of the backfill and plug.	compatibility and reliability of production (see Section 2.2.2)
inflow to deposition hole	Less than *limit to be determined in the design* to allow installation of the buffer.	compatibility and reliability of production (see Section 2.2.2)

Justification

The construction of the underground opening and operation of the repository facility must not impair the safety functions of the host rock, see Section 2.2.2. During the operational phase, the hydrological boundary conditions of the repository are altered. The alteration may result in mixing of different groundwater types thus disturbing the favourable chemical conditions at the site, and even in inflow of water with unfavourable chemical composition. For this reason, the inflow to the repository must be limited. In addition, there are requirements on the inflow to the underground openings with respect to the robust design and reliable production of the buffer, backfill and closure.

Total groundwater inflow to the underground openings shall be controlled to limit changes in the groundwater composition due to upconing, infiltration of surface waters and mixing of different groundwater types, as well as minimizing the environmental impact due to ground water drawdown.

The inflow to deposition tunnels during the installation of the backfill may impact the characteristics of the backfill. The plug shall be tight and must be placed in a location where its functions to resist pressure and restrict flow can be maintained. With respect to this the inflow to deposition tunnels shall be limited to levels acceptable for the installed backfill and plug to conform to their design specifications.

The inflow to deposition holes during the installation of the buffer may impact the characteristics of the buffer.

The acceptable limits will be determined as part of the design of the backfill, plug and the buffer and are out of scope of this report. There are ongoing projects to develop these limits e.g. a joint SKB and Posiva project and the EVA-project (Börgesson et al. 2015) to investigate the acceptable inflow to deposition tunnels and holes in order to allow installation of backfill and buffer according to specification.

Implications for verification and design

Total inflow to the underground openings has to be defined based on site-specific modelling taking into account the time frame of open excavated rooms, the water bearing structures intersected by the excavated rooms and the efficiency of sealing methods applied.

The inflow to the underground openings, and especially to the deposition tunnels and deposition holes, is controlled by selection of the repository depth and placement of disposal areas and location of deposition tunnels and deposition holes, as discussed in Sections 8.3.1 and 8.3.2. The inflow limit for deposition tunnels to allow installation and thereby the performance of the backfill as designed, depends on the site characteristics and installation schedule and shall be based on the results and analyses of the backfill testing (see e.g. Dixon et al. 2008a, b, Riikonen 2009). These tests showed that the risks linked to piping and erosion increase if the inflows are high. In deposition tunnels, high inflows can be managed through technical measures (e.g. grouting of fractures, geotextiles, and temporary pipes and plugs). In the deposition holes, no technical measures to restrict inflows are allowed.

The inflows to the underground openings shall be monitored and inflows to both deposition tunnels and deposition holes shall be measured before the installation of the backfill or buffer. Before the construction of the ONKALO started, the inflow management at different parts of the underground openings were assessed and have been updated as the construction has proceeded. Monitoring of the inflows to the underground openings and the hydrogeological and chemical disturbances caused by the construction has been ongoing at ONKALO since the beginning of construction. Inflow measurements and assessment of their impact on the suitability of the rock for hosting deposition tunnels and deposition holes is incorporated in the RSC-programme Posiva is applying (McEwen et al. 2012). Similar type of actions have been applied by SKB at the Äspö HRL since construction started in 1990, and are being developed also for the Forsmark site.

8.3.5 Properties of the excavation damage zone (EDZ)

Characteristic	Technical design requirement	Safety function
excavation damage zone around underground openings other than deposition tunnels and deposition holes	The specific capacity $(Q/\Delta p)^*$ of the EDZ, that needs to be shown to be achievable with the excavation technique to be applied, shall be such that it corresponds to a transmissivity *to be determined* at maximum.	compatibility and reliability of production (see Section 2.2.2)
excavation damage zone around deposition tunnels	The specific capacity ($Q/\Delta p$) of the EDZ, measured from the pilot hole for the deposition holes, shall be such that it corresponds to a transmissivity of 10^{-8} m^2/s at maximum.	compatibility and reliability of production (see Section 2.2.2)

* Q is the flow in EDZ (m^3/s) and Δp is the drawdown (m).

Justification

The construction of the underground openings must not impair the safety functions of the host rock, see Section 2.2.2. The excavation works will result in mechanical alterations in the rock surrounding the excavated underground openings. Some of these alterations are reversible but there will always be an excavation damaged zone (EDZ) where irreversible alterations have occurred. The EDZ will affect the groundwater flow and transport of solutes and may impair the hydrological and transport conditions in the rock.

The objective is, in particular, to limit the formation of connected flow pathways along a tunnel length, shaft or deposition hole so that the hydraulically and chemically favourable characteristics of the host rock are not significantly disturbed. There shall be no significant increase in the flow rates around the deposition holes and no new flow paths with significantly lower transport resistances than the paths through natural fractures. The key properties to be assessed are the hydraulic properties of the excavation damage zone. The impact of the excavation damage zone on the groundwater flow at a site is dependent on the hydraulic properties of the site in general. The excavation damage zone can provide additional hydraulic connections, but water supply is controlled by the natural fractures.

Recently, detailed characterisation of the EDZ in the tunnels has been carried out in the Äspö hard rock laboratory (Rohs et al. 2016, Ericsson et al. 2015) and is ongoing in ONKALO. In addition to characterisation of the fracturing within the EDZ, hydraulic measurements have also been made. These studies show that the excavation will inevitably induce damage in the rock. The damage can be classified according to the cause and extent, see Figure 8-3. The excavation damaged zone consists of a construction- induced and stress-induced damaged zone. As a result, micro and macro scale damage in the rock occurs. The construction-induced excavation damaged zone is created at the time of the excavation, but additional stress-induced damage may occur after the excavation, normally within a couple of tunnel diameters from the advancing tunnel face. The damage is later amplified by the thermal load caused by the emplaced canisters. There can be site-specific differences in the damage mechanisms due to different rock mechanics conditions and properties of the rock at the sites. The formation of the excavation damaged zone can be controlled by the orientation and geometry of the excavated rooms and by the excavation methods.

The studies of the floor of the drill and blast tunnel in Äspö (Ericsson et al. 2015) and in the ongoing studies in ONKALO, indicate that the fracturing within the construction-induced damaged zone does not form a continuous connected fractured system along the tunnel. Based on the data from the recent tests in ONKALO, the extent of the construction- induced damage below the tunnels is limited to the upper most 30 cm, but additional stress-induced damage (potentially opening of fractures) has been observed also down to 80 cm. This type of fracturing may at least locally increase connectivity of the fracture system. It is noted that the test results from ONKALO are from conditions that are not comparable to the disposal tunnels. The results of the RESKONTR-project indicate a zonation of the EDZ and its hydraulic properties along the tunnel (Ericsson et al. 2015). The hydraulic properties vary also with distance from the tunnel perimeter, the highest hydraulic conductivities are observed in the first 10–15 cm below the tunnel floor and at the end of each blast round where the charge concentration is higher. Further, the results from both studies show that the hydraulic properties of the excavation damage zone vary significantly over short distances from extremely low values, similar to the background rock to local high values. Modelling carried out using data from earlier tests (Posiva-2012b) and the ongoing detailed characterisation campaigns shows that the EDZ will not form a significant flow path, when the excavation is done in a controlled way.

Based on the findings of these recent studies, a design requirement based on the specific capacity of the EDZ below the tunnel floor is proposed. This property considers both intrinsic conductivity and connectivity and this parameter can also be measured from the pilot holes for the deposition holes. The value to be used as a limit value is to be elaborated and it should correspond to a transmissivity of 10^{-8} m^2/s, which has been the value used in the previous safety assessments (SR-Site and TURVA-2012, Posiva 2012b and Posiva 2012d) and has been shown, even for the case of assuming continuous EDZ of 40 cm thickness, to give acceptable results in terms of limiting flow.

The excavation damage zone around the deposition holes bored has been observed to be so minimal that currently no requirements in addition to the excavation method to be used are practical to define. However, the investigations on the properties of the excavation damage zone and methods to verify it are continued.

Implications for verification and design

Based on the discussion above, there is a good confidence that the currently applied excavation techniques will result in an acceptable excavation damaged zone. This relies to a large extent on developed QA/QC procedures for the drill & blast operations (Ericsson et al. 2015). Further, investigation techniques have been developed to characterise the properties of the EDZ. Many of the techniques applied in the tests discussed above are not applicable in the construction of the access, central and deposition tunnels at the production stage of the repository. However, hydraulic testing in the pilot holes of the deposition holes is considered as a promising tool too and should be further developed and tested to get it to the stage of being an operative tool. Injection tests to determine the specific capacity of the EDZ have been tested by Hjerne et al. (2016) and Ericsson et al. (2015). Ground-penetrating radar (GPR) gives information on the extent of the EDZ below the tunnel floor. However, GPR is mainly seen as a tool for quality assessment of excavation quality as the results can give information on the location of the interface of the EDZ rather than its properties. A development of the interpretation of the measurement data and integrating the results obtained with other characterisation data is needed in order to take the method into operational use.

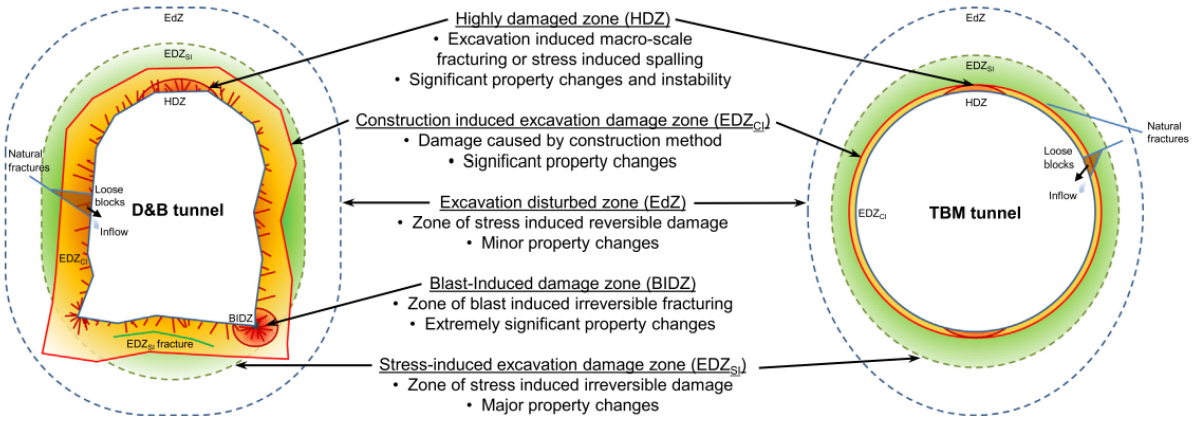

Figure 8-3. *Excavation damaged zone according to Siren et al. (2015). In this report, only the following terms are used: the excavation damaged zone that consists of the construction-induced damaged zone and the stress-induced damage zone.*

In order to qualify the characterisation techniques including the geophysical methods, mainly GPR, mapping and hydraulic characterisation by mean of injection tests and cross-hole interference tests, and verify the results of the tests done so far, it is recommended that the tests are repeated at the eventual repository site and depth to have data from more relevant stress conditions and from a more representative location for the deposition tunnels so that a better understanding of the impact of local conditions like rock type boundaries and are obtained. The detailed characterisation of the EDZ properties in ONKALO have been done at depth of about 350 m i.e. about 100 m above the actual repository depth, also the tunnel profile and orientation with respect to stress orientation are not representative for the deposition tunnels. SKB has carried out tests in Äspö Hard Rock Laboratory (Ericsson et al. 2015).

The excavation method and how the excavation is done affect significantly the type and extent of damage created. Using controlled excavation techniques which is important for the control of the EDZ, also contributes to the quality of the shape of the tunnel profile, including smoothness of the surfaces, which is important for the geometry of the underground openings. The geometry affects the installation of the backfill, initial state and long-term performance of the buffer and backfill. The regularity of the tunnel floor can be further enhanced if mechanical excavation techniques like sawing or grinding are used in conjunction with the drill and blast technique, at least locally. This would allow the removal of the most damaged zone in the first 10–15 cm below the tunnel floor. GPR can be used to control the depth of the EDZ, which is considered as a measure for excavation quality.

8.3.6 Geometry of the underground openings

Characteristic	Technical design requirement	Safety function
geometry of deposition hole	*Geometrical parameters within limits to be determined in the design.*	compatibility and reliability of production (see Section 2.2.2)
geometry of deposition tunnel	*Geometrical parameters within limits to be determined in the design.*	compatibility and reliability of production (see Section 2.2.2)
geometry of the other underground openings	*Geometrical parameters within limits to be determined in the design.*	compatibility and reliability of production (see Section 2.2.2)

Justification

There are requirements on the inflow and acceptable geometry of the underground openings with respect to the robust design and reliable production of the buffer, backfill and closure. If they are not fulfilled, the characteristics of the installed buffer, backfill and closure may not be acceptable and their safety functions may be impaired, see Section 2.2.2.

The geometry of the deposition hole shall be determined so that the installed buffer mass will result in a density that is sufficient for the buffer to maintain its safety functions. The buffer volume is illustrated in Figure 5-1, Section 5.3.5. Within this volume, the dimensions of the deposition hole shall be such that the installed buffer has a density between the lowest and highest values acceptable for the buffer to fulfil its technical design requirements. The dimensions of the deposition hole shall also be such that the installation of the buffer and deposition of the canister is reliable. Characteristics that need to be constrained are deposition hole dimensions e.g. diameter or radius, height and total volume. Their acceptable values are out of scope of this report and will be determined as part of the buffer and deposition hole design.

The geometry of the deposition tunnels shall be determined so that the installed backfill mass will result in a sufficient density for it to maintain its safety functions. Further, the dimensions must allow reliable installation of the backfill and plug. Dimensions for which acceptable values need to be stated are e.g. the tunnel profile and tolerances. Similarly, the geometry of the other underground openings needs to such that the closure can be installed and fulfil its performance requirements. As for the buffer, the determination of acceptable values is part of the design and out of scope of this report.

Implications for verification and design

Since the density is the ratio between mass and volume, the acceptable values on the geometrical parameters will depend on the possibilities to compress and pack the clay materials and to constrain the variations in the deposition hole and tunnel geometries. In addition, the equipment used to install the buffer and backfill must be able to operate at sufficient pace and with sufficient accuracy within the deposition tunnels. In determining the acceptable geometry, the density to be achieved, the properties of the clay materials, the excavation methods and technical equipment for installation must be considered with the aim to assure that the installed buffer and backfill will conform to specification. Verification of the geometry of the deposition holes, deposition tunnels and other underground openings, requires development of the measurement techniques and practices.

8.3.7 Engineered and residual materials

Characteristic	Technical design requirement	Related safety function
composition of residual materials	Only low pH grouting materials yielding a pH < 11 in deposition tunnels are allowed.	compatibility and reliability of production (see Section 2.2.2)
placement of deposition holes with respect to use of residual material	There shall be no grouting of deposition holes.	compatibility and reliability of production (see Section 2.2.2)
	Deposition holes shall not be emplaced along tunnel sections where grouting or other measures to control inflow are applied, if these measures may even locally impair the backfill performance above the deposition hole.	compatibility and reliability of production (see Section 2.2.2)
	Tunnel sections with grouting holes outside the tunnel perimeter shall not be used for deposition holes, if the holes may create a connection to a critical volume of class CV1, CV2 or CV3.	compatibility and reliability of production (see Section 2.2.2)

Justification

Bringing ventilation air, technical equipment, material and people into the final repository facility as well as the excavation of the underground openings and the engineered materials used for rock reinforcement and grouting may impair the safety functions of the rock, see Section 2.2.2.

The compositions, amounts and locations of the engineered and residual materials have to be accepted considering their impact on the favourable chemical conditions in the repository. The pH of the groundwater in the host rock shall be less than 11 for the buffer to fulfil its performance requirements, see Section 8.2.4. The main source of increased pH is grouting, therefore the pH of the leachates shall be limited and not increase the pH of water in contact with the buffer or backfill

to values higher than 11. In practice, this is controlled by using low-pH cements with low Ca:Si ratios or non-cementitious grouts. Currently, there are no quantitative technical design requirements for other materials or characteristics. The composition and amount of these materials as well as locations, where these materials are used, shall be documented. The so far estimated compositions, amounts and locations have been concluded to be acceptable with respect to post-closure safety.

The deposition holes shall not be grouted. By grouting, the hydraulic properties of the host rock and fractures can be enhanced locally and temporarily e.g. to limit inflows. However, as the grout degrades with time, grouted fractures can become of importance as flow routes and enhance the flows around the deposition holes and thereby challenge the safety function of host rock to provide favourable hydrogeological conditions in the long term. Further, the interaction of the grout and its degradation products with the buffer may impair the characteristics of the buffer. In some cases, even if the deposition hole itself is not grouted, signs of grout may be observed in fractures intersecting the deposition hole. Such observations are used as input for assessing the importance of the facture as a hydraulic connection and considered in the classification of the structure.

Deposition tunnels can be intersected by structures that are acceptable in terms of long-term behaviour of the repository, but provide an inflow that needs to be limited in order to allow the installation of the backfill. For this reason, some sections of the deposition tunnels may need to be grouted. Further water handling measures, e.g. use of geotextiles, may need to be applied, if grouting is not efficient. Such methods are currently being developed and they can have local effects on the performance of the backfill. These effects and the potential impacts on the buffer performance in the long term need to be evaluated. Deposition holes shall not be emplaced along sections of the tunnel where grouting or other water handling measures are applied, if these measures may impair the backfill performance e.g. by reducing the density of the installed buffer so that it cannot maintain its safety functions above the deposition hole. Further, no deposition holes shall be emplaced on a tunnel section with grouting holes outside the tunnel perimeter. Such holes, once the grout is degraded, may provide a good connection between the deposition hole and a structure that is not allowed to intersect the deposition hole or cause loss of backfill mass above the deposition hole and thereby affect the performance of the backfill and buffer as well.

Implications for verification and design

The use of engineered materials and amounts of residual materials shall in general be limited and their compositions, amounts and locations documented. This is in general praxis in modern tunnelling contracts. The impact of the engineered materials used e.g for sealing on the post-closure safety shall be assessed prior to their use. If the compositions, amounts and locations prior to use have been shown not to be harmful for the post-closure safety they can be allowed. The compositions, amounts and locations documented for the most recently performed post-closure safety assessment will thus be a basis for checking the planned use.

Monitoring of the impacts of the use of the residual materials shall be carried out during the construction and operation according to a specific plan.

9 Conclusions and recommendations

9.1 Conclusions

The report shows that, in spite of differences between Finland and Sweden e.g. in national regulations, nuclear power programmes and sites, it is possible to harmonize the requirements for the design of a KBS-3 repository. Within the report, safety functions, performance targets and technical design requirements for a KBS-3V repository are stated based on internationally established post-closure safety principles and independently of the country in which the repository is constructed.

The common Posiva-SKB objective of this report presented in Section 1.3 is to:

- state the technical design requirements that the as-built KBS-3 repository shall fulfil,
- present their underlying safety functions and their related performance targets.

These objectives have been achieved, however, in some cases quantitative technical design requirements cannot yet be sated. Further, the project has helped greatly in clarifying different kinds of requirements and how they are addressed within the post-closure safety assessment and in the development of a robust design.

The stated safety functions, performance targets and technical design requirements can form the basis for the development of common designs and the development of common production systems in line with the shared vision for the cooperation between Posiva and SKB.

The remaining differences in performance targets and technical design requirements can be explained in terms of differences in sites, characteristics of the spent fuel or regulatory requirements. Recognizing and explaining such differences will facilitate cooperation between Posiva and SKB, and communication with their respective stakeholders.

For the engineered barriers and for the host rock, performance targets of relevance for assessments of post-closure safety have been stated, as well as technical design requirements for the development of a KBS-3 repository design. There are a few technical design requirements that remain open. They depend on and require results from ongoing research, development and demonstration work, and are further discussed in the relevant sections of the report.

The fulfilment of performance targets will be analysed within the post-closure safety assessment, and will, due to national differences, be done separately by Posiva and SKB. However, the approach to verification of the technical design requirements and determination that the as-built repository conforms to them can be worked out jointly. This report includes references to common projects where the design's conformity to the technical design requirements has been verified. The development of detailed design specifications based on the verified design, as well as of strategies and methods for their verification during the production and operation of the repository will be the objective for future projects.

9.2 Recommendations

Even though Posiva's and SKB's post-close safety assessments will have differences, the long-term performance targets should be harmonised insofar as possible. They express criteria through which the safety functions of a KBS-3 repository, and thus its safety can be quantitatively evaluated. They should be largely applicable for any KBS-3 repository.

For a given KBS-3 design, as for the KBS-3V design presented in this report, it is also possible to derive common technical design requirements. There are several benefits in jointly developing and verifying the requirements. It will open possibilities for the allocation of more resources, both, human, technical and economic, for the remaining research, development and demonstrations required to develop design specifications and to qualify their production systems for industrial operation. A production system that delivers components and repository parts in conformity to specifications is fundamental for the post-closure safety of a KBS-3 repository.

Thus, it is recommended to continue to develop technical design requirements jointly and that the results from this report shall be used as a basis for this development.

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A CO-OPERATION REPORT BETWEEN SVENSK KÄRNBRÄNSLEHANTERING AB AND POSIVA OY

SKB's and Posiva's programmes both aim at the disposal of spent nuclear fuel based on the KBS-3 concept. Formal cooperation between the companies has been in effect since 2001. In 2014 the companies agreed on extended cooperation where SKB and Posiva share the vision "Operating optimised facilities in 2030". To further enhance the cooperation, Posiva and SKB started a series of joint reports in 2016, which includes this report.