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Preface

This consolidated review report (CRR) is a summary compilation of the findings of Radiation and Nuclear Safety Authority's (STUK) expert reviewers in the area of engineered barrier system (EBS) to support STUK's evaluation of Posiva Oy's (Posiva) Construction License Application (CLA) for the planned spent nuclear fuel repository at Olkiluoto.

The Core Review Team was Michael Apted (safety assessment, near-field chemistry, spent fuel; INTERA Inc.), Randy Arthur (buffer, backfill, near-field chemistry, radiochemistry; INTERA Inc.), Tara Beattie (spent fuel, near-field chemistry; MCM International), Steven Benbow (buffer saturation, buffer erosion, coupled processes; Quintessa Ltd.), David Bennett (backfill, buffer, coupled processes, emplacement; TerraSalus Ltd.), Alex Bond (buffer saturation, buffer erosion, coupled processes; Quintessa Ltd.), Richard Metcalfe (buffer saturation, buffer erosion, coupled processes; Quintessa Ltd.), David Savage (buffer stability, near-field chemistry, coupled processes; Savage Earth Associates Ltd.), Göran Sällfors (buffer saturation, buffer erosion, coupled processes; GeoForce AB), Peter Segle (copper canister and insert failure modes; Inspecta) and James Wilson (buffer saturation, buffer erosion, coupled processes; Quintessa Ltd.).

This review and evaluation has assessed the suite of documentation provided by Posiva in support of its TURVA Post-Closure Safety Case, which is a major component of its CLA, submitted in 2012. Each reviewer in the Core Group has assessed the documentation relevant to their own area of expertise, with considerable overlap between the reviewers. Reviewers compiled their own comments and findings in an identical template, developed by STUK.

This report consolidates and summarizes the separate template reports. In the process, material has been significantly condensed and edited to provide a more readable CRR. In support of preparation of this CRR on the EBS, a workshop attended by STUK's external experts was held in May 2014. Discussions between the Core Review Team members in May 2014 allowed identification of the key issues arising, enabled common positions to be reached and facilitated the subsequent consolidation of comments and conclusions. The consolidation was carried out by Dr. Michael Apted, Key Consultant for the Engineered Barrier System and the resulting report was approved by the other members of the Core Review Team. It thus represents a consensus view of the Core Review Team.

The views expressed in this report are those of the consultants only.
The STUK staff plans to develop its own review report.

APTED Michael [INTERA Inc] (toim.). Arvio teknisten vapautumisesteiden osuudesta Posivan rakentamislupahakemuksessa käytetyn polttoaineen loppusijoituslaitokselle Olkiluotoon. STUK-TR 18. Helsinki 2015. 34 s.

Asiasanat: radioaktiivinen jäte, käytetyn ydinpolttoaineen loppusijoitus, KBS-3-konsepti, tekniset vapautumisesteet, kapseli, puskuri, tunnelitäyte, bentoniitti, turvallisuustoiminto, toimintakykytavoite, EBS

Tiivistelmä

Tämä raportti on tiivistetty yhteenveto Säteilyturvakeskuksen (STUK) käyttämien ulkopuolisten asiantuntijoiden tekemistä arviointihavainnoista Posiva Oy:n (Posiva) rakentamislupahakemuksen tarkastuksessa teknisiin vapautumisesteisiin (engineered barrier system, EBS) liittyen.

Arviointiryhmään kuuluivat Michael Apted (turvallisuuden arviointi, lähialueen kemia, käytetty ydinpolttoaine; INTERA Inc.), Randy Arthur (puskuri, tunnelin täyttö, lähialueen kemia, radiokemia; INTERA Inc.), Tara Beattie (käytetty ydinpolttoaine, lähialueen kemia; MCM International), Steven Benbow (puskurin saturaatio, puskurin eroosio, kytketyt prosessit; Quintessa Ltd.), David Bennett (tunnelin täyttö, puskuri, kytketyt prosessit, asennus; TerraSalus Ltd.), Alex Bond (puskurin saturaatio, puskurin eroosio, kytketyt prosessit; Quintessa Ltd.), Richard Metcalfe (puskurin saturaatio, puskurin eroosio, kytketyt prosessit; Quintessa Ltd.), David Savage (puskurin stabiilisuus, lähialueen kemia, kytketyt prosessit; Savage Earth Associates Ltd.), Göran Sällfors (puskurin saturaatio, puskurin eroosio, kytketyt prosessit; GeoForce AB), Peter Segle (kuparikapselin ja valurautaisen sisäosan vikaantumistapahtumat; Inspecta) ja James Wilson (puskurin saturaatio, puskurin eroosio, kytketyt prosessit; Quintessa Ltd.).

Tässä arvioinnissa on käsitelty Posivan TURVA-raporttikokonaisuutta (pitkäaikaisturvallisuusperustelu), joka on vuonna 2012 toimitetun rakentamislupahakemuksen teknisen aineiston keskeinen osakokonaisuus. Jokainen arviointiryhmän jäsen on arvioinut aineistoja omalta asiantuntemusalueeltaan ja koonnut havaintonsa ja kommenttinsa STUKin valmistelemaan arviointipohjaan.

Tämä tiivistetty raportti kokoaa yhteen näkemykset asiantuntijoiden arviointiraporteista. Yhteenvetoraportin valmistelussa alkuperäisiä tekstejä on tiivistetty ja editoitu, jotta raportista on saatu luettava kokonaisuus. Toukokuussa 2014 järjestettiin työpaja, jossa olivat mukana keskeiset arviointityöhön osallistuneet asiantuntijat. Työpaja mahdollisti keskustelut arvioinnin keskeisimmistä havainnoista ja yhteisistä mielipiteistä sekä helpotti raportin jatkomuokkausta. Tämän raportin on koonnut EBS-avainkonsultti Dr. Michael Apted. Kaikki arvioinnissa mukana olleet henkilöt ovat hyväksyneet tiivistetyn raportin, joten se edustaa arviointiryhmän yhteistä näkemystä.

Tässä raportissa esitetyt näkemykset ovat STUKin ulkopuolisten asiantuntijoiden näkemyksiä. STUK julkaisee oman tarkastusraportin aiheesta, jossa esitellään STUKin näkemys asiaan.

Summary of key findings

The Finnish Radiation and Nuclear Safety Authority (STUK) has commissioned a series of review reports by external technical experts on Posiva's construction license application (CLA) related to the KBS-3 engineered barrier system (EBS) for disposal of spent fuel at Olkiluoto. These review reports, integrated and summarized in this Consolidation Review Report (CRR), are based on examining numerous Posiva reports. The individual review reports provide a thorough, competent and independent assessment of topics and issues to supplement STUK's own CLA review. Specific review topics included the copper canister, the cast iron insert, the encompassing bentonite-based buffer, the clay-based backfilling of access tunnels, and the spent fuel, although no integrated EBS assessment was conducted nor were all technical aspects of EBS performance and safety reviewed. This CRR represents an abstraction and summary of the major observations, concerns and recommendations made in these individual review reports.

The basic post-closure safety assessment structure and methodology that Posiva reports in its CLA documents are of high quality, and many of the assessment codes are among state-of-the-art options. Decisions on the selection of assumptions, models and data are generally adequately reported, although reviewers identified specific omissions and preferences for alternatives. These issues ought to be incorporated into STUK's oversight and review of future safety assessments by Posiva.

The general consensus of this CRR is that Posiva's CLA reports provide a suitable, preliminary basis for understanding the role and Safety Functions of the EBS within Posiva's TURVA-2012 safety case. CLA documents present a good description of Posiva's methodology for modeling and assessing the long-term containment and isolation performance of their EBS. The informed judgment of this CRR is based on current data, models and assumptions cited in Posiva reports, as well as other studies on the KBS-3 concept in Sweden and additional studies on EBS and spent-fuel disposal concepts worldwide. Based on this information, long-term safe isolation of spent fuel likely can be achieved by the proposed KBS-3 concept, if Posiva can build the EBS as defined in the CLA documentation. Now, the paramount task for Posiva is to show that they can build and emplace their EBS as intended.

The joint EBS reviews did not find any safety concern/issue that, in the collective judgment of the external reviewers, would prevent STUK to submit an affirmative statement of safety to the government. If a CLA is approved by the Finnish government early in 2015, there are, however, several technical topics and questions raised by external reviewers that are identified in this CRR. Such CRR issues will be reviewed, organized, prioritized, and documented by STUK into at least three categories with respect to a post-CLA/ pre-operating license application (OLA):

- Requirements on issues to be addressed before EBS component fabrication or underground construction in the disposal rock volume should begin;
- Requirements on safety issues to be achieved before a future OLA;
- Topics requiring commitments to longer-term (through and post-OLA) RD&D efforts, assuming a future operating license was to be granted.

It is reiterated, however, that the individual experts contributing to this CRR had limited opportunity to develop a system-level, integrated review of the EBS. Posiva's responses to key RAIs, such as on delayed buffer/ backfill saturation, came after the final joint May 2014 workshop of EBS experts. Furthermore, no total-system performance assessment was conducted to explore and verify the safety-significance of specific concerns and credible alternative EBS models. Certainly Posiva's own analyses, for example as documented in Posiva 2012-12 and Posiva WR 2013-25, compelling indicate that the EBS is the primary sub-system of the KBS-3 repository concept that assures post-closure safety. Of course the successful containment and isolation performance of the EBS relies on the favorable environmental, or 'service', conditions imposed by the Olkiluoto site.

Because of the primacy of the EBS in safety importance, the issues and concerns cited below are particularly noteworthy. Assuming Posiva's CLA is approved, several specific recommendations are made based on this EBS review:

- The most important, near-term priority for Posiva is early demonstration of its ability to reproducibly fabricate, transport and emplace its engineered barrier system at their intended 'initial state' in underground conditions. The necessity for such demonstration by Posiva prior to a future operational license application (OLA) is based on two concerns; (1) if Posiva finds impediments to building the EBS as designed and with designated performance targets, then Posiva without delay would need to explore possible modifications and adaptations to overcome such impediments, and (2) if Posiva still finds it cannot build the EBS as designed, it seems sensible that further extensive underground exploration, excavation and development of rock suitability criteria would need to be postponed until Posiva devised a different, viable EBS disposal concept, established that this new concept would also provide adequate post-closure safety, and demonstrated that is new concept could be built as intended (basically conduct and submit an amended CLA).
- Posiva should make greater use of its safety assessments as a defensible basis to identify, guide, and prioritize technical studies for future general RD&D, and EBS RD&D specifically.
- As a key part of future safety assessments, Posiva ought to apply the same sensitivity analysis methods as illustrated in Posiva WR 2013-25 to a wider range of scenarios and parameters within scenario variants. This will enable Posiva to evaluate and achieve a fuller understanding of the safety importance of Safety Functions, and establish a more rational basis for focusing future RD&D, and post-CLA adaptation/ optimization of their KBS-3 design.
- At this CLA stage, Posiva's Safety Functions are predominately qualitative, possibly to provide Posiva with flexibility and latitude to explore in the future exactly how different design factors and processes might combine or be adapted to contribute to safety. It is expected that underground demonstrations, combined with more detailed sensitivity analyses, will enable Posiva to evolve more quantitative expressions of specific Safety Functions.
- Posiva CLA documents argue for ready substitution of different montmorillonite-bearing "bentonites" if future circumstances dictate. While recognizing that it is sensible to make such contingency plans, any new buffer or backfill material will require substantial testing and modeling to qualify its use as a substitute for the reference MX-80 bentonite.

- The ‘pinhole’ Reference Case derives significant post-closure safety arising from unknown and uncertain properties of a hypothetical ’defect’ (e.g., an unintentional flaw from a electron-beam welding error in the as-emplaced KBS-3 concept) and an extremely pessimistic assumptions regarding rapid corrosion rate of the zircaloy cladding releasing C-14 formed as an activation product. This seems an anomalous and potentially misleading Reference Case on which to establish post-closure safety. The reported change by Posiva from electron beam welding (EBW) to friction stir welding (FSW) further undercuts justification for carrying this hypothetical scenario forward as a Reference Case.
- The earthquake-shear scenario benefited greatly from STUK’s joint site-EBS team evaluating the magnitude, location, timing, and consequences on engineered barriers for different shear displacements during a May 2014 workshop. This earthquake scenario will likely continue to receive updated safety analyses through the entire repository construction and operational period, and should be guided with appropriate experts from both site and EBS disciplines.
- With respect to analysis of alternative, credible scenarios, analysis beyond the ‘pinhole’ scenario would provide Posiva and STUK increased understanding and confidence in the specific roles and impacts of different barrier Safety Functions. Such an expanded set of scenarios would provide meaningful sensitivity analyses of Safety Functions, and might include (a) improper emplacement of waste packages, (b) delayed buffer saturation for many 1000’s of years, (c) potential creep ductility failure of copper canister, (d) consideration of where the failure occurs and hence where the corrosion of the insert occurs, and (e) anaerobic corrosion of the cast iron insert impacting post-containment radionuclide releases.

All repository programs are confronted with the need to evolve and adapt, to overcome the inertia of continuing to do the same activity tomorrow as it did yesterday. It has been necessary to focus on site characterization and siting issues in the lead-up to the Construction License Application. If a construction license is granted, it the strong recommendation of this CRR that Posiva institute a revised and expanded set of priorities to address its relative lack of progress in demonstrating competence and confidence in constructing the EBS as asserted in the CLA documentation. Posiva’s top priority in the period between being possibly granted a CLA and submitting an operational license application (OLA) has be an immediate and focused demonstration of the feasibility of constructing the EBS as set forth in the CLA and confirming its intended performance.

Contents

List of acronyms

AIC	Accelerated insert corrosion scenario and variant cases
BS-RC	Base Scenario, Reference Case
BWR	Boiling water reactor
CLA	Construction License Application
CRR	Consolidated Review Report
DFN	Discrete fracture network, regarding models for hydrological flow
EBS	Engineered barrier system
EBW	Electron beam welding
EDZ	Excavation Damage Zone
Eh	Oxidation potential, affecting the oxidation state of dissolved species in water
EPR	European pressurized reactor
FEP	Features, events and processes
FSW	Friction stir welding
IRF	Instantaneous release fraction of radionuclides in spent fuel
KBS	An abbreviation of Swedish ‘kärnbränslesäkerhet’, thus ‘nuclear fuel safety’
KBS-3	A specific geological repository concept for disposal of spent fuel
MX-80	A type of bentonite (with high smectite content) from Wyoming, USA
NDE	Non-destructive evaluation
PA	Performance assessment
OLA	Operational License Application
pdf	Probability density function
pH	Negative, base-10 logarithm of the hydrogen-ion activity in water
PSA	Probabilistic sensitivity analysis
PWR	Pressurized water reactor
RAI	Request for additional information
RSC	Rock suitability criteria (criteria for assessing suitability of a deposition hole)
RD&D	Research, development and demonstration
SA	Safety Assessment
SKB	Swedish Nuclear Fuel and Waste Management Company
STUK	Finnish Radiation and Nuclear Safety Authority
THMC	Thermal, hydrogeological, mechanical, chemical processes (often coupled)
VAHA	Posiva’s requirement management system
VVER-440	Voda Voda Energo Reactor-440
WR	Working Report

1 Introduction

The Finnish Radiation and Nuclear Safety Authority (STUK) has conducted a review of the construction license application (CLA) submitted by Posiva Oy in December 2012 for a deep repository for the disposal of spent nuclear fuel at Olkiluoto. As part of this CLA review, STUK has commissioned various technical reviews from international and domestic experts to aid in assuring that a thorough and competent assessment would supplement STUK's own internal review. These external technical reviews focused on the various components of the engineered barrier system (EBS) of Posiva's proposed KBS-3 design concept (Figure 1), most notably the copper canister, the cast iron insert, the encompassing bentonite-based buffer, the clay-based backfilling of access tunnels, and the spent fuel.

STUK provided a list of key Posiva reports (particularly Posiva 2012-04, Posiva 2012-07, Posiva 2012-08, Posiva 2012-09, Posiva 2012-12, and Posiva 2013-01), as supplemented by technical experts independently and prudently pursuing additional key references and Working Reports (e.g., Posiva WR 2013-25 and Posiva WR 2012-96), for the CLA for review. STUK also presented templates with 'guidance questions' regarding specific aspects of STUK regulatory guidelines for consideration by these independent reviews (see following sections).

To provide a suitable and sensible context for the reader, a short summary of the nature of STUK's 'guidance questions' are summarized at the beginning of each review section. It is important to stress that STUK's 'guidance questions' common format allowed for subsequent collection and straightforward integration into this Consolidated Review Report (CRR) on the EBS. This CRR, compiled by Dr. Apted, is a collection and abstraction of the many detailed technical observations made by the individual authors who are noted as contributors to this report.

In support of preparation of this CRR on the EBS, a workshop attended by STUK's external experts was held in May 2014. This workshop allowed discussions among the EBS experts on related technical topics and harmonizing common viewpoints. It also permitted useful discussion with external experts from site and PA areas on issues that 'cross-cut' among these three areas, such as the earthquake-shear scenario, saturation of the buffer

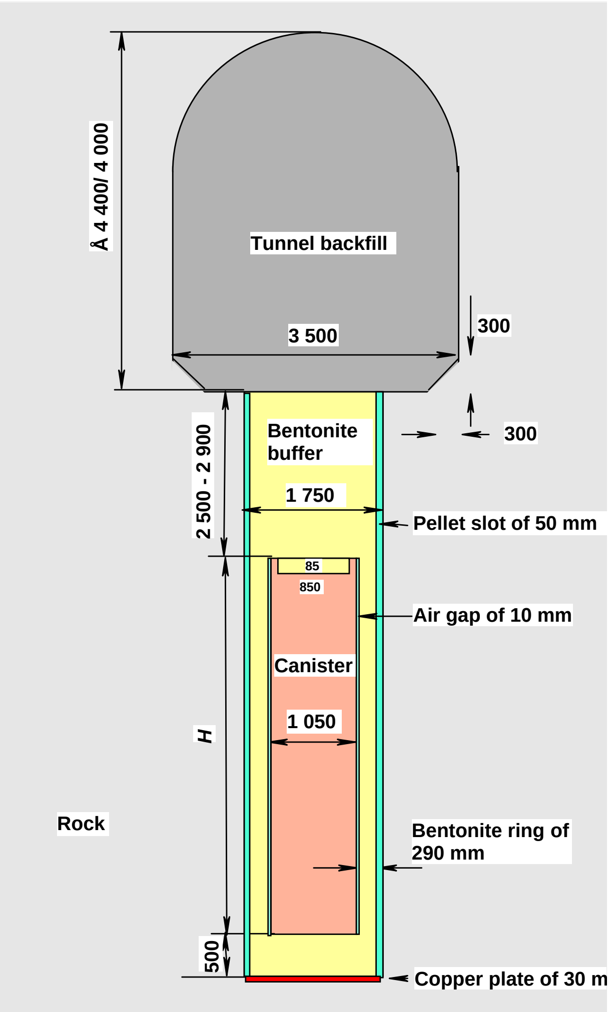

Figure 1. Nominal dimensions of Posiva's EBS canister, deposition hole and tunnel. For the BWR fuel type, height (H) = 4752 mm, for VVER type H = 3552 mm and for PWR fuel type H = 5223 mm (Figure 6-51, Posiva 2013-01).

and backfill, potential onset of future conditions necessarily for 'chemical erosion' of buffer, and the general concern over the lack of demonstration that the EBS can be emplaced with intended and necessary 'initial state/ performance target' properties.

The entire CLA review process was somewhat handicapped by the extended length over which key Posiva technical reports were published for review; for example, the vital "Models and Data" (Posiva 2013-01) and Buffer Design (Juvankoski, 2012) reports were published in 2013, a full year after the nominal beginning of the CLA review. Analysis of some key EBS issues was also impacted by the timing in the Request for Additional Information (RAI) process between STUK and Posiva; for example, a set of technical RAI responses from Posiva on the topic of potential effects of delayed saturation of buffer and backfill were only received after the May 2014 workshop of EBS experts, thus there was no opportunity for a joint, integrated review of this response by the STUK's team of EBS experts. Certainly Posiva's affirmative response to STUK's RAI on this topic indicates that Posiva is now well aware of the topic and seems to be appropriately configuring its R&D efforts with the aim to resolve the issue.

The basic thrust of STUK's 'guidance questions' for the independent reviews was to judge the adequacy, credibility and confidence regarding aspects related to the long-term containment and isolation of radionuclides present in spent fuel within the EBS. Posiva's assigned safety functions (with their performance targets), initial states of as-emplaced barriers, behavior and possible degradation of barrier properties and safety functions over the evolving near-field environmental conditions, and eventual release and migration ("source term") of radionuclides from the EBS were all part of the review topics considered.

Of key concern were possible future conditions that might alter and perturb the performance and safety of the EBS of the KBS-3 repository. This included development of high pH conditions from degradation of cementitious materials, piping erosion of buffer and backfill during the emplacement period, impacts from delayed saturation of the buffer for many 1000's of years, possible shearing of the EBS from future seismic events, and impacts arising from glacial loading and unloading in the far future. While not explicitly considered a "barrier" by Posiva, the performance of spent fuel, especially slow dissolution rate of the UO2 matrix, was also evaluated with respect to such perturbations.

The review reports by the individual technical experts represent state-of-the-art, 'bottom-up' assessments of Posiva CLA documents relevant to the EBS. These reports were at times supplemented by reviews of parallel, topic-specific reports by the Swedish Nuclear Fuel and Waste Management Company (SKB), Stockholm, Sweden. SKB has also recently submitted their own CLA to Swedish regulatory authorities and government agencies for a KBS-3 disposal concept quite similar to that by Posiva, and often Posiva and SKB have shared resources, research and made joint publications on common technical topics.

There was limited opportunity, however, for STUK's external EBS experts to convene and participate in a joint, integrated analysis of EBS performance as a "multi-barrier system". Supplementary, credible scenarios were identified for which Posiva has developed only incipient analyses. In particular based on the initial external reviews, Posiva provided responses to a Request for Additional Information (RAI) on uncertainties associated with delayed saturation of the buffer for many 1000's of years. Such a prolonged delay in saturation needed to fulfill safety functions of the buffer raised numerous concerns, such as coupled thermal–hydrological–mechanical–chemical (THMC) impacts and possibly heterogeneous saturation. Posiva's response to the RAI indicates that Posiva both understands and is conducting further studies to provide confidence regarding their assessment of potential impacts of such delayed saturation.

In addition, there was only limited opportunity for the external EBS experts to conduct a fuller review of possible crosscutting issues arising between the host-rock site and the EBS. Joint collaboration between external site and EBS experts on the "earthquake scenario" and discrete fracture network (DFN) modeling proved especially useful, and it is strongly recommended that such collaborative reviews on crosscutting issues be continued in the future.

Finally, it is noted that it has not yet been possible to evaluate the many individual observations and issues by the several reviewers within a system-level safety assessment to determine the safety-significance of such concerns. The impact of alternative conceptual and mathematical models for processes can only be evaluated by independent assessments of such alternatives, which was beyond the scope of the individual reviews by external EBS experts. Furthermore, Posiva's own safety assessments (e.g., Posiva 2012-12) presented sensitivity analyses as to safety-significant aspects for only a narrow set of scenarios related to a hypothetical initial "pinhole" in the copper canister. It is evident from these limited sensitivity analyses that assumptions about one property or aspect of the EBS can mask the "latent" safety contributions of other barrier safety functions. Going forward, joint STUK-Posiva exploration and testing of safety-significance of key processes and properties ought to become a focus for guiding RD&D priorities, adaptation of design, and increasing confidence in post-closure safety.

2 Multibarrier system description/ Design basis of EBS

2.1 Safety functions and performance targets of the barriers

STUK's 'guidance questions' focused on the degree and adequacy by Posiva identification and definition of safety functions and performance targets for the EBS. Questions also focused on whether all experimental information dealing with the EBS safety functions/ performance targets had been clearly summarized, particularly in the 2103 "Models and Data" report (Posiva 2013-01).

2.1.1 Description of safety functions

Government Decree 736/2008 states "Safety functions mean factors preventing and limiting the releases and migration of disposed radioactive materials." Several reports describe Posiva's approach to Safety Functions. For example Posiva 2012-12 "Synthesis 2012" identifies Posiva's safety function and performance target approach as set forth in the section "The TURVA-2012 safety case". Details of safety functions are referred to in Posiva's VAHA requirements management system. Table 2-1 in this Synthesis report outlines and summarizes safety functions, while tables in Appendix 2 also address safety functions within the context of legal and regulatory requirements. Likewise, in Posiva 2013-01 "Models and Data" report (Sections 1.5, 1.6 and 3.2, as well as Table 1-1) specific Safety Functions. Posiva's VAHA requirements-management system is further cited as the source for the linkages between Safety Functions and eventual, detailed Design Specifications. Maintaining flexibility in development and application of safety functions seems to be guiding Posiva at this stage. Posiva 2012-12 (page 45) for example states about safety functions,

> *"these will be updated as scientific understanding is further developed, taking into account the results of the performance assessment and assessment of radionuclide release scenarios of the current safety case".*

For the TURVA-2012 safety case, the safety functions for each of the EBS barriers are presented in several reports (e.g., Posiva 2012-12 Synthesis report), although the vagueness of the definitions of each of the safety functions renders them of limited value when trying to link these 'safety functions' to possible specific changes in barrier properties. There is an overall absence of explanation of the methodology and radiological basis for the specification of Safety Functions, which are only qualitatively described. It is not clear if Posiva intended that individual Safety Functions be derived from the detailed FEP (features, events and process), or how the ensemble of Safety Functions are envisioned to work together in a unified or integrated manner to assure safety. Clearly, extended containment by the copper canister is anticipated by Posiva to be a principal safety objective of the KBS-3 concept. The longevity of the copper canister, however, relies on the ability of the buffer to provide protection for the canister, whose performance can in turn depend on the backfill and tunnel plugs. It is not clear in detail how these interdependencies have been considered in deriving the individual Safety Functions.

A lesser concern is that no specific Safety Function is assigned to spent nuclear fuel because it cannot be 'engineered'. Incongruously, however, the 'site/ host rock/ hydrology' also cannot be 'engineered', yet Safety Functions are assigned for these parts of the repository system of barriers.

Furthermore, sensitivity analyses by Posiva show that a basic property of spent fuel, the measured low dissolution rate of UO_2 matrix, provides one of the most significant contributions to safety in the KBS-3 system (Posiva 2012-12). This is consistent with other internationally developed safety cases for disposal of spent nuclear fuel where the long-term, slow dissolution rate is considered a key part of the basis for geological disposal (e.g., SKB, 2006). "Slow release from the spent fuel matrix" has long been recognized by Posiva as one of its key pillars of safety [Figure 2].

The dissolution rate of UO_2 is a basic, measurable property of a component that always will be present in any direct disposal system (unlike, for example, the assumed properties of a hypothetical undetected 'pinhole' in the weld of a copper canister). It may be merely a matter of semantics, but neither Posiva nor STUK should lose sight of the importance of processes and barriers that may have no assigned Safety Functions, but nonetheless are highly significant contributors to post-closure safety.

Conclusion: At this stage, Posiva's Safety Functions are predominately qualitative, possibly to provide Posiva with flexibility and latitude to explore in the future exactly how different design factors and processes might combine to contribute to safety. The quantitative performance indicators (criteria) specified for particular safety functions are presented in a decoupled way and does not present upfront the margins of safety provided by each barrier, nor their significance in terms of contributions to safety. Although a few more detailed, quantitative targets are provided for some of the barriers in Posiva's VAHA requirement management system, Posiva will need to progressively and expeditiously evolve its VAHA system to the point that specific aspects and properties of barrier Safety Functions can be stated in sufficient detail to guide construction. The most important, near-term priority for Posiva needs to be early demonstration of its ability to reproducibly emplace its engineered barrier system at their intended 'initial state' in underground conditions.

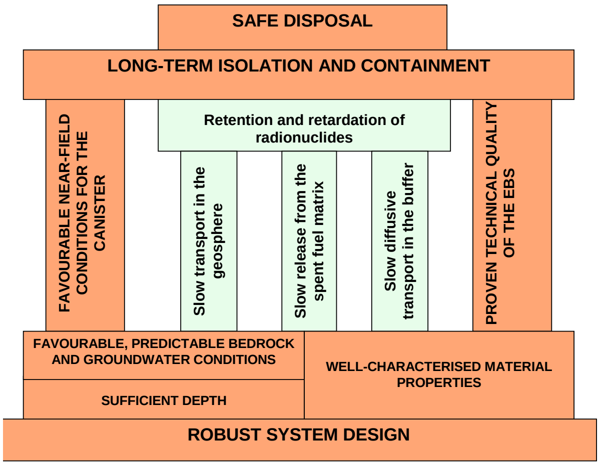

Figure 2. Figure 2.3 from Posiva 2012-12, showing Posiva's outline of its pillars of safety, including "slow release from the spent fuel matrix".

2.1.2 Meeting performance targets

'Performance target' means a measurable or assessable characteristic of a barrier. STUK regulation YVL D.5 requires that a performance target shall include a criterion describing the characteristic that, when met, ensures the performance of a safety function. Operations related to such demonstration and confirmation include the mode of barrier fabrication, materials handling and transport, barrier emplacement methods, and quality assurance of as-emplaced barriers. Demonstration and refinement of such operations are key reasons for moving in a stepwise manner to underground emplacement demonstrations, from which operational modifications and adaptation to assure attainment of 'performance targets' can be achieved.

One top-level issue that has received little attention is demonstrations of proper emplacement techniques to show and assure that suitable methods and management procedures have been developed and can be deployed in underground operations. One key example is the effect of groundwater inflow on the tunnel backfill, and to some extent also on the buffer, before their installation is completed. The presence and possible inflow of water might cause swelling and erosion of the clay materials beyond what is acceptable and lead to reduced density (e.g., through piping/mechanical erosion). This might be a problem, especially for the backfill at the somewhat irregular tunnel floor. It might be difficult to stack the compacted bentonite blocks as planned resulting in larger gaps and, thus, also a lower density. Potential piping during installation and sealing of emplacement drifts is a related issue requiring confirmation of 'constructability' of the intended disposal concept.

As compared to the natural barrier system, demonstration of the ability to achieve the performance targets for the engineered barrier system is the one part of Posiva's overall disposal concept that is fully under its control. Furthermore, because of this ability to control the EBS, Posiva should focus on reducing current uncertainties in Safety Functions (beyond those defined as performance-target criteria) for engineered barriers during the multi-decade repository operations.

Conclusion: Because so little has been tested and confirmed by Posiva regarding 'constructability' of the engineered barrier system at the time of the CLA, the only defensible conclusion is that demonstrations of emplacement of the EBS and other engineered barriers ought to be moved to the forefront of Posiva's planned RD&D program. In particular, confirmation that specific performance target properties of as-emplaced engineered barriers can be met in underground operations needs to be addressed by Posiva in the period between a construction license and an operational license. This is because other RD&D activities (e.g., on hydrogeology or safety assessment methods) would be inconsequential if the as-emplaced properties of Posiva's KBS-3 engineered barriers cannot be demonstrated with confidence to meet their initial states and performance targets.

2.1.3 Fabrication and quality assurance of as-emplaced barriers

Key aspects of demonstrating conformance with safety functions and performance targets include consideration of the methods of fabrication of barriers, non-destructive examination (NDE) of as-fabricated barriers, and the eventual quality assurance methods for as-emplaced barriers. At the time of the CLA, Posiva is making progress on all of these areas, but considerably greater progress and confirmation of these techniques and methods will be a pre-requisite for moving toward an operational license.

Reviewers raised concerns about the fabrication, storage and stability of buffer and backfill rings and blocks, especially under underground conditions. There have been few site-specific, underground tests or demonstrations of emplacing these barriers, hence there are remaining concerns that barrier emplacement can be achieved as envisioned by Posiva.

Posiva's recent decision to select friction-stir welding (FSW) over electron beam welding (EBW)[1] needs to be more fully propagated through Posiva's plans for assessing canister integrity and implications for long-term containment safety functions. Posiva also needs to show how they plan to improve the manufacturing process for EPR/PWR and VVER-440 inserts in order to achieve similar material properties as that for the BWR insert. Furthermore, Posiva should test the EPR/PWR and VVER-440 inserts in the axial direction. Posiva will also need to promptly show how they plan to qualify their NDE-systems used for the welds of canisters, canister copper components and cast iron inserts.

Conclusion: Posiva has achieved only modest progress at this stage in demonstrating and confirming successful fabrication, handling and emplacement of the envisioned KBS-3 engineered barrier system under realistic disposal conditions. This is a significant vulnerability to Posiva's program that should compel Posiva to move expeditiously toward underground demonstrations of EBS emplacement in recognition that this activity probably needs to be their highest RD&D priority in the post-CLA period.

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[1] http://www.posiva.fi/en/media/press_releases/posiva_chose_friction_stir_welding_for_the_encapsulation_of_spent_nuclear_fuel.2277.news

3 Analysis of the safety concept

3.1 Safety functions and performance targets

STUK's 'guidance questions' in this area related how EBS barriers and safety function complement each other and are linked into the analysis of the overall safety concept. This included the initial containment period, the post-containment release period, as well as consideration of scenarios for credible events such as a possible future earthquake shear through the repository. Questions were also made regarding the evolution of conditions affecting safety functions, hence the performance of the EBS.

3.1.1 Complementary roles of safety functions on post-closure safety

Insights regarding Safety Functions (or factors related to Safety Functions) that can contribute to post-closure safety are cited in various places in many Posiva reports of the CLA. Two reports (Posiva 2012-12, and Posiva WR 2013-25) use probabilistic sensitivity analyses to identify which of the multiple barriers and processes significantly affect post-closure safety assessment. Posiva WR 2013-25, in particular, presents at least 4 different, independent calculation methods for assessing sensitivity. Each of these methods potentially provides an independent basis to assess the fulfilment of safety functions and performance targets for each of the engineered barriers within the context of Posiva's overall multiple-barrier concept.

Thus, Posiva's sensitivity methodology has significant promise with respect to enabling it to develop a fuller understanding of how the various engineered barriers contribute to safety and complement each other. Further utilization of this methodology would allow Posiva to better understand if, how and to what extent a deficiency of an individual safety function or a foreseeable geological change might jeopardize the post-closure safety.

However, in the CLA (Posiva 2012-12) these sensitivity analyses were only conducted for two 'pinhole' cases; a Reference Case of a single waste package with an initial small, non-growing defect-hole in the canister, and a variant case of a single defected-canister in which the initial defect grows slowly over an arbitrary period. No detailed evidence is provided by Posiva, however, to defend either the speculative 'fixed pinhole' or the 'slowly growing pinhole' cases. Posiva recognizes that subsequent anaerobic corrosion of the cast-iron insert will lead to hydrogen generation, which necessarily means that there must be formation of iron corrosion products. Such corrosion products will have much larger molar volumes than the un-corroded cast iron, so their formation might lead to widening of the initial defect. Furthermore, anaerobic corrosion of cast iron will release relatively soluble Fe^{+2}, which Posiva already acknowledges will likely interact with smectite in the buffer to transform smectite to more iron-rich clays (Wersin et al., 2007, Posiva 2007-11), and require specific consideration of gas build-up and transport. Such processes ought to be included in future revisions to any 'pinhole' calculations, unless evidence can be provided that convincingly shows such impacts are insignificant to post-closure safety.

Currently, Posiva's selection and concentration on 'pinhole' cases for sensitivity analyses is an impediment to understanding the many different barriers, processes and Safety Functions that collectively provide a robust KBS-3 safety concept. With respect to what insights are identified from sensitivity analyses of these two 'pinhole' cases, the properties of the defect itself dominate the post-closure calculations of radionuclide release. There are at least three problems with this restrictive approach. First, factors such as effective diffusion coefficient of the defect and size of the defect (0.5 mm) control calculated releases, although these are properties that Posiva cannot engineer or control in its design. Second, the properties of the defect control the calculated releases of radionuclides to the point that such sensitivity analyses do not reveal any insights into the potential safety contributions or Safety Functions of the multiple engineered (and natural) barriers of the KBS-3 concept. Third, no credible evidence is presented by Posiva to counter the possibility of expansion of any initial pinhole through formation of large volume corrosion products from anaerobic corrosion of the underlying cast-iron insert.

That so much post-closure 'safety-credit' arises from what is a 'defect' (e.g., an unintentional flaw from a welding error in the as-emplaced KBS-3 concept) seems an anomalous and potentially weak Reference Case on which to establish post-closure safety. Furthermore, such an anomalous case does not provide a basis by which Posiva can use its safety assessment results to properly prioritize and guide its own future RD&D activities on processes and Safety Functions of barriers that are actually most safety-significant.

Analysis of additional possible scenarios, beyond those of the 'pinhole', would provide increased confidence in the specific roles and impacts of different barrier Safety Functions. Such an expanded set of illustrative scenarios to provide meaningful sensitivity analyses of Safety Functions might include (a) improper emplacement of waste packages, (b) delayed buffer saturation for many 1000's of years, (c) potential creep ductility failure of copper canister, (d) consideration of where the failure occurs and hence where the corrosion of the insert occurs, and (e) anaerobic corrosion of the cast iron insert impacting post-containment radionuclide releases.

Conclusion: Posiva has used multiple sensitivity analysis methods to identify and rank the most safety-important Safety Functions. To date, however, Posiva has only applied these sensitivity analysis methods to a restricted set of cases involving an initial 'pinhole' defect in the copper canister. Unfortunately, in these analyses essentially all processes and Safety Functions are masked by the assumed properties of such a hypothetical fabrication defect in the welding of the copper canister. Future safety assessments by Posiva ought to apply the same sensitivity analysis methods to a wider range of scenarios, so that a fuller understanding of the safety importance of Safety Functions can be evaluated, and a more rational basis for focusing future RD&D by Posiva can be established.

3.1.2 Safety functions contributing to containment

Posiva's CLA documentation considers various processes that could affect containment. Potential failure of the copper canister from chemical corrosion by bisulfide (HS^-) diffusing from the host rock and the hydrological system through buffer to the copper surface is examined and analyses presented that suggest that the supply of corrodant will be sufficiently slow that the copper canister will not be penetrated fully by this form of corrosion. The corrosion analyses that are presented focus on demonstrating that the copper canister will not be fully penetrated by corrosion, but there appears to be no consideration of possible coupled mechanical effects on regions of the canister surface that are locally weakened by corrosion. Isostatic loading analyses to show adequate mechanical strength of the cast iron insert are also examined and bounded.

Posiva's chemical modeling of expected evolution of the near field, and its effects on safety functions, has certain limitations and omissions that will need to be addressed in future assessments. One major omission is that the geochemical models being employed by Posiva do not include clay mineral hydrolysis, dissolution and precipitation reactions, which are likely to control chemical conditions over the time scales of repository assessments. The potential impact of cementitious, high pH waters coming from cements used as structural and grouting materials will need continuing "real time" analysis during the construction and operational period, and there needs to be a demonstrable feedback 'loop' between operations and safety assessment. Future analyses will need to recognize important factors such as the amount and type of cement used, the degree of dilution and dispersion of high pH waters generated, and the basic thermodynamic and kinetic data used in modeling cement reactions with EBS and rock phases. Likewise, Posiva's CLA modeling of possible chemical transformation of smectite in buffer and backfill seems to focus exclusively on illitization, a process that can be dismissed for entirely credible reasons. However, Posiva has seemingly not considered the potential for zeolitization of smectite under elevated pH and thermal conditions of the near field.

Containment failure arising from potential future seismic events is another concern. Installing the buffer to within a certain density range is important for this scenario because of the potential for stiffening of the buffer after emplacement as the initial Na-rich smectite clay in the buffer evolve towards a more Ca-rich smectite. Posiva (Juvankoski, 2012) relies on tests conducted by SKB for MX-80 bentonite, as recently summarized by (Börgesson et al. 2010). This report describes the latest material model of bentonite used for analyzing a rock shear through a deposition hole. It is based on new measurements, which have yielded updated models for MX-80 and for the Ca-bentonite end-member that can be expected to be the result of ion-exchange of initial Na by Ca. Since it cannot be ruled out that there will be ion-exchange of Na by Ca and since future site groundwater may have a variation in composition, these processes must be considered. Shear tests have been performed on MX-80 both after ion-exchange to Ca and after exposure to high salt content of NaCl in the pore water (Börgesson et al. 2010, p. 13).

More work to define/confirm particularly the upper density limit for the buffer, which is determined by the shear scenario (Posiva 2012-14), will be needed. The initial state of the cast-iron inserts, including any undetected manufacturing defects, may also make waste packages more susceptible to failure during an earthquake event. More work on establishing the capabilities and adequacy of non-destructive examination (NDE) techniques by Posiva will be needed to further address this concern.

Additionally, concerns have been raised about the possible impacts on containment arising from the extremely long (100's to >10,000 years) saturation period of the buffer following emplacement that Posiva has acknowledged (Posiva 2012-04, page 221; Posiva 2012-48). The treatment of delayed saturation, the uncertainties in the evolution of near-field conditions, and potential effects of delayed saturation have only just begun to be evaluated in recent Posiva reports, which were provided in response to a Request for Additional Information (RAI) only after the final May 2014 workshop of STUK external EBS experts. Potential issues such as drying and cracking of initially 90% saturated buffer, inhomogeneous wetting fronts, and enhancing vulnerability to creep-ductility failure of copper canister seem to be possible implications arising from delayed saturation, and more studies to confirm current interpretations on these issues are clear priorities to be conducted by Posiva in the pre-OLA period.

Lastly, the current level of data, modeling and assessment of possible slow-strain rate, creep ductility and failure of copper needs further confirmation. Design countermeasures such as adding phosphorous to copper seem empirically to aid in mitigating this concern, but the long-term viability of such modification is open to debate, as are the applicability of short-term, high strain-rate test data to long-term, low strain-rate disposal conditions (e.g., Andersson et al., 2005; Petterson, 2006; Holmström, 2007; Holmström and Auerkari, 2009; Holmström et al., 2012). The concern is that creep ductility rupture could be a 'common-mode failure' process, in which many copper canisters might fail earlier than expected.

Conclusions: In the CLA documents, Posiva has focused its analysis of the potential for container failure and loss of containment on chemical corrosion and mechanical loading scenarios. Extended safety analyses to specifically examine impacts, if any, arising from delayed saturation of the buffer should be conducted. Evaluation of creep-ductility failure of copper canisters should be a key containment concern for future study, safety assessment, and possible design modifications by Posiva because of concerns regarding this process as a potential 'common-mode failure'. Therefore, Posiva will need to further develop and strengthen its models of creep-ductility for the container materials to demonstrate more clearly that creep ductility will not lead to canister failures.

3.1.3 Safety functions contributing to post-containment radionuclide release

The various Posiva CLA reports discuss and document information on processes and safety functions related to the post-containment release of radionuclides from the EBS. Dissolution/ corrosion rate of components of spent fuel (e.g., UO_2 matrix, gap/grain boundary source, cladding, instant release fraction [IRF]), solubility of radioelement-bearing secondary phases that may form, transport properties of buffer, sorption of radioelements on EBS and natural barrier materials, and other factors relating to release of radionuclides from the EBS are all presented. There are several areas that need to be considered by Posiva in extending future analyses of radionuclide releases, however.

A prominent concern is the anaerobic corrosion of the cast iron insert that will occur once the copper canister is penetrated. First, the time needed for the corrosion of the insert to allow water to reach the spent fuel needs further analysis and confirmation. In variants to the pinhole Reference Case, such as the Accelerated Insert Corrosion (AIC) case, a 1000-year time period for complete corrosion of the zircaloy is conservatively asserted, although a much longer corrosion time of 25,000 years is asserted for the cast iron insert undergoing general corrosion. Second, the structural impacts of insert corrosion should be more closely examined. There will be a significant increase in volume as iron corrosion products form from the corrosion of cast iron, and this may deform and enlarge any initial hole in the copper canister. The same swelling may act to further compact and increase the density surrounding the buffer, with uncertain implications on the mechanical properties of the buffer. As corrosion progresses, the thickness of the remaining cast iron will eventually be sufficiently reduced so that the external pressure load will cause the insert to buckle into the void spaces of the channels. Therefore, assumptions regarding the formation and persistence in maintaining an idealized circular geometry (e.g., pinholes) for radionuclide release through failed waste packages seem dubious.

Anaerobic corrosion of the insert will likely impose an extremely reducing Eh, basically pinning the near-field Eh to a value at the lower stability limit of water and generation of elevated H_2 partial pressure equal the hydrostatic pressure. Taken together, such impacts need to be considered in evaluating the validity of Posiva's claim of low UO_2 dissolution rate as one of their pillars of safety, and which sensitivity analyses in Posiva 2012-12 indicate is one of the key safety-significant features for controlling long-term radionuclide release.

Lastly, the anaerobic dissolution of cast iron would also generate soluble Fe^{2+}, as well as high H_2 pressures. Taken together, these chemical changes in the near-field environment could lead to transformation of Na/Ca-smectites into more Fe-rich clays, a concern that Posiva began to examine in their parallel RD&D program on the 'super-container' for the KBS-3 horizontal variant design (Wersin et al., 2007).

Once the insert also fails (either by anaerobic corrosion or mechanical buckling of the insert once it is sufficiently thinned by corrosion), water can contact the spent fuel. Posiva conservatively assumes no containment credit for the irradiation zircaloy cladding of spent fuel. Therefore, at the time of failure of the insert, the multiple sources of radionuclide-containing components of spent fuel can begin to dissolve/ corrode.

The IRF nuclides are conservatively modeled by Posiva to be completely released at the time of insert failure. IRF nuclides include Cs-135, I-129, and other volatile radioelements that escape from the UO_2 matrix and migrate to the relatively cooler boundary between the matrix and cladding because of the elevated temperature of reactor operations. The percentage of IRF nuclides formed will, therefore, be a function of reactor operations, and particularly burn-up. As current reactors move to ever-higher burn-up, the derived spent fuel will have higher amounts of IRF nuclides.

Because many of the IFR nuclides are highly soluble and non-sorbing, there is a corresponding "spike" in the release of IRF nuclides from the spent fuel when the insert fails. The remainder of the nuclide inventory for spent fuel is assumed to be uniformly mixed within UO_2 matrix and structural materials, and to be released congruently with the respective low dissolution and corrosion rates of these materials over time. Unfortunately the assumed hypothetical "pinhole" geometry used by Posiva in it Base case scenario effectively masks the more likely release behavior of a failed waste package (for example, compare the release curves for the AIC cases to the Base Scenario-Reference Case (BS-RC) in Figure 8-11 from Posiva 2012-12).

Conclusion: Posiva's CLA adequately describes and justifies how the safety functions effectively prevent releases of disposed radioactive materials into the bedrock for at least several thousand years. Future Posiva analyses, however, will be expected to expand their assessments to include the potential impacts on radionuclide release and post-containment barrier safety functions of the anaerobic corrosion of the cast iron insert. Posiva should also update and confirm its estimate of the percentage of IRF nuclides as Finnish reactors move to higher burn-up.

3.1.4 Identifying key issues to establish future RD&D priorities

Section 10.2 of Posiva 2012-12 briefly identifies certain topics for RD&D focus in the future. Two of the three topics deal with operational issues of RSC and emplacement demonstrations, however they do not directly reflect processes and properties affecting specific Safety Functions of barriers.

The limited sensitivity analyses around variant scenarios to the Reference Case, as illustrated by Figure 8-6a in Posiva 2012-12 (Figure 3), show relatively low (negligible) safety-significance of certain alternative assumptions and safety functions of the far-field host rock and hydrogeology; clearly it is the performance of the EBS that dominates the safety of the KBS-3 system.

Figure 8-2 Posiva 2012-12 (shown as Figure 4) would seem to confirm the relative lack of post-closure safety contribution that can be attributed to far-field transport, thus indicating the lack of safety-importance of concerns about EDZ, long-term integrity of seals and plugs, and radionuclide sorption by far-field host rock. Of course for other scenarios, especially those involving early (within the first several 1000 years) failure of multiple canisters without the masking effect of a 'pinhole', the far-field transport Safety Functions and properties could become more safety-significant.

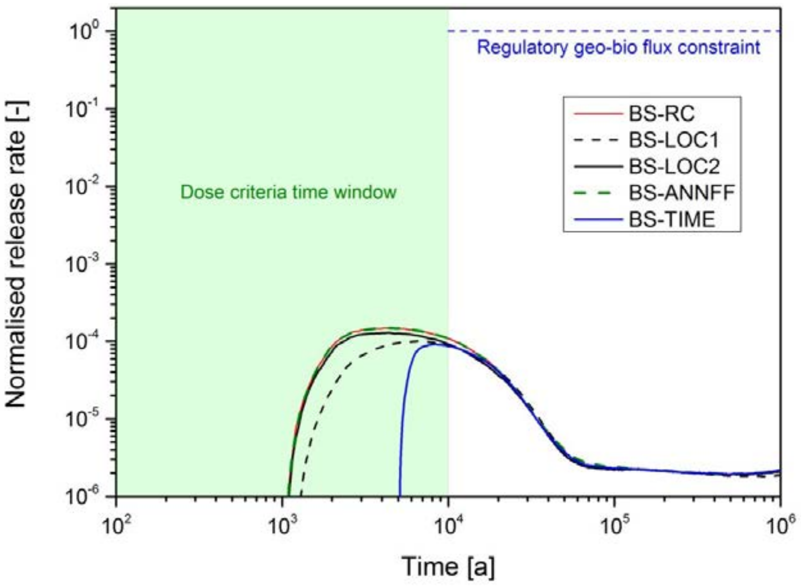

Figure 3. Figure 8-6a from Posiva 2012-12, showing relative lack of impact on peak radionucldies release rate for a variety of alternative far-field assumptions and models.

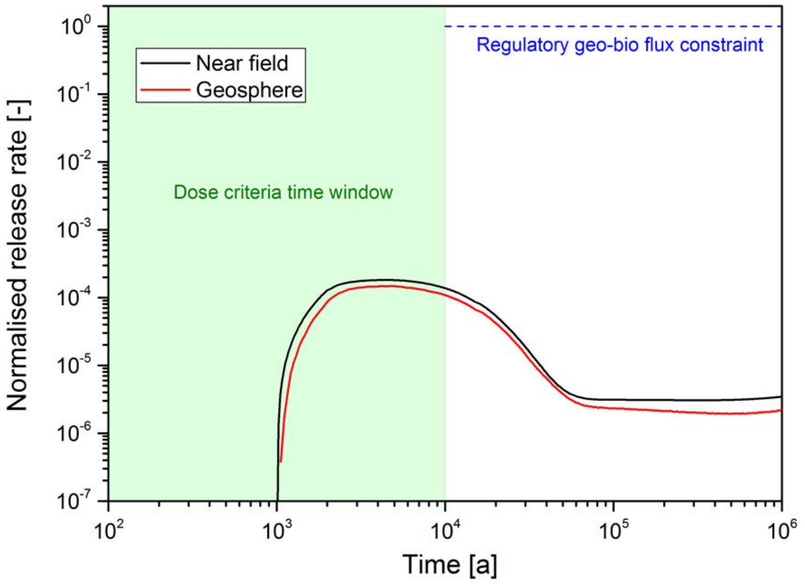

Figure 4. Figure 8.2 from Posiva 2012-12, illustrating the minor reduction in release rate of radionuclides attributable to all aspects of the "geosphere".

Paradoxically, certain apparently high safety-significance factors (e.g., spent fuel matrix dissolution rate, also termed “fuel alteration rate”, see Figure 8-17, Posiva 2012-12, shown as Figure 5) evident from Posiva’s own PA results (and as also argued in the parallel CRR on performance assessment) have not been identified as RD&D priorities in Section 10.2 of Posiva 2012-12. General conclusions on the importance of ‘fuel (UO_2) alteration rate”, however, need to be made carefully because Posiva’s use of sensitivity analyses in the CLA has been limited to examining factors controlling the release behavior for only certain radionuclides for a limited set of scenarios. It is notable in this context that independent safety assessments for a parallel KBS-3 type spent fuel repository presented by SKB in Sweden show that releases from the repository become proportional to the fuel alteration rate for values at or below 10^{-6} parts per year (see Figure 10-44, SR-Can, SKB, 2006). As a general observation, there seems Posiva has developed in the CLA the suitable methodology to use such PA sensitivity results to prioritize its future RD&D, so that the potential importance of fuel alteration rate can be assessed.

Conclusion: The linkage between Posiva’s RD&D plans and the results from its CLA sensitivity analyses of safety are preliminary and limited. Going forward, Posiva should make greater use of its safety assessments as a defensible basis to identify and help compare and prioritize technical studies for future RD&D.

3.1.5 Robustness of post-closure safety analyses

Posiva’s KBS-3 concept for spent fuel disposal relies on both the EBS and suitable environmental, or “service”, conditions of the Olkiluoto site. Posiva 2012-04 (page 31) for example states

> *“Posiva’s safety concept is based on long-term isolation and containment, which is achieved through robust engineering barrier system design and favourable geological conditions at the repository site, as discussed in Section 1.5 and outlined in Figure 1-5.”*

The robustness in Posiva’s CLA post-closure safety assessment, however, is difficult to judge since Posiva presents somewhat circular reasoning for its design basis case. For example, Posiva 2012-12 (page 52) states:

> *“The repository system is designed in a way that, for the design basis scenarios, except for incidental deviations, each component of the EBS meets the performance targets, assigned to it, and the host rock conforms to its target properties. In this case, the copper-iron canisters remain intact for the whole assessment time frame and there is no release of radionuclides. This is confirmed by the performance assessment.”*

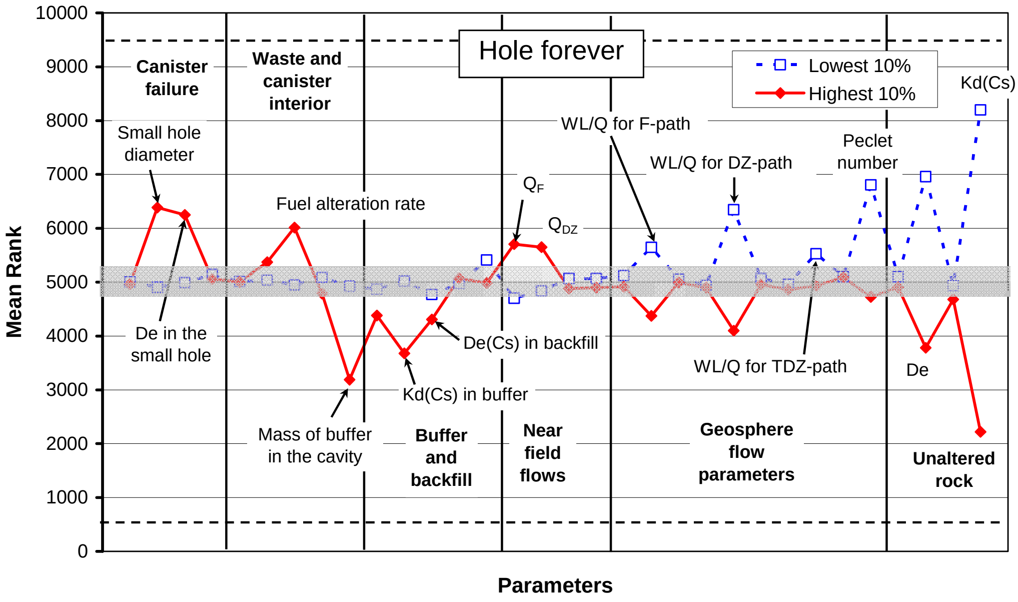

Figure 5. Figure 8-17 from Posiva 2012-12, showing the relative safety ranking of various barriers and properties affecting peak Cs-135 release rate.

In essence this says the obvious that if everything works and evolves as expected, then performance assessment shows that the repository system will safely isolate the spent fuel.

As further noted in Posiva 2012-12 (pages 52-53), however, Posiva's CLA performance assessment:

"…shows, however, that there are some plausible conditions and events (incidental deviations) that could lead to reduction of one or more safety functions, and thus may give rise to radionuclide releases. In addition, there are some very unlikely events and processes that could disrupt the repository, e.g. related to human intrusion and rock shear. These incidental deviations and unlikely events are systematically examined to define a set of scenarios that encompass the important combinations of initial conditions, natural evolution and disruptive events."

Conclusion: There certainly are many analyses in the various CLA reports from Posiva (e.g., Posiva 2012-12; Posiva 2013-01) that indicate that Posiva's KBS-3 system will provide wide margins of safety for an extended range of credible conditions (for example, see Figure 8-18, Posiva 2012-12, presented here as Figure 6). However, the linkage from multiple safety functions to post-closure safety is not directly traceable for the several variant and disruptive cases that are assessed, not least because supporting sensitivity analyses have not been reported in the CLA.

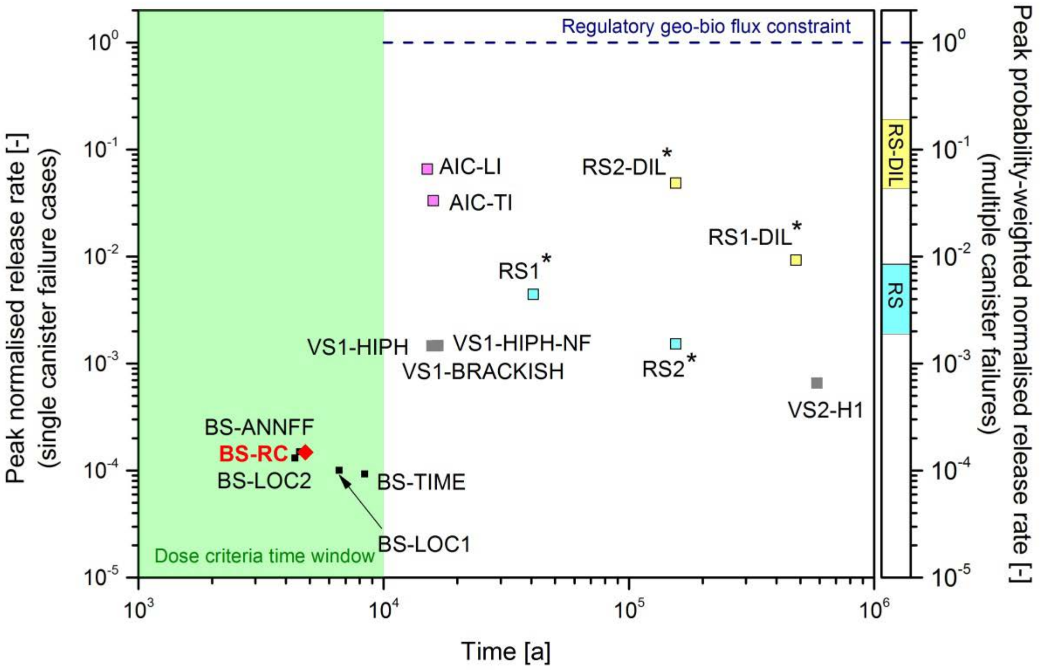

Figure 6. Figure 8-18 from Posiva 2012-12, indicating large margins of safety with respect to the STUK geosphere-biosphere flux constraint.

4 Scenarios

4.1 Formulation methodology

The ‘guidance questions’ provided by STUK on this topic focused on the methodology for formulation of EBS scenarios. Additional questions requested judgments as to the completeness and adequacy of the scenarios presented in Posiva’s CLA reports.

4.1.1 Completeness of scenarios

Posiva’s formulation of scenarios is described, justified and summarized in Posiva 2012-09 and 2012-12, as well as other CLA documents. Posiva’s approach (Posiva 2012-07) examines how features, events and processes (FEPs) may affect safety functions for different EBS components for the Reference Case of expected evolution of the repository system, and identifies events (e.g., earthquakes, glacial loading, ground freezing) that may possibly impact upon the properties, behavior, and hence Safety Functions of the barriers. Posiva’s approach to developing and applying scenarios has parallels with international programs for the disposal of spent fuel and high-level waste.

While the Posiva approach to scenario development is systematic and combined scenarios are explicitly analyzed, a key concern is the completeness of the set of scenarios evaluated by Posiva in the CLA reports. There seems to be additional, credible scenarios that could and perhaps should be evaluated in future safety assessments by Posiva. As noted in other sections of this report, scenarios could include (not an exhaustive listing), (a) incorrect or poorly constructed emplacement of engineered barriers, including backfill, (b) zeolitization of smectite, (c) dilution, dispersion and neutralization of high pH waters, (d) rapid (100’s of years) enlargement of initial pinhole defects, (e) delayed saturation of buffer, (f) anaerobic corrosion of cast iron insert in the post-containment/ radionuclide release period, and (g) seismically-induced shearing along a hydraulically transmissive fracture that has already conducted water to the buffer (thereby possibly contributing to enhanced buffer erosion and corrosion of the canister).

Conclusion: Examination of a greater breadth of credible scenarios ought to be expected prior to future operational licensing. Such scenarios should closely examine impacts from earlier-than-expected containment failure of multiple canisters and impacts from evolution in near-field environmental conditions following penetration of the copper canisters.

4.2 Scenario classification

STUK’s ’guidance questions’ in this area related to how scenarios were classified within Posiva’s CLA, and the adequacy and completeness of identified variant and disturbance scenarios that were evaluated.

4.2.1 Adequacy of scenarios

Posiva’s Reference Case is described as an initial, undetected 0.5 mm diameter pinhole on the weld of the copper canister. Posiva defends this base case as based on the potential flaw arising from electron beam welding (EBW) of the copper canister. Posiva also argues that this Reference Case definition meets STUK’s guidance and instructions with respect to defining a Reference Case in which early radionuclide release may occur, although Posiva carefully notes it does not believe such early release will occur for any waste package.

However, as noted in other sections of this report, this fixed, small-diameter pinhole Reference Case masks more than it reveals about the various safety functions of different barriers of Posiva’s multiple-barrier KBS-3 disposal concept. The mass-transfer resistance of this hypothetical small pinhole dominates the release of all radionuclides, as illustrated by sensitivity analyses reported in Posiva 2012-12 and Posiva WR 2012-25.

This leads to the somewhat absurd position that Posiva's Reference Case achieves highly favorable radionuclide-release performance, not on the basis of any intended and engineered barrier Safety Function, but on the properties of an unintended and arbitrarily assumed properties of an undetected flaw (i.e. error) in the fabrication of a KBS-3 waste package.

Posiva further compounds its misleading Reference Case by arbitrarily selecting an unrealistically short corrosion time of 1000-years for the spent fuel cladding, a material that is used because of its exceptionally low corrosion rate under the extreme conditions of reactor operations (e.g., Posiva 2012-12, page 78). The C-14 neutron-activation inventory in cladding, therefore, is calculated to be the key dose-contributing radionuclide for the Reference Case, a result that masks or misrepresents the likely performance behavior of most of the different materials and components of the actual KBS-3 EBS. Posiva's pinhole variant, that allows for growth of the initial pinhole over an arbitrarily assumed 25,000-year interval, also potentially clouds a more realistic assessment in which anaerobic corrosion of the underlying cast-iron insert might open this pinhole faster (10's to 100's years) and lead to a more general exposure of spent fuel to contacting pore water. Thus, Posiva's selection and focus on the 'pinhole' Reference Case (as well as variants) for sensitivity analyses impedes development of an understanding of the many different barriers, processes and Safety Functions that collectively provide a robust safety concept.

Variant cases in the CLA for other modes of failure and radionuclide release are more appropriately broad in their consideration of possible scenarios affecting long-term performance of a KBS-3 repository. It is notable that for the variant cases Posiva considers, they all reveal adequate safety margins (defined as the ratio of the allowable release rates divided by the calculated release rates) of many orders of magnitude.

As for disturbance cases, other sections of this report have already identified additional credible events (e.g., creep-ductility failure of copper canisters) and conditions (e.g., persistence of high pH waters; improper emplacement of barriers; piping erosion; delayed buffer saturation) that ought to be considered as supplemental scenarios for Posiva to conduct further safety assessments. Furthermore, Posiva should address in detail post-containment scenarios based on impacts arising from the anaerobic corrosion of the cast iron insert as part of future safety assessments.

Conclusion: The scenarios and their classification within CLA is an adequate starting point for Posiva in a step-wise licensing process. However, Posiva and STUK should consult on the identification of a more useful Reference Case scenario, especially as Posiva's recent decision to select friction stir welding (FSW) over electron beam welding (EBW) would seem to invalidate the possibility of this specific 0.5-mm diameter undetected pinhole in the weld. Further exploration of additional variant and disturbance scenarios would also seem to be appropriate for both Posiva and STUK to be able to develop a better and deeper understanding of what properties, Safety Functions, processes and events have the greatest significance with respect to post-closure safety.

5 Post-closure safety assessments

5.1 Methodology (GD 736/2008 14, 15 §)

STUK's 'guidance questions' on this topic focused on the assumptions, models and data used in the EBS portion of the overall post-closure safety (PA) assessment as presented in CLA reports, and the adequacy of decisions made and supported by Posiva. Because there is typically an 'abstraction', or simplification, of fundamental process models as they are linked into a total system PA model, the method and assumptions employed by Posiva were also reviewed.

5.1.1 Adequacy of Assessment methods

Posiva's CLA modelling and determination of input data is generally based on high-quality scientific knowledge and expert judgment obtained through experimental studies, site investigations and evidence from natural analogues. Posiva's program seems well integrated and collaborative with other national programs and international organizations in obtaining up-to-date information, data, and modelling insights and techniques. Notably, Posiva has moved away from deterministic assessment codes to assessment codes with probabilistic capabilities and these have allowed Posiva to explore a wider range of alterative conceptual models, databases and modelling assumptions.

Numerous examples have been identified in CLA reports, however, of where further explanations and justifications are needed on decisions regarding bounding assumptions, data selection, range of parameter uncertainties, and modelling choices. For example, the various geochemical models deployed by Posiva are particularly limited because of their failure to incorporate certain mineral hydrolysis reactions leading to the dissolution and potential precipitation of solids. Not all choices were found to be as bounding as assumed by Posiva (e.g., the location of a fracture intersecting a deposition hole with respect to chemical corrosion by HS^- diffusing from the rock through the buffer to the surface of the copper canister). The individual and cumulative effects of alternative modelling choices and extended uncertainties have not been examined as part of this CRR.

The need to incorporate uncertainties in models and data into safety assessments is crucial. Posiva's emerging application of sensitivity analyses, as detailed in Posiva WR 2012-25 seems a strong indicator of the direction that future Posiva safety assessments need to follow. While the CLA sensitivity analyses were only applied to an arbitrary pinhole Reference Case and variants of this case, the multiple sensitivity methods that Posiva utilized illustrates a potentially powerful and flexible methodology that Posiva can usefully emphasize in future safety assessments.

Conclusion: The basic post-closure safety assessment structure and methodology that Posiva reports in the CLA documents are of high quality, and many of the assessment codes are among state-of-the-art options. Decisions on the selection of assumptions, models and data are generally adequately reported, although reviewers identified specific omissions and preferences for alternatives. These issues ought to be incorporated into STUK's oversight and review of future safety assessments by Posiva. In particular, Posiva ought to expand its use of multiple sensitivity analysis techniques to further identify and explore the potential safety-significance of processes, barrier properties, Safety Functions, and the more probabilistic aspects and factors of post-closure safety assessment (e.g., the temporal and spatial distribution of canister failures).

5.2 Safety analyses, models and data (GD 736/2008, 14, 15 §)

In this area, STUK's 'guidance questions' addressed the appropriate selection and implementation of models used to analyze the post-closure behavior and safety of the EBS. Questions were also raised regarding the scientific quality of the data used.

5.2.1 Buffer and backfill modeling

For the scenarios considered, Posiva's main CLA reports, and supporting documentation, cover and address many of the key physical phenomena and processes affecting post-closure safety of their KBS-3 repository concept. Concerns focus on the possibility of additional credible scenarios (and associated processes) not explicitly considered by Posiva, as well as the use of empirical models rather than phenomenological models for several of the key processes (e.g., bentonite erosion) potentially impacting upon performance and safety functions of certain barriers.

One fundamental topic needing further consideration is the inter-changeability among types of "bentonite" asserted by Posiva. Current CLA models are heavily based on data from tests on Wyoming bentonite MX-80, with fewer data on the stated alternative bentonite, Ibeco-RWC (formerly called "Deponit-CAN"). While identifying the potential need for flexibility and substitution of one type of bentonite with another is a sensible precaution by Posiva, "bentonites" are a type of rock with significant ranges in properties such as amount of smectite, amount and types of various minor mineral phases, amount of organics, ratios of Fe(II)/Fe(III) in the smectite, etc. It is likely that any future decision to replace MX-80 by another type of bentonite will require significantly more data and associated modelling of behavior to confirm the suitability of such a substitution.

Piping/ mechanical erosion of buffer and especially backfill is also a concern. Posiva currently has limited, short-term, small-scale laboratory test data on this process and applies non-mechanistic, empirical models to assess the possible long-term rate of such erosion. While perhaps suitable for initial scoping of piping, the lack of a phenomenological understanding of piping erosion, and the factors that affect its extent and rate, may limit Posiva's ability to develop and deploy effective countermeasures for maximizing suitable regions for constructing access tunnels and deposition holes within the limited rock volume at the Olkiluoto site. It may be futile, and certainly sub-optimal, for Posiva to devote extensive efforts in developing "rock suitability criteria" without parallel testing and modelling of exactly what water inflows can actually be tolerated in the emplacement of buffer and backfill.

The current level of understanding and THMC (thermal-hydrological-mechanical-chemical) modelling of buffer and backfill homogenization during saturation is also rather uncertain. Uniformity in saturated buffer is particularly important to fulfillment of performance targets (e.g. mechanical protection of the canister). The saturation process itself cannot be uniform, however, given that the surrounding rock water flows through fractures that have heterogeneous hydraulic properties, or from the overlying tunnel backfill. Hence, there will be some period of time at least for which the buffer is heterogeneously saturated. Such non-uniform saturation might engender localized mechanical effects on the canister that perhaps ought to be further evaluated. In the future, additional evidence may be needed to confirm that couplings between saturation/ homogenization processes and the evolution of transport and mechanical properties of the buffer (and backfill) could not lead to poorer EBS performance than is represented by the cases that are presented in the CLA.

As mentioned elsewhere in this report, a key issue lies in the area of modelling potential impacts arising from delayed saturation, possibly taking many 1000's of years. Drying-out of the initial moisture in buffer could lead to desiccation, causing local cracking of buffer. The buffer, in turn, may or may not uniformly 'heal' upon eventual saturation, in limiting cases possibly leading to temperatures near the canister above the bounding temperatures calculated by Posiva. Dissolution and precipitation of different minerals driven by extended thermal and humidity gradients might also lead to modification of the initial state of the as-emplaced buffer. The potential consequences of delayed buffer saturation also need to be considered jointly with the possibility of early earthquake-related rock shearing events. Delayed saturation of the buffer would also delay compressive loading and closure of the installation gap between copper canister and cast iron insert, with possible implications for vulnerability of such waste packages to creep-ductility failure of the copper. Addressing the likelihood and possible impacts on barrier safety functions and overall performance of the EBS ought to be a near-term focus for Posiva.

Posiva has identified the potential for "chemical erosion" of buffer from sustained contact with dilute glacial waters that might penetrate to repository depths in the future. Current hydrogeological data and modelling of consequences of future glacial events, as summarized in the parallel CRR for site, does not seem to support the likely establishment of the necessary dilute conditions for such erosion at repository depths. Likewise, the limited number of deposition holes with sufficient erosion rate to cause a substantial diminishment in buffer density would also seem to militate against the safety significance of this scenario. Because of it potential impact in enabling chemical erosion of buffer to occur and uncertainty as to whether the re-distribution of buffer material within a deposition hole would keep pace with the local loss of buffer at an intersecting fracture, however, this topic of dilute water penetrating to repository depths will need to be continually re-evaluated as newer site data are collected.

Conclusion: Posiva ought to present and more fully defend its approach to use of its empirical models for buffer behavior regarding saturation, piping and chemical erosion. Although not under review now, the suitability of exchanging one bentonite for another would need careful evaluation, and probably extensive testing if such a future proposal is made by Posiva.

5.2.2 Thermal modeling

Posiva's thermal models used in CLA calculations themselves are adequate and verified for their purpose. The main concerns by external reviewers has been on the parameterization and conceptualization used in those models, and whether alternative assumptions and data might lead to important implications for compliance with Posiva's thermal criterion, L3-BUF-6, and on plans for repository layout.

Independent calculations by external reviewers suggest that Posiva bounding models reported in the CLA documentation are not truly bounding. These independent results indicate peak temperature 3-4 °C higher than those calculated by Posiva for the same inputs. This might be a consequence of a lower *heat flux reduction factor* applied by Posiva; the value used by Posiva was slightly lower than that calculated by the external reviewers and by similar work conducted by SKB (SKB, 2009). It was also noted that thermal results are sensitive to buffer composition, with higher smectite content leading to higher calculated peak temperature. This relates back to the noted concern about Posiva's assumed inter-changeability among bentonites.

The implication of such a discrepancy related to whether Posiva's temperature limit of <100 °C in the buffer might be exceeded in certain locations. Countermeasures involving increased spacing of deposition holes might, in turn, require a larger repository if the limit is to be respected.

Independent areal thermal calculations considering the influence of adjacent disposal panels suggest that delays in completion of adjacent panels could lead to higher temperatures. If this effect is confirmed, contingency plans for impacts on layout and construction of the overall repository ought to be explored by Posiva.

Conclusion: Posiva's commitment to a peak temperature of <100°C in the buffer has key implications for repository layout. Temperature is also an important driver for the evolution in near-field conditions immediately following emplacement of waste packages, including water saturation of the buffer, re-distribution of mineral phases, and mechanical effects (e.g., spalling of adjacent rock surfaces in the deposition hole). As Posiva updates its designs, emplacement procedures and possibly materials, it will be vital to assess their impacts on thermal behavior.

5.2.3 Geochemical modeling

As has been previously observed, the geochemical models employed by Posiva do not include alumino-silicate hydrolysis reactions. Thus, known reactions involving dissolution and precipitation of such minerals (especially clays) under evolving near-field conditions are not included in CLA geochemical modelling results.

For example, independent geochemical models relying solely on ion-exchange reactions (as assumed by Posiva) suggest clogging of the buffer by a silica polymorph only after about 100,000 years after emplacement, whereas independent calculations and models that include kinetics of dissolution/ precipitation, indicate clogging could occur within hundreds of years. The potential impacts on the saturation process, buffer properties and safety functions for such different evolution in geochemical and mineralogical conditions within the buffer are not clear.

Likewise, independent calculations of the effect on the buffer from sustained contact by dilute, cool sub-glacial groundwater indicate that significant dissolution of smectite might occur. It would be impossible for Posiva's CLA geochemical models to show such an impact.

Finally, although Posiva has been concerned about smectite transformation to illite, external review suggests that other transformations, including smectite to zeolite under elevated pH conditions, and smectite to more iron-rich clays during anaerobic corrosion of the cast iron insert may be of greater concern. And again, Posiva's current geochemical models are intrinsically incapable of evaluating stability relationships and possible clay transformations.

Conclusion: Posiva needs to improve its geochemical modelling capabilities, for example, to include alumino-silicate hydrolysis reactions. Posiva's current assertion for compliance with its L3-ROC-16 criteria, that the buffer and backfill remain stable (no montmorillonite dissolution), seems largely based on the inability of their geochemical model to show such a consequence. Furthermore, a more capable geochemical model is needed to confidently evaluate (1) the effects of the possible mineralogical alteration within the buffer on overall performance, notably the swelling pressure, and (2) potential coupling of chemical reactions to erosion processes.

5.2.4 Modeling the mechanical integrity of the canister and insert

Mechanical integrity is crucial for fulfillment of the safety function assigned to the combined waste package of copper canister and inner cast-iron insert, i.e. containment of the spent nuclear fuel. The EBS reviews have been focused on scenarios where mechanical or thermal loads act on the canister. These reviews conclude that there are two issues that are of most importance for the mechanical integrity of the waste package. These are:

- Sufficient ductility of the copper canister material.
- Sufficient yield/tensile strength and fracture toughness of the insert materials.

These two issues interact with a number of other issues and factors such as level and evolution of mechanical and thermal loads, manufacturing of canister components, defects and non-destructive testing systems, constitutive modelling of canister component materials, radiation embrittlement, accelerated testing, etc.

A key concern is that the required ductility of the copper canister material, as well as the needed yield/tensile strength and fracture toughness of the insert materials, are not explicitly addressed by Posiva in their structural verification of the mechanical integrity of the canister. Regarding the copper canister, Posiva instead determines *available ductility* as a function of time based on modelling, in which results from accelerated creep testing are used as inputs. The concern with such an approach is that the structural verification of the canister is fully dependent on modelling that is verified and validated against data from experiments conducted at much shorter timescales than those of interest. Regarding the insert materials, Posiva bases their defect tolerance assessment on the initial yield/tensile strength and fracture toughness.

There are complementary approaches that Posiva might consider to assess more broadly the mechanical integrity issues, especially creep ductility. The current inclusion of phosphorous into the copper can be shown to avoid creep failure, but the mechanism is not well understood and the long-term (> several years) persistence of such favourable behavior is not established. Creep is also a difficult process to reliably model over extended timescales because of reliance on short-term, high strain-rate testing as opposed to strain over repository-relevant long-term, slow strain-rate conditions.

Posiva could determine the *needed ductility* of the copper canister material and the *needed yield/tensile strength and fracture toughness* of the insert materials where the interaction with the other issues and factors mentioned above is investigated. Results from such an analysis would give additional understanding and confidence in the structural verification of the mechanical integrity of the canister. This complementary approach might also give an extra margin for unknown/unexpected phenomena.

One way to investigate the minimum copper ductility needed under the different loading scenarios might be to use a *continuum damage mechanics* concept. In such an approach, total strain can be divided into elastic and inelastic parts where the latter represents both plastic and creep strain. It should be possible to make this approximation/simplification, as the load on the copper canister is mainly deformation controlled. By use of the continuum damage mechanics concept, the impact of localized straining at geometrical discontinuities could be taken into account in a more realistic way.

Conclusions: The current database on the *ductility* of the copper canister material needs further extension. In particular, potential creep-ductility failure of copper, especially for cases of delayed saturation of buffer preventing closure of the canister-insert tolerance gap, needs further examination. Sustained creep could lead to scenarios of common-mode failure of the copper canister at time periods much earlier than that calculated for the nominal chemical corrosion by HS^- diffusing from the rock through the buffer to the copper surface. The *yield / tensile strength and fracture toughness* data of the insert needs further confirmation, especially for planned PWR inserts, which are now below that achieved for BWR inserts.

5.3 Uncertainty assessment (GD 736/2008 15 §)

'Guidance questions' by STUK in this are addressed issues regarding the identified, quantification and inclusion of uncertainties into the assessment of the EBS post-closure evolution and performance.

5.3.1 Treatment of uncertainties

The parallel CRR for performance assessment (PA) includes a broad global review of the treatment of uncertainties within Posiva's CLA reports. Within the narrow areas of process modelling reviewed by the EBS review group, the general consensus was that Posiva's CLA reports and calculations did identify, quantify to the degree possible, and attempt to propagate uncertainties in such modelling. More basic concerns were, however, raised in several related areas:

- conceptual model uncertainties arising from different, but credible, alternative models of processes;
- consistency in the treatment of uncertainties when abstracting detailed process models into higher-level performance assessment calculations;
- limited time available to review and fully explore uncertainties as treated in the Models and Data report (Posiva 2013-01).

On the general topic of treatment of various sources and types of uncertainty, it is noteworthy that Posiva did conduct an initial set of probabilistic safety assessments (PSAs) [Posiva 2012-12; Posiva WR 2013-25] in which probabilistic density functions (pdf's) of uncertainties for certain parameters were identified and quantified in sensitivity calculations. Posiva WR 2013-25 was especially useful in this regard, as it illustrated at least 4 different methods for exploring the effects of uncertainties on calculated long-term radionuclide release. Unfortunately, these methods were only applied to the pinhole Reference Case and variants in which the tremendous mass-transfer resistance of the hypothetical pinhole dominated the release of radionuclides, masking the many other isolation safety functions of actual engineered barriers.

Conclusion: Posiva has used various approaches for managing uncertainty when modelling the behavior of the engineered barriers. Furthermore, Posiva has deployed a set of different sensitivity techniques to allow it to identify and quantify how uncertainties of different parameters affect long-term release rates. Posiva should be encouraged to improve consistency in its approach to managing uncertainties and to provide stronger justifications for the approaches adopted in each particular modelling area. Posiva should also extend its system-wide sensitivity methods to a wider set of credible scenarios. This will allow Posiva to more clearly recognize the multiple barrier attributes of their KBS-3 repository concept. From such insights, Posiva can focus its future RD&D into areas for which reduction in current uncertainties will have the greatest impact on improving and assuring post-closure safety.

6 Reliability of models and data of the post-closure safety case

6.1 Models and data (EBS)

STUK's 'guidance questions' on models and data asked if these were based on high-quality research, and appropriate application of expert judgment. In instances where probabilistic analyses were conducted in the CLA (most completely provided in Posiva WR 2013-25), STUK's questions related to what, why and how distributions in parameters values were selected.

6.1.1 Reliability of models and data

In general the data used by Posiva in their process-model calculations for the engineered barrier system seem to be of high quality and to have been used in an appropriate manner. A few areas have, however, been identified where alternative, high-quality data reported in international literature might imply different parameter values. Because neither STUK nor Posiva have necessarily examined all such alterative data sets in performance assessment calculations, it is difficult to confirm whether such alternatives would lead to significant changes in predicted evolution of the EBS or in containment and release of radionucldies.

As noted in other sections, the models used by Posiva in its CLA are generally of high quality and adequate for the purpose to which they are applied. Three specific exceptions to this observation are on geochemical models (which neglect the important alumino-silicate hydrolysis reactions), erosion models for buffer and backfill (which are empirically based), and creep-ductility of copper canisters (empirically based on extrapolation of short-term, high strain-rate test data to long-term, low strain-rate repository conditions).

Where they have been applied the quality of Posiva's sensitivity analyses is state-of-the-art. However, these techniques have only been applied to a few pinhole failure cases that are both hypothetical and that intrinsically mask the potential safety-significance of many barrier safety functions.

Conclusion: Posiva should be encouraged to further apply its sensitivity analyses techniques to more fully identify and quantify the safety significance of key parameters and the associated uncertainties of such parameters. In this way, Posiva should aim to better construct and guide an effective future RD&D program that can effectively and cost-efficiently lead to greater confidence in the KBS-3 concept.

6.2 Conceptual models

STUK's 'guidance questions' here focused on whether all relevant processes affecting EBS performance and safety were included in the safety assessment, and whether credible alternative conceptual models were identified and considered.

6.2.1 Reliability of conceptual models

The reliability of Posiva's own conceptual models, as well as alterative conceptual models, has been discussed throughout this report. In many cases Posiva explicitly identifies and evaluates alterative conceptual models to those it has selected. In other cases, Posiva identifies alternative conceptual models, and presents reasoning as to why such alterative models have not been used (typically on the basis of that Posiva selected a more conservative model – e.g., chemical erosion of buffer).

Other sections of this report have noted where alternative conceptual models were not recognized or employed by Posiva (e.g., geochemical models that include alumino-silicate hydrolysis reactions), or where there is dispute in the reliability or conservativeness of the conceptual model selected by Posiva (e.g., creep ductility of copper).

Without undertaking extensive independent safety or performance assessment calculations, which was beyond the remit of CRR reviewers, it has not been possible to estimate with any certainty the effects of alternative models on Posiva's calculation cases. Thus, the safety-significance of such alternative conceptual models (and uncertainties associated with such alternatives) is currently unknown and unquantified. Because the KBS-3 concept is a multiple-barrier concept with strong couplings and interdependencies between individual barriers, care must be taken in speculating on the impact of changes or alternatives to any single process-level model. In the same way that the extreme mass-transfer resistance of the hypothetical pinhole masks any observable safety-contributions by many barriers and processes, it may be that other attributes of the KBS-3 concept (e.g., low dissolution rate of the UO_2 matrix, as illustrated in Posiva 2012-12 and Posiva WR 2013-25) may dominate and mask safety contributions for other barriers and processes, even for non-pinhole cases.

Conclusion: Posiva ought to consider extending its current performance assessments to examine a broader range of credible, alternative conceptual models. In such calculations, it will be useful for Posiva to utilize its various sensitivity techniques to identify and quantify specific safety-significance of barrier safety functions.

6.3 Mathematical models

Here STUK's 'guidance questions' addressed how Posiva applied and justified their selected mathematical models for specific processes.

6.3.1 Reliability of mathematical models

Posiva's CLA reports generally used process-model codes for which the mathematical verification has already been tested and established. Where potential issues on reliability of mathematical models resides in the abstraction of detailed process-level models into higher-level performance assessment (PA) codes. Such examinations were reviewed and considered by STUK's external PA consultants, which are presented in the parallel CRR on PA.

Conclusion: Mathematical reliability was not a key activity within the reviews conducted by STUK's external experts on process modeling of the EBS.

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