STUK-TR 19 / AUGUST 2015

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ISBN 978-952-309-277-8 (print, Erweko Oy, Helsinki/Finland 2015)
ISBN 978-952-309-278-5 (pdf)
ISSN 1796-7171

SAGAR Budhi [Southwest Research Institute] (ed.). Review of safety assessment in Posiva's construction license application for a repository at Olkiluoto. STUK-TR 19. Helsinki 2015. 92 pp + Appendices 12 pp.

Keywords: radioactive waste, disposal of spent nuclear fuel, KBS-3 concept, post closure safety case, safety function, performance target, performance assessment, scenario analysis, consequence analysis

Preface

In December 2012, Posiva Oy submitted a construction licence application (CLA) to the Finnish Government proposing construction of encapsulation and disposal facilities for spent nuclear fuel at Olkiluoto. An important part of the CLA is a safety case that includes a demonstration of the operational safety for about 100 years of operational period and long-term safety for up to 1,000,000 years after repository closure. The Radiation and Nuclear Safety Authority of Finland (STUK) are evaluating the CLA. To assist in review and evaluation of the long-term safety, STUK engaged several consultants with expertise in various disciplines and formed three core teams: (1) site, (2) engineered barriers, and (3) safety assessment. STUK designated one consultant in each core team as “key consultant”. The key consultant had the responsibility for coordination within the team and compilation of the consolidated report. This report is a compilation of the review comments from and findings of STUK's consultants in the area of safety assessment.

Review responsibilities of members of the Safety Assessment Core Review Team were defined by STUK as follows. Ryk Klos (Aleksandria Sciences) was responsible for reviewing the biosphere component of the safety assessment; Quintessa staff – namely George Towler, Claire Watson, Philip Maul, and Peter Robinson – reviewed the aspects related to radionuclide transport and conducted limited confirmatory calculations; and Budhi Sagar (Southwest Research Institute®) reviewed the overall safety assessment and was the designated key consultant. Karl-Heinz Hellmuth (STUK) provided input to the review on the subject of Posiva's treatment of sorption in the safety case.

The CLA consists of 14 Turva-2012 Portfolio Main reports and 7 Supporting reports (list can be viewed at pages 379–380 of Posiva 2012-09) and a much larger set of other references. STUK contractually assigned selected reports (or parts of reports) for review to various members of the review team. Workshops were held periodically at STUK offices where consultants could discuss each other's review comments. Some workshops involved meeting with Posiva staff aimed at getting clarifications on certain selected topics. Based on consultant comments, STUK also sent written “requests for additional information (RAIs)” to Posiva.

The Government Decree on Waste Disposal (GD 736/2008) sets the policy for geologic repositories in Finland. STUK's Guide YVL D.5 lays out the regulatory requirements for implementing the government decree. These regulatory documents cover the whole life cycle of a disposal facility (site investigations, design, construction, operation, and closure). STUK also developed a review plan based on these two documents. The aim of STUK's review plan is to conduct the review of the CLA in a manner that will lead to appropriate conclusions regarding the adequacy and quality of Posiva's CLA in general and the safety case in particular. It tends to focus the regulatory review on topics that are highly relevant to long-term safety. To organize the review from individual reviewers, STUK provided to each reviewer a template based on its review plan. Following STUK's instructions, the structure of this review report follows that template.

This report was developed by Dr. Budhi Sagar, the key consultant for safety assessment. The report is based on inputs received from core team members and other reviewers. The core team members were provided an opportunity to review the draft report and provide comments. All comments were incorporated in the report to the extent possible. Effort was also made to coordinate the review with the other two key consultants; however, some differences in opinions may exist among the three consolidated reports. The review resulted in formulating some requests for additional information (RAIs) to Posiva. At least two of the RAIs pertain to the topics of this consolidated report: (1) post-closure safety assessment, and (2) buffer saturation. Posiva's responses to these RAIs were reviewed when these were received and the review is included in this consolidated report as Appendices A and B respectively. In addition to the main text, the reader should refer to these appendices for additional review comments on these topics.

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

SAGAR Budhi [Southwest Research Institute] (toim). Arvio turvallisuusanalyysistä Posivan rakentamislupahakemuksessa loppusijoituslaitokselle Olkiluotoon. STUK-TR 19. Helsinki 2015. 92 s + liiteet 12 s.

Avainsanat: radioaktiivinen jäte, käytetyn ydinpolttoaineen loppusijoitus, KBS-3-konsepti, pitkäaikaisturvallisuusperustelu, turvallisuustoiminto, toimintakykytavoite, toimintakykyanalyysi, skenaarioanalyysi, säteilyannosten arviointi

Tiivistelmä

Posiva Oy (Posiva) toimitti joulukuussa 2012 Olkiluodon käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitoksen rakentamislupahakemuksen valtioneuvostolle. Rakentamislupahakemuksen keskeisiä osia ovat alustava turvallisuusseloste ja turvallisuusperustelu, joilla osoitetaan hankkeen turvallisuus noin sadan vuoden käyttöjakson ajalle ja noin miljoonan vuoden ajalle laitoksen sulkemisen jälkeen. Säteilyturvakeskus (STUK) tarkastaa nämä aineistokokonaisuudet. Pitkäaikaisturvallisuustarkastuksen tukena STUK käyttää kolmea ulkopuolista asiantuntijaryhmää: (1) Paikkatutkimukset, (2) Tekniset vapautumisesteet (EBS) ja (3) Turvallisuusanalyysi. Jokaisessa asiantuntijaryhmässä on yksi avainkonsultti, joka koordinoi ryhmän työtä ja kokoaa ryhmän arviontien perusteella yhteenvetoraportin. Tämä raportti on turvallisuusanalyysiryhmän yhteenvetoraportti arviointiahavainnoista ja kommenteista.

Turvallisuusanalyysiryhmässä arviointivastuut jakautuvat seuraavasti: Ryk Kłos (Aleksandria Sciences) vastasi turvallisuusperustelun biosfääriosien arvioinnista. George Towler, Claire Watson, Philip Maul ja Peter Robinson (Quintessa) vastasivat radionuklidien kulkeutumisen arvioinnista. Arvioinnin lisäksi Quintessan ryhmä teki vertailevaa mallinnusta arvioinnin tueksi. Budhi Sagar (Southwest Research Institute®) arvioi turvallisuusanalyysiaineistoja kokonaisuutena avainkonsultin roolissa. Karl-Heinz Hellmuth (STUK) osallistui arviointityöhön radionuklidisorption osa-alueelta.

Rakentamislupahakemuksen pitkäaikaisturvallisuutta käsittelevä Turva-2012 aineisto koostuu 14 pääraportista ja 7 tukevasta raportista sekä suuresta määrästä taustaraportteja. STUK määritteli tilauksissa ne raportit, joita ulkopuoleiset asiantuntijat tarkastivat. Asiakirjatarkastusten lisäksi STUK järjesti säännöllisesti työpajoja, joissa arviointiryhmät kokoontuivat ja keskustelivat arviointihavainnoista. Osassa työpajoista oli kutsuttuna myös Posivan edustajia, joiden kanssa keskusteltiin tarkastushavainnoista. Osa konsulttien tarkastushavainnoista johti myös STUKin viralliseen selvityspyyntöön Posivalle.

Valtioneuvoston asetus ydinjätteen loppusijoituksen turvallisuudesta (VNA 736/2008) määrittelee, että geologinen loppusijoitus on Suomen ratkaisu käytetyn ydinpolttoaineen osalta. STUKin ohje YVL D.5 määrittelee viranomaisvaatimukset valtioneuvoston asetuksen toteutukselle. Nämä kattavat toiminnan koko elinkaaren (paikkatutkimukset, suunnittelu, rakentaminen, käyttö ja sulkeminen). Näiden pohjalta STUK on koonnut arvioinnin tueksi review plan-dokumentin, jolla ohjataan tarkastusta ja fokusoidaan sitä keskittymään turvallisuuden kannalta keskeisiin asioihin. STUK toimitti jokaiselle ulkopuoliselle arvioijalle oman review planiin perustuvan arviointilomakepohjan. Tämän yhteenvetoraportin sisällysluettelo vastaa STUKin review plan-dokumentin sisällysluetteloa.

Yhteenvetoraportin on koonnut Dr. Budhi Sagar, turvallisuusanalyysiryhmän avainkonsultti. Raportti perustuu yksittäisten STUKin ulkopuolisten asiantuntijoiden tekemiin arviointeihin. Arviointiryhmän jäsenet ovat kommentoineet yhteenvetoraporttia sen luonnosvaiheessa. Nämä kommentit on huomioitu tämän raportin lopullisessa versiossa mahdollisuuksien mukaan. Arviointiryhmän sisäisten kommenttien lisäksi eri ryhmien avainkonsultit keskustelivat yhteenvetoraporteistaan, mutta tästä huolimatta yhteenvetoraporteissa saattaa esiintyä toisistaan poikkeavia näkemyksiä. Osa ulkopuolisten asiantuntijoiden arviointihavainnoista johti STUKin valmistelemaan selvityspyyntöön Posivalle. Posivan vastaukset pitkäaikaisturvallisuutta ja puskurin saturaatiota koskeviin selvityspyyntöihin käsiteltiin myös turvallisuusanalyysiryhmän toimesta ja niihin liittyvän arvioinnin tulokset on esitetty tämän raportin liitteissä A ja B. Lukijan kannattaa tutustua myös näiden liitteiden sisältöön.

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

Summary of key findings

A brief summary of key findings is provided below. Expanded summaries are provided at the end of each report section. At the end of the report, in Table 1, based on review comments, topics are identified and categorized as potential license conditions, STUK requirements and/or Posiva commitments. Our review focused on only the long term safety of the repository; STUK has conducted a separate review of the operational safety.

1. Posiva provides information in its safety case that is adequate for the first phase (construction authorization) of the repository licensing process. The second phase will request authorization to receive the spent fuel and start operations. The third and final phase will request closure of the repository and decommissioning of the site, including the encapsulation plant and the small facility for disposing intermediate and low level waste emanating from the encapsulation plant. These later facilities are co-located with the spent fuel repository. As noted in the CLA, significant residual uncertainties remain in describing the long-term evolution of the system. We expect that these uncertainties will be reduced as more information is gathered during underground construction, fabrication of engineered barriers, and testing during operations and the quality of the safety case, and confidence in it, will improve. However, we recommend that Posiva should fully integrate the safety case documented in Posiva 2012-37 for the co-located intermediate and low level waste disposal facility with the safety case for the spent fuel repository.

2. In its safety case, Posiva demonstrates that the proposed repository for spent fuel will comply with the safety standards set in GD 736/2008 and in YVL D.5 with comfortable safety margins. For the purpose of this report, safety margin is defined as the difference between the regulatory constraint and Posiva estimates of either the radiation dose or normalized release rate. We interpret substantial safety margins as indicators of system robustness. We did not find any serious flaw in Posiva's compliance demonstration, but some points for clarification and topics for future work are noted throughout this report and summarized in Table 1. With the current status of the information, we don't believe that any of the additional information we are seeking has the potential to alter the overall safety-related conclusion.

3. Regarding safety assessment methodology, Posiva should more clearly explain the formulation of the calculation cases and the lesson learned from each. In future licensing steps, Posiva should consider achieving an appropriate balance between the use of deterministic and probabilistic sensitivity analyses to demonstrate the robustness of the system and clearly identify processes, models and parameters that most influence the safety measures (annualized normalized releases and radiation doses). The use of the probabilistic sensitivity analysis is limited in the current safety case and should be enhanced in the next iteration of performance assessment. There should then be a clear link between the uncertainties in the identified processes, models, and parameters important to safety and the plans for future research, development and demonstration (RD&D). Also, the models, parameters, and processes that influence safety measures should be documented in greater detail and in a cohesive manner.

4. In Turva-2012, Posiva proposes a large number of topics for future RD&D. However, a prioritization of these topics is not provided. We recommend that the topics for RD&D be prioritized based on the significance of these topics to design, operational, and long-term safety. A plan for performance confirmation that would include monitoring underground during construction, monitoring of surface environment, testing of engineered barriers at suitable-scales, demonstration tests to show that rock can be excavated to specifications and barrier components can be manufactured as per design, and model validation using site data and data on engineered barriers, as it becomes available should also be prepared. RD&D topics suggested by us and other reviewers should be evaluated for inclusion in this list.

5. The results of the future RD&D and the natural progression of technology could lead to a change in design, either because safer, more efficient, and/or more economical technical solutions become available or because a solution to a current issue requires such a change. For example, Posiva may switch from vertical emplacement to horizontal emplacement, substitute other barrier materials, or decide to use an alternate welding technique. STUK's oversight process defined in YVL D.5 is appropriate to assure that any such change will be evaluated and approved before implementation.

6. Posiva's current CLA documentation is voluminous and extensive. However, as reviewers, we found that it lacks consistency, clarity, and transparency. There is much duplication in documents and yet important information is missing from the top-level documents. A significant number of the documents were not even published at the time the review began, even though these were referenced. We recommend that a more cohesive documentation hierarchy should be formulated and implemented in the next licensing phase. A better implementation of the QA/QC process is also needed, as the reports had several errors in referencing and contained typographical errors.

7. Posiva should establish and document clear links between the design specifications and overall safety; this relation is obscure in the current safety case. The descriptive safety functions and performance targets are good as a guidance tool but these do not provide a clear picture of the capabilities of the individual barriers. Posiva should devise a modeling approach to clearly describe the capability of each barrier, whether or not the capability will be called for safety during the assessment period. Such analysis will clearly show the built-in robustness in the system.

8. Posiva should consider constructing a more illustrative “base” scenario then the current pin-hole scenario. From the safety case, we get the overwhelming sense that Posiva believes that the design-basis or expected scenario will have zero release during the entire compliance period. This could be stated and then an illustrative scenario that will moderately challenge the engineered barriers and illustrate barrier functions could be constructed and analysed.

9. Posiva should consider the possibility that its implementation of quality assurance/quality control system will not be flawless. The potential for human errors during construction, waste emplacement, and closure, and their impact on safety should be discussed and analysed in the safety case. This could be done by formulating additional calculation cases.

10. In the next licensing phase, Posiva should include, in much greater detail, analyses of ‘what-if’ scenarios that include common cause failures of the barriers. The purpose of these analyses should be to demonstrate the extreme (and therefore unlikely) failures that will be required for exceeding the regulatory safety measures.

Contents

List of acronyms

Aleksandria	Aleksandria Sciences
AIC	Accelerated insert corrosion scenario
BS-RC	Base Scenario-Reference Case for geosphere
BSA	Biosphere Safety Assessment
BSA-RC	Biosphere Safety Assessment-Reference case
CLA	Construction License Application
DFN	Discrete Fracture Network (model)
DS ( )	Disturbance scenario(s)
EBS	Engineered barrier system
EDZ	Excavation damaged zone
FEP	Features, events and processes
IRF	Instantaneous release fraction of radionuclides in spent fuel
LDF/LDZ	Layout determining feature/zone
LSM	Landscape model
NRR	Normalized release rate of a radionuclide (estimated/regulatory constraint)
PA	Performance assessment
PSA	Probabilistic sensitivity analysis
QA/QC	Quality assurance/ quality control
RAI	Request for additional information
RS, RS1, RS2	Rock Shear scenarios (rock shear due to a large earthquake event)
RS-DIL	Rock Shear-Dilute Water scenario
RS-LI	Rock Shear-Leaky Insert scenario
RSC	Rock suitability criteria (criteria for determining suitability of a deposition hole)
RD&D	Research, development and demonstration
SA	Safety Assessment
SHYD	Surface hydrology model
SwRI®	Southwest Research Institute
THMC	Thermal, hydrogeological, mechanical, chemical (properties, behaviour, parameters)
TESM	Terrain and ecosystems model
VAHA	Posiva requirements management system
VS1	Variant Scenario 1 for geosphere
VS2	Variant Scenario 2 for geosphere

1 Introduction

This report documents review in three areas: (1) disposal concepts and general principles, (2) scenarios, and (3) post-closure safety assessment. The scope of the review is limited to the Posiva reports assigned to individual reviewers by STUK. The structure of this report is based on STUK's review template. The review template is partitioned into review areas and each review area is then subdivided into review topics. While we have tried to avoid duplication yet because of the nature of the review template and to maintain clarity, some duplication was unavoidable.

The following is a list of the Posiva documents reviewed for this report and the reviewers assigned to each document.

Posiva 2012-01 – Monitoring at Olkiluoto–a Programme for the Period before Repository Operation. [Also referred to as *the Monitoring report;* review of Chapters 2, 3 and 7 assigned to Klos (Aleksandria)]

Posiva 2012-03 – Design Basis. [Also referred to as *the Design Basis report*; review assigned to Klos (Aleksandria)]

Posiva 2012-04 – Performance Assessment. [Also referred to as the *Performance Assessment report*; review assigned to Sagar (SwRI®), and Klos (Aleksandria)]

Posiva 2012-05 – Description of the Disposal System. [Also referred to as *the Description of Disposal System report*; review of Chapters 2 and 10 assigned to Klos (Aleksandria)]

Posiva 2012-06 – Biosphere Description. [Also referred to as *the Biosphere Description report*; review assigned to Klos (Aleksandria)]

Posiva 2012-07 – Features, Events and Processes. [Also referred to as *the FEP report*; review of Chapters 2, 9, and 10 assigned to Klos (Aleksandria)]

Posiva 2012-08 – Formulation of Radionuclide Release Scenarios. [Also referred to as *the Formulation of Release Scenarios report*; review assigned to Sagar [(SwRI®), and Chapters 2, 3, and 4 to Klos (Aleksandria)]

Posiva 2012-09 – Assessment of Radionuclide Release Scenarios for the Repository System. [Also referred to as *the Assessment of Release Scenarios report*; review assigned to Sagar ((SwRI®), Towler et al. (Quintessa), Klos (Aleksandria), and selected Chapters to Hellmuth (STUK)]

Posiva 2012-10 – Biosphere Assessment. [Also referred to as *the Biosphere Assessment report*; review assigned to Klos (Aleksandria)]

Posiva 2012-11 – Complementary Considerations. [Also referred to as *the Complementary Considerations report*; review assigned to Sagar [(SwRI®), Towler et al. (Qunitessa), Chapter 10 to Klos (Aleksandria), and Hellmuth (STUK)]

Posiva 2012-12 – Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Synthesis. [Also referred to as *the Synthesis report*; review assigned to Sagar [(SwRI®) and Towler et al. (Quintessa)]

Posiva 2012-20 – Representing Solute Transport Through the Multi-Barrier Disposal System Simplified Concepts. [Review assigned to Towler et al. (Quintessa)]

Posiva 2012-26 – Climate and Sea Level Scenarios for Olkiluoto for the Next 10,000 Years. [Review assigned to Klos (Aleksandria)]

Posiva 2012-28 – Data Basis for the Biosphere Assessment. [Review assigned to Klos (Aleksandria)]

Posiva 2012-29 – Terrain and Ecosystem Development Modelling in the Biosphere Assessment. [Review assigned to Klos (Aleksandria)]

Posiva 2012-30 – Surface and Near-Surface Hydrological Modelling in the Biosphere Assessment. [Review assigned to Klos (Aleksandria)]

Posiva 2012-31 – Radionuclide Transport and Dose Assessment for Humans in the Biosphere Assessment. [Review assigned to Klos (Aleksandria)]

Posiva 2012-32 – Dose Assessment for Plants and Animals in the Biosphere Assessment. [Review assigned to Klos (Aleksandria)]

Posiva 2012-41 – Radionuclide Migration Parameters for the Geosphere. [Review assigned to Hellmuth (STUK)]

Posiva 2013-01 – Models and Data for the Repository System. [Also referred to as *the Model and Data report*; review assigned to Sagar (SwRI®) and Towler et al. (Quintessa)]

Working Report 2013-25 – Probabilistic Sensitivity Analysis for the "Initial Defect in the Canister" Reference Model. [Review assigned to Sagar (SwRI®) and Towler et al. (Quintessa)]

Working Report 2013-61 – Selection of Probability Density Functions (PDFs) for the Probabilistic Sensitivity Analysis (PSA) of the "Initial Defect in the Canister" Reference Model. [Review assigned to Sagar (SwRI®) and Towler et al. (Quintessa)]

Working Report 2014-09 – Hydrogeochemical Evolution of the Olkiluoto Site. [Review assigned to Hellmuth]

Working Report 2014-13 – Sorption of Cesium on Intact Rock. [Review assigned to Hellmuth]

Posiva 2014-02 – Radionuclide Transport in the Repository Near-Field and Far-Field. [Review assigned to Towler et al. (Quintessa) and Hellmuth (STUK)]

The following two Regulatory documents are referenced throughout this report.

1. Government Decree (736/2008) on the Safety of Disposal of Nuclear Waste, Issued in Helsinki, 27 November, 2008. This is referenced as GD 736/2008 in text.
2. STUK Guide YVL D.5, Final Disposal of Nuclear Waste; Draft L5/29.5.2013.

As can be seen from the description of the review assignments, not all reports listed above were reviewed by all review team members. In addition, there are many more Posiva documents, not listed above, that were not reviewed by the members of the Safety Assessment team. Therefore, the review comments in this report may not be comprehensive.

In the following, reports are referenced by their report number (e.g., Posiva 2012-12) but alternate descriptions are also sometimes used, especially when a direct quotation is taken from Posiva.

Suggestions and recommendations stemming from the review are summarized in text boxes at the end of each review topic.

2 Disposal concepts and general principles

Section 10 of the Government Decree (736/2008), requires that the disposal plan be implemented in stages with particular attention paid to aspects affecting long-term safety and §11 of the decree requires the long-term safety to be based on safety functions achieved through mutually complementary barriers. The CLA is the first stage of the implementation of the disposal plan. The following comments are based on a review of Chapters 2, 3, and 7 of Posiva 2012-01 on monitoring at Olkiluoto by a member of the core team.

2.1 Review Topic 1: Surface monitoring system

The biosphere or the surface system is not assumed to be a barrier by Posiva. It comprises the "living environment" that is isolated from the disposed radionuclides by the natural (i.e., rock) and engineered barriers (canister, buffer, backfill, seals, and plugs). From the biosphere perspective; the methods, intended locations of monitoring points, monitoring technique and technology, frequency of observations set out in Posiva 2012-01; are comprehensive and appropriate for both aims of the monitoring programme: (1) to provide data for modelling the biosphere and (2) to verify that the environmental protection objectives have been met in respect of the construction (and later operational) activities at the site. The latter focuses primarily on the immediate vicinity of Olkiluoto Island. Many of the measurements and observations are helpful in populating the data bases that are later used for biosphere safety assessment. The staged nature of the disposal programme means that changes in and extension of the monitoring programme may occur because of an appraisal of the results of the CLA and regulatory feed-back.

Chapter 7 of Posiva 2012-01 covers a broad range of issues relevant to surface monitoring. It is apparent that the main motivation for collecting surface data is to use it in biosphere performance assessment. This document appears to cover all the elements necessary to the creation of a valid and comprehensive database for the surface environment in its current state. How the accumulated data are used in the assessment of the potential radiological impact is crucial and that will determine the requirements of the monitoring and data acquisition programme in the future.

Posiva is making major efforts to determine site-specific geochemical properties of selected radioelements, such as the sorption coefficients. But this is all local to Olkiluoto Island (Posiva 2012-01, Section 7.2.2). With this focus, it is not clear that adequate temporal coverage to accommodate future conditions is achieved since Olkiluoto is already identified to have conditions that are typical of coastal areas. From details provided in Posiva 2012-01, 2012-11, and 2012-06, it is not clear what differences exist, if any, between the biotope properties at the coast and inland (i.e., young terrestrial environments and older environments). It is noted in Posiva 2012-01 that podsolization operates on a centennial timescale. Posiva 2012-11 briefly discusses a set of lakes and mires chosen for study at different distances (and thereby ages) inland. The ages are not noted and this suggests that coverage in not as complete as it might be.

The extension of the monitoring programme into the operational period is not well documented. It is understood from the documentation that the process is iterative. There are implications for future research, development and demonstration (RD&D) programme, for example, (1) the succession and the biotope record inland of the coast is potentially important; (2) C-14 and the carbon cycle for the biotopes identified for the site and its future is important; and (3) consideration might be given to "exotic nuclides" that might arise from the disturbed release scenarios if it is concluded that these need to be studied in greater detail.

Summary

(1) On the whole, the surface monitoring programme is exemplary and thorough, and it is complemented by the routine monitoring of the nuclear power plant environment.

(2) Some knowledge gaps have been identified by POSIVA. We believe that Posiva will address these gaps in future iterations of the disposal programme.

(3) From a long-term safety assessment point of view, we recommend that Posiva pay special attention to monitoring activities related to defining the future evolutionary features of the system and also for validating/verifying models and confirming performance.

3 Scenarios

The Finnish regulations at YVL D.5 §312, require an assessment of long-term safety of the proposed deep geologic repository for spent nuclear fuel. Posiva conducts two sets of analyses related to long-term safety. In the first set of analyses, Posiva estimates the annual dose to the most exposed individual and average annual dose to other individuals. In this regard, YVL D.5 §307 requires, “The disposal of nuclear waste shall be so designed that the radiation impacts arising as a consequence of expected evolution: (a) the annual dose to the most exposed individuals remains below the value of 0.1 mSv and (b) the average annual doses to other individuals remain insignificantly low. These constraints shall be applied over an assessment period, during which the radiation exposure of humans can be assessed with sufficient reliability, and which shall extend, at a minimum, over several millennia (Government Decree 736/2008, section 4).” Posiva asserts that the conditions in the surface environment can be assessed reasonably well for 10,000 years after repository closure and hence conducts dose assessment for this time period. This period is referred to as the dose time window.

In the second set of analyses, Posiva estimates the release rates of selected radionuclides to the biosphere for up to 1,000,000 years. Regulatory constraints for these release rates are provided in YVL D.5 §313 in terms of GBq/a. Results of performance assessment are reported in terms of normalized release rates (NRR) that are obtained by dividing the estimated release rates of a radionuclide by its regulatory limit in §313. Releases meet regulatory constraint as long as NRR ≤ 1. Note that the releases at the geosphere-biosphere boundary during the dose time window become inputs for the calculation of biosphere doses. The quantity (1 – estimated NRR) is a measure of the safety margin.

Formulation of scenarios describing the possible future evolutions of the system is an integral and important part of the safety assessment because it is through the use of scenarios that the effect on safety of potential degradation of the engineered components and the changes in the geologic setting and the surface environment (e.g., changes in climate) can be demonstrated. We use the plural “possible future evolutions” because there is no reliable and universally accepted scientific method to define one unique evolutionary path for the system. Therefore, the postulated system evolutions are analysed taking into account the uncertainties that are inherent in such descriptions. This is acceptable because the repository is a “passive” system in the sense that, after closure, there are no active or moving parts that will need monitoring or maintenance. The evolutionary paths therefore will consist of degradation of engineered barrier system (EBS) components, external disturbances such as geologic and climatic changes and evolution of the surface environment and ecosystems.

3.1 Review Area I: Scenario formulation methodology

3.1.1 Review Topic 1: Scenario construction and description

Posiva’s approach for scenario definition is a pragmatic straightforward approach derived from the aim of complying with the regulatory requirements. This regulation-centric methodology focuses on potential future radionuclide releases and their consequences rather than on defining broadly “all possible evolutions” of the disposal system. Overall, Posiva’s approach is reasonable but it does not easily lend itself to concluding whether all safety-significant evolutionary uncertainties have been accounted in the analysed scenarios. For the next iteration of the safety assessment, Posiva should consider developing a more systemic approach that is more transparent and easier to evaluate for comprehensiveness.

In Posiva's performance assessment, the repository system is conceptualized to have three connected parts: (1) the near field consisting of the near field fractured rock and the engineered barriers, (2) the far field fractured rock, and (3) the biosphere or the surface environment. In Posiva's safety assessment, these three parts are modeled in a series, that is, in response to some process (e.g., corrosion) or an event (e.g., an earthquake), the near field generates a radionuclide source term (e.g., leak from the canister) which is then transported in the far field rock via its dominant features (e.g., fractures) to the biosphere where living entities are exposed to radioactivity. Posiva defines two sets of scenarios; one set for the geosphere (in our terminology, the geosphere includes engineered barriers) and the second set for the biosphere. The two sets of scenarios are developed more or less independently of each other. The primary interaction between these two sets of scenarios is through water and radionuclide fluxes at the host rock – surface soil overburden. This partitioning of scenarios into geosphere and biosphere may not strictly fulfill the formal requirements of an integrated 'systems approach' but we believe that Posiva's current approach is adequate for this first phase of licensing.

For geosphere scenarios, the guidance in YVL D.5 §A104 sets the stage: "The safety case shall include a scenario analysis which covers both the expected evolutions and unlikely events impairing long-term safety. The scenarios shall be constructed so that they cover the features, events and processes which may be of importance to long-term safety and which may arise from (1) interactions within the disposal system, caused by radiological, mechanical, thermal, hydrological, chemical, biological or radiation induced phenomena and (2) external factors, such as climate changes, geological processes or human actions."

The emphasis in §A104 is on consideration of features, events, and processes (FEPs) that can 'impair long-term safety'. Because radiological consequences are of the greatest interest, an appropriate measure of long-term impairment is release of radionuclides to the biosphere. Therefore, it is reasonable to focus on those FEPs that can cause a failure of one or more barriers leading to radiological consequences.

Posiva 2012-08 is the primary report where the scenario methodology is described. To fully understand the implementation of the methodology, however, we reviewed several reports, including Posiva 2012-04, Posiva 2012-09, Posiva 2012-11, and Posiva 2012-12. There may be other documents with greater level of detail that were not reviewed by our team.

With regard to the scenario approach, Posiva states (Posiva, 2012-08, page 105), "… the Finnish regulatory guidelines in Guide YVL D.5, which are in accordance with the IAEA Safety Standard Series No. GSR Part 4 (IAEA, 2009), SSG-14 (IAEA, 2011) and SSG-23 (IAEA, 2012), have been followed. A comprehensive set of safety functions for the repository system components has been identified and reported in *Design Basis* and assessed in *Performance Assessment* under the framework of the expected or normal evolution of the repository system."

The Posiva scenario formulation methodology for geosphere scenarios consists of (Posiva, 2012-08, page 40):

1. The safety functions for each of the repository system components are defined and acceptable characteristics of those components (performance targets/target properties) are identified (see Table 1-1, page 18, Posiva 2012-08 and Posiva 2012-03 for further details);
2. FEPs that could adversely affect one or more safety functions at a given time or place or under specific conditions within the repository are identified;
3. The effects of uncertainties in the expected evolution of the repository system are identified and taken into account;
4. Lines of evolution that describe the evolution of the repository system leading to canister breaching form the basis for the definition of radionuclide release scenarios; and
5. For each of the scenarios, a set of calculation cases is defined to analyse the potential radiological impacts. The calculation cases take into account uncertainties in the assumptions and data through variations in the models and parameter values.

Table 9-1, page 107, Posiva 2012-08 provides a good summary of the relationship between FEPs and the scenarios. The large number of yellow boxes in this table represents the FEPs that are considered in all scenarios. The FEPs in 8 green boxes are additionally included in variant scenario, VS1, and the 3 FEPs colored blue are included in the variant scenario, VS2. Only 2 additional FEPs colored brown are used to define the disturbance scenarios. In our review, we paid special attention to the FEPs that are screened out (uncolored boxes). Of concern are any FEPs that, if excluded, would limit the source term of the radionuclides. One of these is the radiolysis of the canister water (see column titled 'Spent Fuel'). As discussed later, this FEP may be important in the base scenario. The other excluded FEP of concern is advection (see the column titled Canister). This means that radionuclides migrate from the inner void space of the canister to the buffer by diffusion only. Posiva defines a term called the equivalent flow rate, Q_c (Posiva, 2012-09, page 63), to estimate the rate of release of radionuclides from the initially defective canister to the buffer. Q_c (m^3/a) is defined such that when it is multiplied by concentration difference (gm/m^3), the product is the diffusive mass flux. The maximum value of Q_c used by Posiva in the reference case is 4.9×10^{-7} m^3/a (see Figure 4-12, page 107, Posiva, 2012-09). This limits the release rate of radionuclides from the canister's initial defect to the buffer. If there were two defects in the canister then, at least conceptually, an advective path can be established for the radionuclides to be transported from the canister to the buffer. Therefore, the success of the non-destructive testing of the canister welds becomes of central importance for the base scenario. From Table 9-1, it is apparent that Posiva has considered the significant FEPs in developing geosphere scenarios but it is not obvious that all the possible failure modes of the barriers have also been considered; another table mapping the failure modes (non-fulfillment of safety functions) of various barriers should be developed to show that all potential failures have been considered.

Because the biosphere has no assigned safety functions (that is because it cannot be designed or configured), the approach for constructing biosphere scenarios is based much more on estimating evolutionary trends of the surface environment and consequent dispersal and dilution of discharged radionuclides. The two main pathways for radionuclide transport from the repository to biota are through discharge of contaminated groundwater to surface and near-surface biosphere objects (see page 26, Posiva 2012-31 for definition) and the secondary contamination of sea bottom sediments that later emerge as new land due to land uplift (estimated roughly to be 50 m in next 8,000 years, Posiva 2012-29, page 36). The dispersion and dilution processes in the surface environment do significantly affect the estimated dose and can be thought of as biosphere's safety function (Posiva 2012-29, page 90).

Again, Posiva follows guidance in various sections of YVL D.5. §308 require that, "… account shall be taken of the changes in the living environment that arise from changes in ground and sea level. The climate type as well as human habits, nutritional needs and metabolism can be assumed to remain unchanged." §309 require consideration of: "... (a) The use of contaminated water as household and irrigation water and for animal watering and (b) the use of contaminated natural or agricultural products originating from terrestrial or aquatic environments." §310 sets the dose standards for humans: "… for the most highly exposed individuals, 0.1 mSv per year, stands for the average individual dose in a self-sustaining family or small village community living in the environs of the disposal site, where the highest radiation exposure arises through different exposure pathways. In the living environment of this community, a small lake and a shallow water well, among other things, are assumed to exist." §311 sets dose standard for the average individual: "… the average annual doses to larger groups of people living in the environs of a large lake or sea coast shall be … in the range of 1 to 10 % of the dose constraint for the most highly exposed individuals…" and finally, §318 sets the standard for flora and fauna: "The disposal shall not have detrimental radiation effects on species of flora and fauna…"

In addition to following the guidance in YVL D.5, Posiva's approach for defining the biosphere scenarios follows the guidance documented in the European Pilot Study (Vigfusson et al., 2007) and WENRA (2012). Posiva uses a "mixed" approach to define biosphere scenarios: (1) most likely lines of evolution are defined for natural FEPs, such as crustal uplift; (2) stylised lines of evolution are defined for human action FEPs, such as current human habits, nutritional needs and metabolism, which are assumed to remain unchanged; and (3) conditional most likely lines of evolution are defined for certain FEPs – for example, the cultivation of arable land is based on the expected evolution of the soil suitable for cultivation, under the assumption that humans will exercise the same agricultural practices as today.

The procedure for defining biosphere scenarios is reasonably clear. The evolutionary path for the surface environment is reasonably well understood and described by a small number of terrain and ecosystems modelling (TESM) variants. The main uncertainty in defining the future biosphere is in tracking of biotopes of different maturity such as soil evolution during the succession caused by land rise. Other biosphere related issues of concern are: (1) the reliability of the discrete fracture network (DFN) model in identifying the release paths and exit locations (the estimated dose depends significantly on release location); (2) the evolution of soils and their geochemical properties; (3) screening out of certain radionuclides, such as Ra-226 in Tier 2 screening (page 40, Posiva 2012-29); and (4) lack of alternative assumptions about human behaviour such as possible use of a domestic well by a small family or the most exposed group depending on a kitchen garden.

The screening out of sorbing radionuclides is of concern in case a disturbance scenario, in which a seismic event occurs before 10,000 years and sorbing radionuclides have the opportunity of not only entering the biosphere but also has an opportunity of concentrating in certain biotopes. The potential importance of long-timescale accumulation is illustrated in the results for the most exposed population in Figure 9-1, page 226, Posiva 2012-10. Additional nuclides might potentially be important in the event of an extreme tectonic disturbance scenario (M > 5) before the 10,000 year.

Posiva's approach for combining effects of external and internal factors in defining scenarios is reasonable. On page 109 of Posiva 2012-08, Posiva states, "The entire disposal system has been taken into account in formulating the scenarios. Climate and climate evolution constitute the envelope for the evolution of the disposal system. In the expected/normal evolution, no canister failures are projected to occur in the first 10,000 years and not even within 100,000 years. Nonetheless, and to account for incidental deviations, in the base scenario one canister is assumed to have an undetected initial penetrating defect through which releases will occur 1,000 years after emplacement, whereas the safety functions of the rest of the barriers are maintained."

Posiva's rationale for assuming that release will not begin before 1,000 years in the base scenario is described in Appendix J, page 757, Posiva 2013-01. Posiva states that the cast iron insert is a massive structure and it will serve as a temporary barrier to groundwater intrusion. However, the main reasons for assuming the 1,000 year delay are (1) the defect will be in the lid weld and it will be located at the top of the canister and (2) the canister will have to fill with water before any radionuclides can exit the canister from this defect at the top. Posiva estimates that it will take time of the order of 1,000 years before this happens (see scoping calculation on page 763 of Posiva 2013-01). However, this leaves the question of whether a weld will be used at the bottom of the canister as Posiva considers manufacturing copper shell by using either the extrusion method or pierce-and-draw method (Posiva, 2012-13, page 117); the extrusion method will require a weld at the bottom. The worst case will be a defect at the bottom and another at the top weld that would create a pathway for water to enter at the top and radionuclide laden water to exit at the bottom. Posiva should provide a clarification on the method to be used for manufacturing the copper shell and whether or not there will be a weld at the bottom.

In addition to climate change, geologic processes giving rise to earthquakes capable of shearing the canister (M > 5) are also considered in formulating scenarios. While the link between climate change and the likelihood of a capable seismic event is discussed in the safety case, this link is ignored in estimating the probability of the seismic event. In other words, the higher probability of a capable seismic event during the post-glaciation period, while acknowledged, is ignored. Instead an average probability of 10^{-7} per year for an event with M > 5 within 5 sq. km of the site is used. It is clear that the probability per year of an earthquake will be higher than this average in the post-glacial period and it will be smaller than this average in the period before the first glaciation episode. In addition, the reasoning for not considering the occurrence of a large earthquake in the first 10,000 years (i.e., the dose time window) is also not explained. Posiva acknowledges that the timing of the earthquake (40,000 years) considered in scenario named RS1 is arbitrary (i.e., does not have a geologic basis). There probably is also no geologic basis to consider such an event at a time < 10,000 years (say 200 years) but it seems reasonable to analyse this (unlikely) scenario to see its effect on the biosphere (i.e., on dose to humans and the environment). In response to a request for additional information, Posiva provided an analysis that assumed an earthquake at 200 years. For a review of this additional information, see Appendix A.

Regarding internal factors, Posiva states (Posiva, 2012-08, page 61), "During the expected repository system evolution (see Chapters 5, 6, and 7 in Performance Assessment), most performance targets and target properties hold for tens to hundreds of thousands of years. Also, by following improved quality control measures in canister manufacturing and emplacement, it is expected that there will be **no canisters with an initial penetrating defect in the repository** and, thus, there will be no radionuclide releases, at least within the first several millennia (emphasis added)." This statement contradicts the basis for the base scenario in which a small initial defect is assumed in one canister. Also, in a meeting in Helsinki in September, 2013, in response to a question from STUK regarding whether all the safety functions of all barriers were simultaneously fulfilled, Posiva responded by saying that the target properties were fulfilled when needed implying that safety functions may be fulfilled at various times as and when needed. The safety functions and design requirements for engineered barriers defined by Posiva (see Posiva, 2012-04, page 33–42) are descriptive or non-quantitative, but the design specifications are quantitative. For example, many of the safety functions of buffer depend on its saturated density for which a design target of 2,000 kg/m^3 is set (Posiva, 2012-04, page 223). The design value for the initial saturation of buffer is 60 percent and the hydraulic conductivity at this saturation is 5.59×10^{-14} m/s (Posiva, 2012-04, page 218). Considering the range of inflow conditions, Posiva calculated (See Figures 6-17 and 6-18 in Posiva, 2012-04, page 219) a saturation time varying from 600 years to 12,000 years. Clearly, the time at which the buffer will attain its target hydraulic and mechanical properties will vary widely from deposition hole to deposition hole. It certainly will not be attained simultaneously at all locations, nor will it be simultaneous with other engineered barriers attaining their target properties.

The important question from the safety perspective, in the above example, is whether Posiva considered impacts of such delayed saturation in its safety demonstration. We note that the only breach in the canister considered by Posiva in the first 10,000 years or even in 100,000 years is the 1 mm initial defect in one canister (up to four canisters in the sensitivity case). For the safety assessment, Posiva assumes that this canister is emplaced in a deposition hole that has a high inflow rate, that being the pessimistic assumption. If it were placed in a deposition hole in which the buffer was still unsaturated, a plausible transport path would not exist. The other possibility is that a canister is breached during the period of saturation, say, by a large earthquake. Again, with no transport path, the release to geosphere will not take place. The other possibilities that one may have to consider are that the long-term unsaturated conditions may give rise to (1) a temperature higher than 100 °C in the buffer, (2) an existence of an adverse microbiological or chemical transformation, and (3) a homogenization process that is not as homogeneous as assumed, affecting its mechanical properties. STUK has sent Posiva a request for additional information on this topic. In response to a request for additional information, Posiva provided several analyses explaining the buffer saturation process. Our review of this additional information is documented in Appendix B.

Posiva makes an overriding assumption in its safety case that all manufacturing processes, transportation, emplacement, operations, etc., will follow the Posiva-established (and presumably STUK-approved) quality assurance processes and procedures. As a consequence, except for assuming a small initial non-enlarging defect in one canister (or in up to four canisters in a calculation case), all other steps in manufacturing, emplacement, and closure are assumed to be flawless, at least in the design-basis or the base scenario-reference case (BS-RC). For example, no initial defect is assumed in any of the hundreds of thousands of buffer components. Similarly, potential multiple small defects in canister welds, including defects in the weld of the bottom plate are ignored. That Posiva will be able to follow perfectly its emplacement criteria based on the Rock Suitability Classification (RSC) criteria is also doubtful. Some, but not all, of these potential “incidental” deviations are considered in the variant scenarios. We understand that STUK is developing its inspection procedures that would be applied during underground construction and during fabrication of engineered barrier components, and during operations to assure that the specifications that form the basis of the CLA are fully honored or the differences are taken into account in revised safety assessments. STUK is also developing a process to define how variances from design specifications and breaches of quality control during construction and emplacement will be dealt with. Review of additional information on this topic provided by Posiva is documented in Appendix A.

References

IAEA. “Safety Assessment for Facilities and Activities – General Safety Requirements.” IAEA Safety Standard Series No. GSR Part 4. Vienna, Austria: International Atomic Energy Agency (IAEA). 2009

IAEA. “Geological Disposal Facilities for Radioactive Waste – Specific Safety Guide.” IAEA Safety Standard Series No. SSG-14. Vienna, Austria: International Atomic Energy Agency (IAEA). 2011.

IAEA. “The Safety Case and Safety Assessment for the Disposal of Radioactive Waste – Safety Specific Guide.” IAEA Safety Standard Series No. SSG-23. Vienna, Austria: International Atomic Energy Agency (IAEA). 2012.

Vigfusson, J, Maudoux, J, Raimbault, P, Röhlig, K-J, & Smith, R E. European Pilot Study on the Regulatory Review of the Safety Case for Geological Disposal of Radioactive Waste Case Study: Uncertainties and their Management. 2007.

WENRA. Draft Report: Working Group on Waste and Decommissioning (WGWD), Radioactive Waste Disposal Facilities Safety Reference Levels Report. 2012

Summary

(1) Posiva has described its approach to defining scenarios in sufficient detail such that it can be understood by an informed reader.

(2) Posiva’s scenario approach meets the intent of identifying system evolutions to account for possible impairment of long-term safety. However, Posiva should provide a clearer picture of relationship between impairment of barrier performance targets and scenarios (for example, a table similar to Table 9-1, Posiva 2012-08, page 107 except that the new table should map barrier target properties to scenarios).

(3) The scenario approach is not as systematic as it can be but it is sufficient for safety assessment at this stage of the licensing process.

(4) The scenarios appropriately take into consideration the combined effect of the external and internal factors on the repository system.

(5) No quality non-conformances, except for assuming an initial defect in one canister, have been considered in defining scenarios. STUK is (a) conducting an in-depth review of the welding methodology and the application of the non-destructive testing to identify possible common cause failures in these processes; (b) considering the type of inspection procedures that it will need to develop and implement during the operational period; and (c) defining how variances from design specifications and breaches of quality control during construction and emplacement will be dealt with and Posiva should be asked to consider the potential of quality non-conformances in defining scenarios.

(6) The rationale for not considering the most exposed group as one with a home garden is not provided. STUK has requested a clarification on this topic from Posiva.

(7) The reasoning for not considering the occurrence of a large earthquake in the first 10,000 years should be explained or an analysis conducted of such a scenario.

(8) STUK has requested Posiva to provide a more complete analysis of buffer saturation and its impacts on performance.

3.1.2 Review Topic 2: Inclusion of key factors in scenarios

The temporal scale (one million years) and the spatial scale (≈10 km^2) of the repository system is large enough to make description(s) of its evolution complex and uncertain. One way to handle this complexity is to identify the key factors affecting safety and consider the possible evolution of these factors. In this section, we review this aspect of the scenario construction. As stated in YVL D.5 §A04, the scenarios shall be composed to include, "radiological, mechanical, thermal, hydrological, chemical, biological and radiation-related factors internal to the disposal system; …"

Posiva's definition of a scenario is reported on page 27 of Posiva 2012-08: "… a scenario represents one time history of conditions, (called hereafter a line of evolution) or more than one (lines of evolution)." A finite set of discrete and deterministic "postulated paths of development" are defined by considering the applicable FEPs and performance targets during four discrete time periods: (1) operational period of 100 years, (2) the dose window of up to 10,000 years in which present-day temperate climate and current human habits are expected to continue to prevail, (3) up to the beginning of the first glacial cycle – 155,000 years after present, and (4) up to 1,000,000 years with repeated (eight) cycles of glaciation. While this time discretization does not provide a continuous evolutionary picture, we believe that it is sufficient to demonstrate safety. It is obvious that the accuracy of the postulated evolutionary path is diminished with increasing time. This lack of accuracy is somewhat balanced by the decrease in radiological risk from the repository with increasing time. In this deterministic-discrete approach, the completeness of the scenario set is the question that demands examination. The comprehensiveness of the scenario set is discussed by Posiva on page 106, Posiva 2012-08 and in Table 9-1 on page 107. Table 9-2 on page 109, Posiva 2012-08 also rationalizes the binary combination of the scenarios. In general, in a scenario the future situation is described conceptually which is then represented by appropriate conceptual/mathematical/numerical models. Even the base scenario-reference case, which is the simplest of all scenarios, requires a set of mathematical models with many assumptions and 160 parameters. Because of the large number of FEPs, safety functions, models, and parameters, it is not easy to describe clearly and unambiguously each of the scenario and the associated calculation cases. We found that Posiva's documentation of scenarios is not very transparent and at places it is confusing. There is no single Posiva document that lists all the geosphere and biosphere scenarios and calculation cases for a reader to get a sense of the breadth of this work and the safety information garnered from each scenario or calculation case. This is one part of the deficiency in Posiva documentation as will be discussed at several places in this report. Posiva should be urged to rethink its document hierarchy to make it less fragmented; especially, Posiva should provide a complete description of scenarios in one document.

As noted earlier, while there is a strong link of FEPs to scenarios, the same is not true of the link between performance targets and scenarios.

An example where the fulfilment of key safety functions remains unclear is the case of the buffer. A low rate of inflow to deposition holes is generally considered positive for repository safety. To emphasize this, Posiva has defined RSC criteria (Posiva 2012-24) to limit the inflow to a deposition hole at the time of canister emplacement to 0.1 L/min; holes with greater inflow are not used. Another performance target limits inflow under saturated conditions to 1 L/year/meter of intersecting fracture. However, the lower the inflow rate, the longer it takes to saturate the buffer. Buffer saturation is required for its swelling property to be activated. Swelling is important to fulfil the transport- and strength-related target properties of the buffer. Posiva states that it may take many thousands of years for the buffer to saturate in some of the drier deposition holes (see Appendix B for some additional information). All scenarios assume that the buffer fulfills all its safety functions irrespective of the time it takes to saturate the buffer. STUK has requested additional information on this topic. This aspect was also discussed in Review Topic 1.

Earlier, we pointed to the exclusion of two possible FEPs from consideration in defining geosphere scenarios (i.e., advection from the container defect and hydrolysis of container water). Other than those, we find that, significant FEPS have been considered. For the biosphere, the FEP defining the characterization of the "critical group" or the 'most exposed group' has ignored the possibility of a group of people using a kitchen garden rather than a commercial farm for producing food. In general though, the expert judgment used to define scenarios identifies futures for the system adequately. The issue is more one of completeness of the range of futures addressed.

Posiva describes the initial state of the system or the present conditions in Chapter 3 of Posiva, 2012-04. That is the starting point for defining the future lines of evolution. The link between the present conditions and the future is described by identifying the evolutionary FEPs, that is, those FEPs that describe the space-time evolution of various repository components (Chapter 4 of Posiva, 2012-04). The major processes involved in system evolution are well known and these have been investigated for a long time (see page 189 of Posiva, 2012-04). For the geosphere, these are heat transfer, groundwater flow, rock stress redistribution, rock-water interaction, montmorillonite transformation, alteration of accessory minerals, chemical and physical degradation of closure material, corrosion of copper overpack, and stress corrosion cracking. For the biosphere also, the processes are well known, i.e., climate, land uplift, surface and near surface hydrology, land use, and human habits. Posiva considers all the processes, some in simplified form, others in more detail in modelling system behaviour in performance assessment. Because of the large spatial and temporal scales and also other uncertainties, the cause and effect links make numerous assumptions. The impact of some of these assumptions is then investigated through calculation cases (deterministic sensitivity analyses) and probabilistic sensitivity analysis (PSA).

The biosphere scenarios also present plausible cause and effect links connecting a future condition with the present. Expert judgment is applied to the driving FEPs, sea level rise and land uplift. The main issue concerns the interpretation of land use. While this is a difficult matter to address, the method used in UNTAMO tool box (Posiva 2012-29, starting on page 65) appears to be quite practical. Biosphere scenarios take uncertainties into consideration adequately in terms of the evolution of the surface system; the UNTAMO results suggest that there is little variation in terms of landform. This is related to the prescriptive nature of the regulatory guidelines. While land rise is relatively easy to understand and implement in the models for dose assessment, yet It is not clear if the changes in flow system with land rise are adequately implemented. The selection of the appropriate flow system from the discrete fracture network (DFN) model sample space is also an issue for the model implementation. As noted above, however, there are concerns about the definition of exposed groups at the higher end of the dose distribution. This does not relate to how the model landscape is configured and described, rather it is the identification and characterisation of human behaviour that, we believe, is not adequately addressed.

Assumed impairments of safety functions are central to Posiva's approach in defining scenarios. We understood that STUK interprets its requirement in YVL D.5 §704 b, "Compliance … shall be proven through a safety case that shall at least include: the specification of performance targets for the safety functions" to mean specification of quantitative performance targets. STUK requested Posiva to provide quantitative performance targets. While, some additional information was provided by Posiva in response, the performance targets/criteria remain qualitative. However, for engineered barriers (canister, buffer, backfill, and closure), Posiva provides quantitative design specifications. In Posiva 2012-04, performance requirements and the key factors contributing to the performance are given in Table 2-1, page 33 for canister, Table 2-2, page 35 for buffer, Table 2-3, page 37 for backfill, Table 2-4, page 39 for closure, and Table 2-5, page 41 for the host rock. Posiva asserts, although we have not seen documentation, that the design specifications are based on iterative optimization of the functioning of the various components throughout the compliance period (1,000,000 years) and under various scenarios. Such documentation can go a long way in clarifying the relation between performance targets, design specifications, built-in safety margins, and their overall impact on repository safety. We have identified need for documentation showing the rationale for design specifications and how these are derived and how these are optimized with respect to safety, ease of handling, constructability, fabrication and cost, etc. as a STUK requirement for the next phase of licensing. The net effect of assuming the attainment of performance targets is the assumption that components built to the specified design can be

Summary

(1) There is a reasonable link between FEPs and the scenarios; however the link between performance targets and scenarios is not so transparent.

(2) The discretization of time period into four intervals to describe system evolution is reasonable and each scenario is able to describe postulated path to the future.

(3) Conceptually, scenarios provide appropriate cause and effect links.

(4) Documentation of scenarios is distributed over many documents. The documents have lot of duplication and yet each document leaves out crucial information. This situation should be remediated by developing a single document containing a clear and transparent description.

(5) We were unable to find a clear description of the link between the EBS design specifications and the RSC criteria to overall safety. For clarity and better understanding of system robustness, a clear link should be established and documented. Posiva should provide rationale for the engineered barrier design specifications and RSC criteria based on their relationship to fabrication, construction, transport, emplacement, and operational and long-term safety.

(6) Posiva should clarify the effect of future human behaviour on definition of the most exposed group.

(7) The effectiveness of the QA / QC system needs to be documented with special attention to potential random and systematic human errors.

and are assumed to experience no failures in the base case scenarios, except for the artificial assumption of one canister having a pin-hole defect. However, to account for inherent uncertainties, Posiva constructs a few variant scenarios based on assuming incidental deviation (incidental meaning unforeseen and neither expected nor designed for; we don’t understand why the scenario with one canister having an initial defect doesn’t fall into this category) in the performance of one or more components. However, the link between specific non-fulfillments of performance targets to scenarios is not systematically examined or fully documented.

One of the primary issues is the assumption that the quality assurance/quality control (QA/QC) procedures (ISO 9001-2008, page 26, Posiva, 2012-04 and in other reports) will work flawlessly. Human errors during construction, fabrication and assemblage of engineered barriers, transportation, emplacement, and operations seem to have been ignored. It would be interesting to analyse the past quality record to see how many major and minor quality breaches were observed. This can provide a trend for the future. This can also be used by STUK to design its future quality auditing process.

3.1.3 Review Topic 3: Comprehensibility, consistency, transparency, and traceability of scenarios

The “paths to the future” in Posiva’s safety case are comprehensible in the sense that Posiva provides adequate reasoning for defining such paths. These are traceable in the form of models and parameter values (which can vary in space and/or time) that are used in the analysis of each path. We did not trace the parameter values used by Posiva to the source and did not form a judgment regarding the correctness of these input parameters; that could be the subject of more detailed reviews. The paths to the future defined by Posiva are plausible and distinct but there can be other plausible paths. In our view, from the safety perspective, what is important is to ascertain whether the evolutionary paths used in safety assessment reasonably bound the doses and/or releases from the repository. That is, there should be reasonable assurance that there is not another plausible, consistent path that can lead to release higher than calculated in the safety case. As indicated above, a few additional plausible evolutionary paths can be identified. Examples of such paths include: (a) large earthquake during the dose window (see Appendix A for additional information); (b) more than one defect in one canister; (c) several canisters with multiple defects; (d) defects in initial configuration of buffer and closure components; (e) consideration of human habits in definition of ‘most exposed group’, etc. These additional scenarios can either be eliminated through reasoning (low likelihood of occurrence or low consequence) or additional analyses could be performed.

Because of the large volume of Posiva documents, traceability is an issue. Relevant information is spread across a number of reports that could be better structured. There is much duplication across reports. This has presumably been done so individual reports form ‘standalone’ documents,

Summary

(1) Posiva's definition of the paths to the future is Plausible, although one can define other plausible paths. We have suggested a few other plausible scenarios at various locations in this report. However, we believe that the Posiva-defined scenarios reasonably bound the system risk for this first phase of licensing.

(2) The future paths are comprehensible and distinct as these paths are defined clearly via the use of model parameters that can vary in space and / or time.

(3) Scenarios are traceable via the defining model parameters.

(4) The credibility of the evolutionary path selected as the base scenario (a small time-invariant defect in one canister) is difficult to justify; Posiva should consider using another scenario as the reference scenario.

(5) The transparency can be improved by developing a better-defined document hierarchy. Documents developed in the PDF format should have bookmarks.

and also reflects the sequence in which reports were completed and issued. However, this approach makes it difficult to ensure consistency, and greatly increases the amount of material to be read, especially when seeking specific details; often we had to review broadly similar material across a number of reports to find the one report which included the detailed information we required. Because reports were produced at different times, there are instances of circular referencing, where reports refer to each other without providing the referred information in any of them. Given that none of the reports are fully comprehensive; for future iterations of the safety assessment, it would be preferable if Posiva reduced the amount of duplication across reports. This will require application of a rigid document structure, but it should improve quality, transparency and traceability. Another detriment to transparency is that the documentation has not been created with embedded bookmarks in documents produced in the portable document format (PDF). To have done so would have greatly aided navigation. Future documents in the portable document format should include this feature.

As stated earlier, there are concerns that the biosphere scenario analysis may not be comprehensive and that some aspects, particularly of human behaviour and the interaction of potentially exposed groups with their environment is incomplete.

3.2 Review Area II: Scenario classification

3.2.2 Review Topic 1: Methodology for scenario classification

The Posiva methodology used to classify scenarios closely follows STUK guidance in YVL D.5. The methodology is described in detail and it is sufficient for an informed reader to understand. For each of the base, variant, and disturbance scenarios, Posiva defines calculation cases categorized into reference, sensitivity and "what-if" cases. In addition, there are "complementary cases" that according to Posiva enhances the understanding of the system. According to Posiva, these additional cases are required to delineate the impacts of model and data uncertainties (Posiva 2012-08, page 29). While there is some logic to all these categories, yet there is a lot of arbitrariness in classifying the calculation cases. This makes tracking of scenario characteristics and their effect on the performance somewhat difficult.

Biosphere scenarios do not so readily fit into the classification scheme used for the geosphere; namely base, variant and disturbance. The methodology used to classify biosphere scenarios could be revised to improve transparency but we believe that an appropriate set of scenarios for the biosphere are generated.

Summary

(1) Posiva's scenario classification strategy is based on requirements in STUK regulations at YVL D.5.

(2) Posiva's division of calculation cases into reference, sensitivity, what if and complementary cases is arbitrary and does not add to clarity. Posiva should consider developing a correlation matrix that would show the relationship between main arguments of a calculation case and the model result.

3.2.3 Review Topic 2: Sufficiency of baseline scenario (GD 736/2008, §14; YVL D.5 §A105)

The baseline geosphere scenario is based on the assumption that the rock fulfils all its safety functions and the engineered barriers perform as designed, meaning that they too meet all their safety functions, which, as stated before, are qualitatively described. This meets the definition in YVL D.5 §A105, "The base scenario shall assume that the performance targets defined for each safety function are met." There is only one exception to this and that is that one of the canisters is assumed to have a small (1 mm diameter) penetrating hole in upper lid weld because it was undetected defect during fabrication. The reason for making this exception to the basic assumption may stem from the (possibly incorrect) interpretation of the wording in YVL D.5 §306 that talks about non-zero dose as a consequence of "expected evolutionary scenarios". Posiva's safety case makes it clear that there is no such "expected evolutionary scenario." The baseline biosphere scenario uses the discharge locations calculated in the geosphere baseline scenario and assumes that present-day demography such as number of inhabitants in the region and human habits such as land use continue to prevail. The discharge locations are a function of the deposition hole location in which the defective canister is emplaced. The base scenario-reference case could also be called the design basis scenario except for that one defective canister.

Posiva recognizes five barriers in its repository system: (1) canister, (2) buffer, (3) backfill, (4) closure components, and (5) host rock. Among these, we believe that the canister is the most important barrier as it is this component that isolates the waste from the geosphere for a very long period. So long as the canister is not penetrated, the spent fuel inside the canister decays safely. Each of the other four barriers has a dual function – to protect the canister and, in case the canister fails, to minimize the migration of radionuclides through host rock to the biosphere. From Figure 8-2, page 187, Posiva 2012-12, that presents the results of the base scenario, it is apparent that the difference between the near field and the far field releases is exceedingly small (almost negligible). Therefore, it is the contribution of the near field host rock that is really important to long-term safety except that the far field rock does provide protection to the integrity of the engineered barriers. The host rock together with the buffer, backfill, and closure is designed to prevent and/or slow down the movement of chemicals that can corrode the canister, as well as to protect the canister structurally. The cast iron insert inside the canister is expected to take all expected mechanical loads with some help from the host rock and buffer. Even though the spent fuel itself is not termed a barrier by Posiva, it nevertheless provides considerable resistance to release of radionuclides. Except for the instant release fraction (IRF), the release of other radionuclides is controlled by the spent fuel dissolution rate. Posiva assumes that the spent fuel will maintain its integrity throughout the assessment period and will maintain a constant dissolution rate. In this regard, Figure 13-1, page 323, Posiva 2012-09 is instructive. The figure shows that for the entire time period of 1 million years, the spent fuel continues to hold the majority of the radioactivity (90% or more) and of the activity that does leak, majority is held by the canister. Further, this figure shows that at one million years, less than 0.001 % of the activity would have entered into the biosphere. As stated by Posiva, "This illustrates the effectiveness of the spent nuclear fuel and canister in providing long-term containment …" Despite Posiva not categorizing spent fuel as a barrier, it is clear that it is indeed a highly effective barrier to release. It should be noted that containment of radionuclides in the near-filed forms the foundation of Posiva's safety case. It is not clear to us how the integrity of spent fuel will be ascertained before encapsulating it in the canister. A longer-term experiment, during the operational period, of remotely monitoring the health of spent fuel may be a worthwhile effort, given its importance. Also, a sensitivity analysis assuming damaged spent fuel may also provide a measure of confidence in safety assessment (see Appendix A for some additional analysis provided by Posiva).

That the performance targets for various safety functions are likely to be fulfilled in the base scenario is demonstrated by Posiva by modelling the evolution of the system. Posiva's arguments are presented in Posiva 2012-04, Chapters 5–8. These demonstrations take the form of modelling system components as they evolve in the four assumed time frames. Posiva recognizes that some conditions and some uncertainties may cause deviations from fulfilling the performance targets. These are discussed in Chapter 9 of Posiva 2012-04. On page 419, Posiva 2012-04, it is stated that, "The assessment presented in Chapter 6, and especially in Sections 9.2.3, 9.3.3, 9.4.3, and 9.5.3 demonstrates that for the expected evolution of the site and the repository, all requirements in terms of performance targets and target properties for the rock, the closure, the backfill, the buffer and the canister will be met during the assessment period with the following exceptions…." The exceptions include: (1) a few deposition holes may have a flow greater than 0.1 L/min; (2) for a few deposition holes and for a limited period, the groundwater composition may differ from target values; and (3) buffer in a few depositional holes (less than 10 out of 5,000) may be subject to chemical erosion. Such potential deviations are analysed in calculation cases.

The rock and engineered barriers related assumptions for the base scenario-reference case are summarized in Posiva 2012-08, page 49, Table 3-1. The primary assumption for the bedrock is that the RSC criteria are successfully applied. This assumption implies that the hydrogeological and geochemical conditions in the bedrock fulfill the target properties. It also implies that external conditions such as climate change and seismic activity do not alter rock conditions to an extent that the performance of engineered barriers is degraded. In other words, all system components behave according to their design basis except that one container has a 1 mm initial time-invariant defect (incidental deviation); colloidal transport and advective transport are not considered; the initial defect is small and has a transport resistance which is assumed to be lost after 1,000 years; the insert corrosion rate is very small (0.1 to 1 µm/year); and water quality is assumed brackish. The defective canister is cautiosiously assumed to be placed in a deposition hole with relatively high inflow rate but less than 0.1 L/min. The impact of this cautious assumption is that the peak release rate is an order of magnitude higher than that calculated by assuming a random placement of the defective canister (Posiva 2013-01, page 595 and Figure 7-20, page 596). Although this result shows the sensitivity of release rate to water inflow into the deposition hole, it still does not fully explain the basis of the 0.1 L/min RSC criteria. In the absence of information, we speculate that the RSC criteria result from ease of construction and emplacement of engineered barriers.

Posiva expects conditions in the repository to be chemically reducing, and notes that fuel dissolution rates could be higher under oxidising conditions. Radiolysis of water generates oxygen. For the majority of scenarios this will not be important because the canister provides complete containment until the radiation fields diminish significantly. Posiva (2012-11, Section 8.1.2) provides complementary evidence that the impacts of radiolysis by alpha radiation will not be important in the long term. However, radiolysis might be important for the base scenario. Although there are no releases from the canister until after 1,000 years, water enters the canister during this period. Radiolysis of water then could lead to enhanced dissolution of the fuel. The reasons for excluding this process from the base scenario are not clear. We note that accelerated corrosion of zirconium-based fuel cladding alloy and other metals have been considered. It is not clear whether the cladding is considered to protect the fuel from oxygen while the radiation field decays, even under conditions of accelerated corrosion. Overall, radiolysis may not be an important process for release of key radionuclides, but the treatment of radiolysis and reasons why it is not a key process should be made clearer.

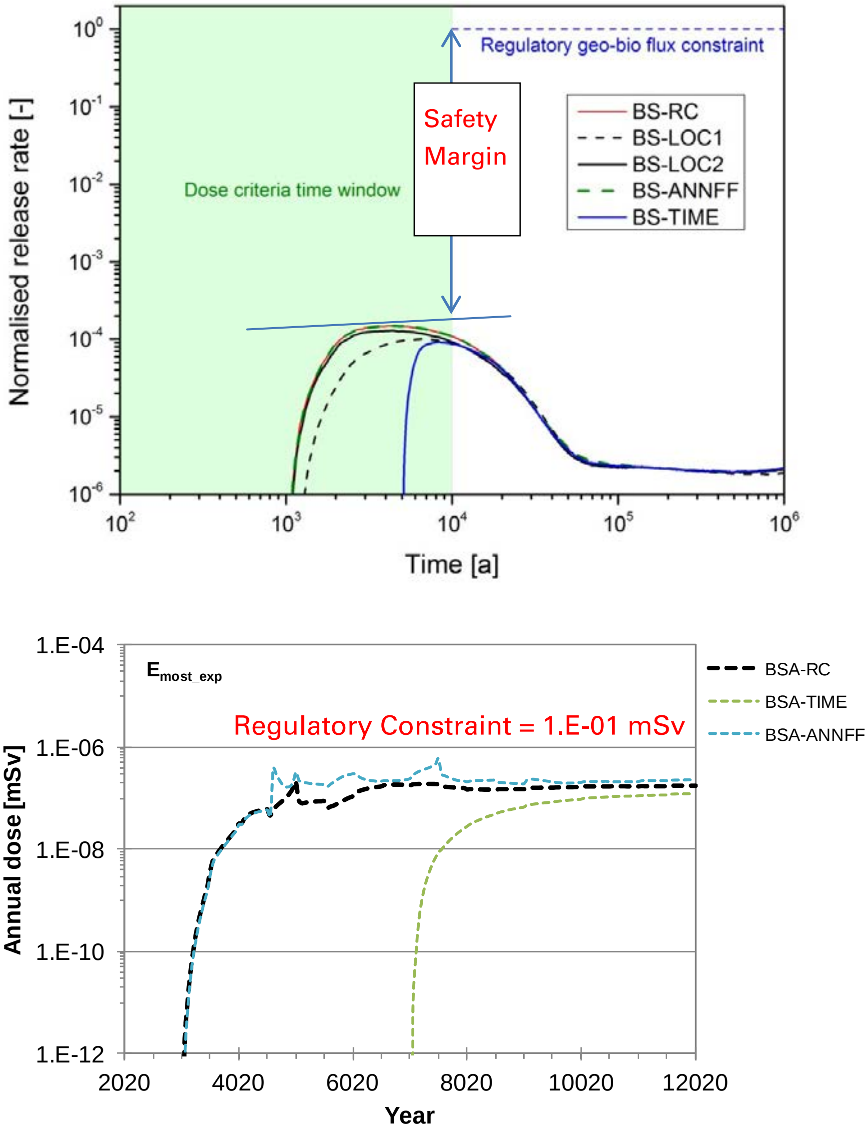
The key assumptions for defining the biosphere base scenario are related to sea level change, climate change, and land use. In brief, the assumptions include (i) a discharge location that is calculated in the geosphere base scenario, (ii) today's climate continue for 10,000 years, (iii) humans consume contaminated produce at the site without preference, (iv) current land use pattern is maintained, (v) number of wells are consistent with present day average well density, and (vi) plants and animals continue to occupy biotopes consistent with current information.

The assumptions with respect to the five barriers in the base scenario are succinctly summarized in Table 7-1, page 165, Posiva 012-12. From this table, we can conclude that all the assumptions necessary for the realization of the base scenario are clearly presented.

The uncertainties in defining the base scenario-reference case (BS-RC) are accommodated by defining calculation cases and complementary scenarios. For the bedrock and EBS, Posiva considers four calculation cases: (1) BS-LOC1 and (2) BS-LOC2 – Defective Container Located at Different Deposition Holes: (3) BS-TIME – Transport Allowed from the Defect at a Specified Time (transport resistance is lost in 5,000 years); and (4) BS-ANNFF – Speciation of some Ions as Anions – Ag, Mo, and Nb migrate as anions. No calculation cases are defined for biosphere base scenario-reference case (BSA-RC).

Results for the base scenario are presented in Figures 8-1, 8-2, 8-6a, 8-6b, POSIVA 2012-12. Two representative figures showing results for the base scenario are reproduced below. As can be seen in these figures, the maximum normalized release rate of approximately 10^{-4} occurs at about 3,000 years. Results of all calculation cases are similar except for the BS-Time [blue curve in Figure 1(a)] where the transport resistance of the defect is lost in 5,000 years instead of in 1,000 years in the BS-RC. Figure 8-2, page 187, Posiva 2012-12, not reproduced here, shows that there is little difference between the release rates at the near-filed and far-field boundaries. Most of the release is made up of C-14, I-129, and CL-36 which are non-sorbing radionuclides with unlimited solubility. This means that the far-field rock's contribution to mediation of radionuclide transport is minimal. Of course, let us not forget that the far field rock does provide a safe environment for the EBS. Figure 1(b) shows the dose to the representative person in the most exposed group. The peak annual dose is estimated to be less than 10^{-6} mSv compared to the regulatory constraint of 10^{-1} mSv. It is apparent that under the "expected" evolution of the base scenario, the system is designed to have a large amount of safety margin – a factor of 10^5 better than the dose safety standard and a factor of 10^4 better for the normalized release standard. We have raised some questions about both the geosphere and the biosphere assessment and those should be clarified but it is clear that, at least for this scenario, there is no possibility of exceeding the regulatory dose standards.

In addition, independent calculations of normalized release rates by a member of the core review team obtained results similar to Posiva's results, thus confirming Posiva's calculations. The independent calculations concluded that even if all the canisters were to have similar initial defect,



(a)

(b)

Figure 1. Results for the base case scenarios. The figure (a) shows the normalized release rates and the figure (b) shows the annual doses to representative persons within the most exposed group.
[Adapted From Figure 8-6a and 8-6b, pages 195 and 196, Posiva 2012-12]

the regulatory radionuclide flux constraint will likely not be exceeded. This conclusion is also supported by the calculations presented in Section 6 of Posiva 2014-02. Independent calculations of human dose, using a much simpler model, by another member of the review team indicate that while the doses calculated by Posiva using the complex fully dynamic model may not be conservative (the independent estimate was an order of magnitude higher than Posiva's estimate), there is little risk of exceeding the regulatory constraint.

The reference cases, the BS-RC and the BSA-RC and their combination are the simplest scenarios defined by Posiva. These are essentially based on assuming (i) all safety targets of the host rock and engineered barriers are fulfilled "when needed" and (ii) present surface conditions will continue except for the land uplift in the surface environment. Posiva expects these scenarios to be the most likely. Even though these scenarios are simple, they form the bases for defining all other scenarios. That is, the variations in one or more of the assumptions of the BS-RC and BSA-RC define the other scenarios.

If we accept, at face value, that the capability of the far-field host rock in either delaying or attenuating the leaked radionuclide pulse is really not needed for safety than STUK may want to pay greater attention to reviewing the near field, meaning the estimation of source term. Note that in the BS-RC, the only source of radionuclides is the small initial defect in one canister that is assumed to be placed in a pessimistic location. To judge the realism of this scenario, it is critical to review in detail the methodology for canister manufacture and the non-destructive techniques used to detect flaws in canister welds. It is also recommended that an in-depth review be conducted of the welding methodology and the application of the non-destructive testing that will be used by Posiva.

A primary drawback of the BS-RC is that in it none of the safety targets of any of the barriers are even minimally challenged and thus it is not informative with respect to the strengths and weaknesses of the system. There is little doubt in our mind that Posiva believes that in the expected evolution of the system, the release will be zero at all times. Posiva includes an initially defective canister in its reference case only because it interprets the STUK regulations to require inclusion of a non-zero source term in the reference case. We suggest that Posiva should either define the reference case as the zero release case or consider that all aspects of the design basis will likely not be realized in the 1,000,000 years and define a reference case that is more realistic and informative. One of the more likely variant cases could actually serve as the reference case.

Summary

(1) The baseline scenario is somewhat artificial because of the assumption of one canister with a small initial unchanging defect. It is neither a design basis nor a realistic scenario to demonstrate the performance characteristics of the system.

(2) All performance targets are fulfilled; in fact none of the performance targets are even minimally challenged in this scenario.

(3) Under Posiva's design basis scenario, there would not be any release from the repository.

(4) Results in Figure 8-2, page 187, Posiva 2012-12 shows that the contribution of the far-field rock in delaying or attenuating the releases to the biosphere is minimal (although obviously the far field rock provides "safe environment' for the engineered barriers); therefore, relatively more resources should be spent on evaluating the performance of the near-field rock and the EBS.

(5) Posiva should consider defining a more illustrative baseline scenario.

3.2.4 Review Topic 3: Sufficiency of variant scenarios (GD 736/2008, §14; YVL D.5 §A105)

In Posiva's methodology, variant scenarios are constructed by assuming degraded performance of a safety function as required in YVL D.5 §A105, "The influence of declined performance of single safety function or, in case of coupling between safety functions, the combined effect of declined performance of more than one safety functions, shall be analysed by means of variant scenarios." The primary objective of defining variant scenario is to analyze the impact of uncertainty inherent in defining the "expected" evolution represented in the Base Scenarios. Posiva states that the variant scenarios can also be considered "expected or likely" which is confusing because at many places in its documents, Posiva characterizes these scenarios as unlikely.

Two variant scenarios, variant scenario-1 (VS1) and variant scenario-2 (VS2), are defined for the geosphere. In VS1, the initial defect, assumed in the base scenario, is assumed to enlarge gradually from 1 mm to 10 mm in 25,000 years, resulting in advective water flow and erosion of buffer and in VS2, one canister is assumed to fail by corrosion. In VS2, the failing canister does not have an initial through penetrating hole (as in VS1) but has some other (undefined) defect such as a thin wall, tiny crack(s), or rough canister surface causing failure by accelerated corrosion. In both VS1 and VS2, performance target L3-BUF-13 ("The buffer shall be impermeable enough to limit the transport of corroding substances from the rock onto the canister surface"; Posiva 2012-04, page 35) is not fulfilled. Sensitivity cases in VS1 investigate the effect of pore water chemistry. Uncertainty in ground water composition is considered through analysis of calculation cases VS1-BRACKISH (brackish water), VS1-HIPH (high pH water), and VS1-HIPH_NF (high pH in the near field). In VS2 sensitivity cases analyse effect of location of the failed canister. The primary reason for corrosion failure in VS2 is considered to be the penetration of low ionic strength water during ice sheet retreat causing chemical erosion of the buffer. The failed canister provides the source term for analyzing transport of radionuclides to the geosphere-biosphere boundary. The buffer, backfill, and closure are assumed to have been affected at least partially by mechanical and/or chemical processes (e.g., piping and erosion, and interaction with cementitious high pH leachates) driven either by thermal gradients and/or groundwater flow and chemistry. See Table 7-3, page 170, Posiva 2012-12 for a summary of the variant calculation cases. We note that results of an independent calculation of VS1-BRACKISH by a member of the core review team showed good agreement with Posiva results.

On page 200, Posiva 2012-12, Posiva states, "… penetration of low ionic strength water to repository depth will probably not occur, and so there will be no canister failures by corrosion following chemical erosion of the buffer. Currently, however, a few canister failures in this scenario cannot be ruled out." So, on the one hand the event is considered improbable but on the other hand, if it did occur then multiple (how many?) canisters may fail. As discussed in the next section, Posiva should consider analysing this, possibly low probability but potentially high consequences scenario, as one of the disturbance scenarios.

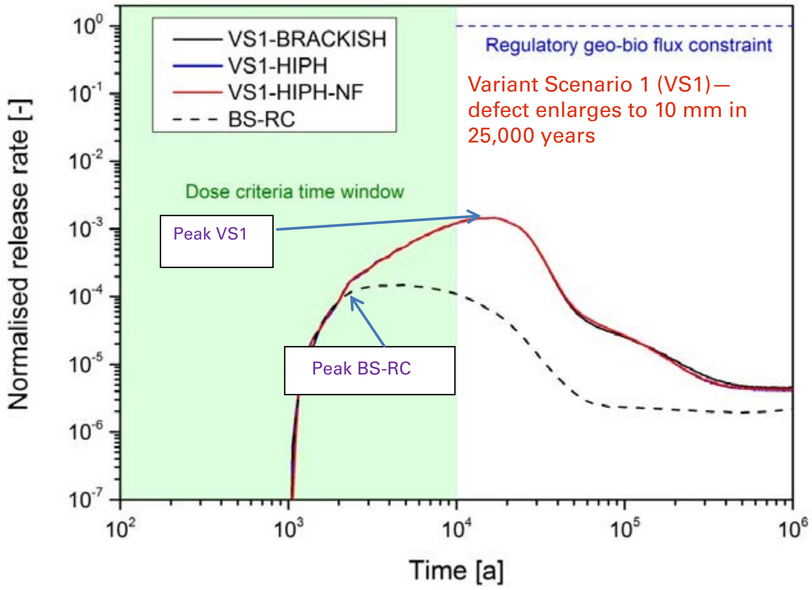
For the surface environment (see Chapter 6 of Posiva, 2012-08), seven variant scenarios are stipulated by assuming deviations in discharge locations [VS(A)]; sea level change [VS(B)]; land use [VS(C)]; use of a well [VS(D)]; radionuclide transport routes [VS(E)]; human habits [VS(F)]; and combined sea level change and land use [VS(G)]. The calculation case VS (E) considers the possibility of radio element accumulation. Dose is calculated only for the releases calculated in the geosphere VS1 scenario as the release in the VS2 scenario occurs at the time of ice sheet retreat (>155,000 years) that is beyond the dose window. Table 7-5, page 172, Posiva 2012-08 summarizes the biosphere calculations cases for the variant scenario.

Representative results for variant scenarios are shown in Figure 2.

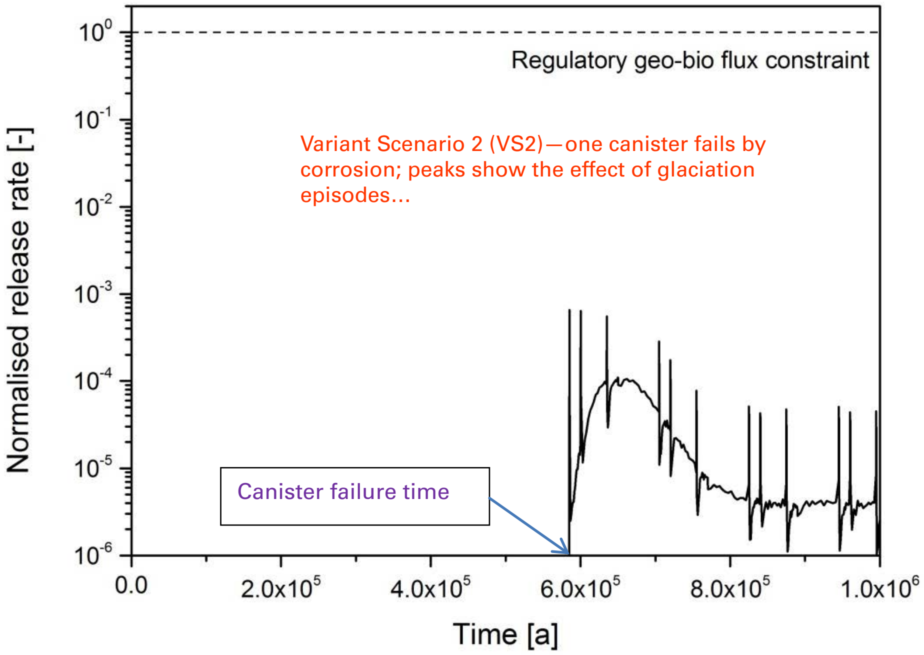
Figure 2(a) shows a peak annual normalized release rate approximately an order of magnitude higher than obtained in the base scenario. The time of occurrence of the peak is controlled by the time at which the defect grows to 10 mm size which is 25,000 years (that is greater than the dose time window and therefore does not affect dose calculations). The calculated dose is shown in Figure 8-10, page 202, Posiva 2012-12 (not reproduced here). In this figure, the peak annual dose to the most exposed representative is shown to be about 10^{-4} mSv. Of greater interest is that the peak dose depends on the location of the failed canister and the resulting discharge location estimated from the use of the DFN model (the highest peak dose is estimated for discharge locations south of the repository). Figure 2(b) shows reoccurring narrow peaks due to rapid flushing of non-sorbing radionuclides (primarily I-129 but also CL-36 and Se-79) from the geosphere during high flows at times of ice age retreats. Based on these results for one failed canister, Posiva asserts on page 200, Posiva 2012-12, "… release rates calculated for a single failed canister in scenario VS2 indicate that the few canister failures that could potentially arise in a more likely lines of evolution could easily be tolerated…" There is some inconsistency in the use of terms in Posiva documents. For example, as just stated if "a few" failed canister is a "likely" evolution then that should be defined as the reference case or the variant case. The depth to which dilute water may penetrate and the numbers of canisters that may be affected depend on the results of the DFN model. We know that the water travel time in fractures calculated in the DFN model is relatively low; therefore, the above results will be sensitive to the time for which the source of dilute water is allowed to exist. The discharge locations (not so much the timing of the discharge) on which the annual dose depends also is determined by the DFN model. This is further discussed in the next section on disturbance scenarios. To build confidence in the safety case, Posiva should consider conducting a PSA of this case.

Note also that in both Figures 2(a) and 2(b), the highest annual normalized release rate is approximately 10^{-3}. Although strictly not true, one could guess from this result that at least 1,000 canisters either have to have large defect (large enough to have advective transport) or fail by some other process (e.g., corrosion or rock shear) for the release rate to exceed the regulatory constraint.

There are three sources of substantiation for Posiva's assumptions of barrier function degradation: (1) theoretical, (2) experimental, and (3) natural analogues. Experiments have



(a)



(b)

Figure 2. Results of variant scenarios; (a) shows results for VS1 and (b) for VS2. [Adapted from Figure 8-8 (a), page 198 and Figure 8-9, page 201, Posiva 2012-12]

Summary

(1) In VS1 scenario, performance targets L3-CAN-5 and L3-BUF-13 and in VS-2, performance targets L3-CAN-7, L3-BUF-13, and L3-ROC-10 are considered to be impaired.

(2) The case of penetration of low ionic water can be a low probability high consequence scenario; Posiva should consider analysing it fully, deterministically and in PSA under the category of disturbance scenarios.

(3) Posiva should explain why only one canister (rather than a few as Posiva admits is likely) is assumed to fail in the VS2 scenario.

(4) As a part of checking system robustness, Posiva should subject the system to a few extreme (multiple canister failures) scenarios and demonstrate the system tolerance limits.

been performed wherever possible. For example the degradation of buffer has been extensively studied through experiments. But because, these components have to function for a million years, no set of experiments can completely provide confidence. Both theoretical arguments (e.g., related to copper corrosion and mechanical distortion by creep) as well as natural evidence from natural analogues is presented to support the assumptions. Clearly, any such assumption has significant uncertainties. Because of the deterministic nature of Posiva's analysis, such uncertainties are not explicitly included in the analysis of scenarios, except through calculation cases. However, Posiva does perform Monte Carlo analyses in the nature of probabilistic sensitivity analysis (Posiva WR 2013-25) to delineate the impact of some of these uncertainties.

3.2.5 Review Topic 4: Sufficiency of disturbance scenarios (GD 736/2008, §5.14; YVL D.5 §A105)

Disturbance scenarios are low probability but potentially high consequence scenarios. These scenarios are significantly beyond the design basis and are expected to challenge the performance targets of barriers much more severely. The low probability aspect of these scenarios is recognized in YVL D.5 §314, 315, and 316. For such scenarios, §316 requires estimation of expected value of dose and/or annual normalized release rate and the expected value compared to regulatory constraints in §310 for dose or in §312 for release rates. The expected value takes into account the probability of occurrence of the event or a chain of events giving rise to radionuclide release from the canister. §315 specifies that at the least potential canister failure due to rock movement and boring of a medium-deep water well hitting a waste package must be considered. In addition, §313 allows activity releases to be averaged over no more than 1,000 years, to smooth out sharp and short-term peaks. The disturbance scenarios include large earthquakes capable of causing shear movements at repository depth, inadvertent human intrusion and penetration of dilute glacial melt water, etc.

For the geosphere, three disturbance scenarios are identified: (1) accelerated corrosion of the iron insert (AIC), (2) canister failure by rock shear due to a seismic event (RS), and (3) canister failure by rock shear followed by buffer erosion because of penetration of dilute glacier melt water (RS-DIL). In the AIC scenario, a canister is assumed to have an initial defect that allows water to enter the canister and lets the cast iron insert to corrode at an accelerated rate (> 1 µm/year) and the increased volume of corrosion products are assumed to cause the canister to completely fail suddenly at 15,000 years. The assumptions in this scenario are more pessimistic than those in VS1 in which the initial defect enlarges gradually to 10 mm size in 25,000 years but the canister never fully fails. In the RS scenario, the evolution is assumed to be normal until a large seismic event occurs. The seismic event is assumed to cause canister failures due to rock shear movement on existing fractures from seismic ground motion at either 40,000 years (pre-glaciation period) or at 155,000 years (first glaciation period) and beyond. As stated on page 65, Posiva 2012-08, "The selection of 40,000 years AP is absolutely arbitrary and selected for comparison to the results for a later time." The 155,000 years' time corresponds to the postulated time for retreat of an ice sheet after glaciation. The RS-DIL assumes canister failures as in the RC but because of the perturbation of the fracture network by the earthquake; it is assumed that dilute water reaches the failed canisters at the same time that they are breached. The dilute water corrodes the buffer degrading its performance with regard to its resistance to water flow rates and radionuclide transport. The RS-DIL scenario is the most severe scenario considered by Posiva in its safety assessment. Posiva provided additional probabilistic sensitivity analysis for the RS-DIL scenario, the review of the additional information is documented in Appendix A. The calculation cases for the disturbance scenarios are tabulated in Table 7-4, page 170, Posiva 2012-12.

For the surface environment, changes in land use, DS (G), biotope occupancy, and change in river direction, and use of deep wells DS (D), are considered. The inadvertent human intrusion scenario considers penetration of a canister [DS (F)-HI-CANISTER] or buffer [DS (F)-HI-BUFFER] or backfill [DS (F)-HI-BACKFILL] by a drill. See Table 7-6 on page 174 and Table 7-7 page 175 of Posiva 2012-12 for details. There are only 9 geosphere calculation cases that result in non-zero release to the biosphere during the dose time window. These 9 cases, tabulated in Table 7-10, page 179, Posiva 2012-12 are analysed for dose in biosphere with selected biosphere calculation cases. Of the 9 cases, only the releases from the BS-RC are analysed for all the biosphere calculation cases. In other words, the analysis of variability and uncertainty in the biosphere is mostly conditional on the BS-RC being realized. That is why the BS-RC (a constant pin-hole in one canister) becomes the most emphasized scenario in Posiva's safety case. The only disturbance scenarios analysed for doses is the human intrusion scenario which is assumed to occur at 1,000 years and the accelerated insert corrosion with a leaky insert or AIC-LI. In the AIC-LI scenario, water enters the initial defect at 1,000 years after closure and the insert starts to corrode and begins to release the radionuclides within the dose time window.

There are only two external processes that drive the safety case, the climate change (and related land depression/uplift during glaciation/deglaciation) and the seismic/tectonic activity. Climate change is expected to occur although its timing and magnitude are uncertain (see Appendix A for some additional information). Seismicity is also expected to occur but earthquakes of magnitude greater than 5 are considered to have very low probability of occurrence. The canisters are designed to withstand a static mechanical load of 45 MPa and a shear movement of 5 cm at the rate of 1 m/s (Posiva 2012-13, page 31). A movement greater than this is assumed to fail the canisters but not the buffer or the spent fuel. The only other unlikely event analysed is inadvertent human intrusion into the repository. The inclusion of both the seismic/tectonic scenario and the inadvertent human intrusion are mandated by STUK regulations at YVL D.5.

Posiva presents an argument for not combining several unlikely factors in a disruptive scenario. In the context of not combining say an initially defective canister with corrosion failure by rock shear, Posiva states on page 368, Posiva 2012-09, "According to Guide YVL D.5, the probability of unlikely events giving rise to radionuclide releases may be taken into account when assessing compliance with the geo-bio flux criteria, and the probability that the VS2, RS or RS-DIL scenarios affect an initially defective canister is low. Four canister failures by corrosion following chemical erosion of the buffer are considered in the analysis of the VS2 scenario. The probability that one of these canisters has an initially penetrating defect is around 1/4500 × 4 (i.e., about 0.08 %) cautiously assuming there to be one defective canister somewhere among the 4,500 present in the repository. The probability of at least one large earthquake occurring during the million year assessment time frame is estimated at between 0.12 and 0.23 (i.e., between 0.0048 × 24 and 0.0096 × 24, see Section 11.2.5). The number of canisters in critical positions is between 35 and 78. Thus, the probability that a canister that fails due to RS also has an initial penetrating defect is between around 1/4500 × 35 × 0.12 and 1/4500 × 78 × 0.23 (i.e., between about 0.1 and 0.4 %)." A foot note appended to this paragraph states, "As noted in Section 9.2, the assumption of even one defective canister in the repository is probably cautious; the probability of there being no such canisters has been estimated at around 90 %, see Table 9-1." Based on the low probability of a scenario in which several safety functions are degraded, Posiva concludes on page 369 of Posiva 2012-09, "… the increase in peak normalised release that occurs if the canister affected by corrosion failure or failure due to rock shear is assumed to have an initial penetrating defect is more than offset by the reduction that occurs when this peak is multiplied by the probability of occurrence of these combined scenarios. The combined scenarios are thus less penalising than the VS2, RS or RS-DIL scenarios alone."

We agree with Posiva's basic argument of not considering an event chain made up of several low probability events. If the events are independent of each other than the probability of the event chain will be obtained by just multiplying probabilities of individual events. If events are correlated (e.g., ice sheet retreat and large earthquake are correlated), then joint probabilities may have to be calculated.

Are there other known unlikely factors that Posiva has not considered? We have no suggestions for adding to the list of disruptive scenarios. However, we do have some suggestions with respect to the details included in the analyses of these scenarios. Such suggestions, discussed later, include the assumption of a large earthquake occurring sooner than at 40,000 years, say at 100 years; the possible degradation of both the buffer and spent fuel in the seismic scenario, the possibility of dilute water penetrating the rock for an extend period during glaciation etc. See Appendix A for some additional information on these topics.

Figure 3 shows that the AIC and the RS-DIL scenarios produce the highest expected peaks of normalized release (see Appendix A for probabilistic sensitivity analysis for RS-DIL). The safety margins during the dose time window and the longer period are also marked with blue arrows. Posiva considers the possibility of these two scenarios occurring together. The results presented in Figure 15-3, Posiva 2012-09 show that the peak releases from the AIC scenario dissipate long before the peak release from the RS scenario occurs. Note the significant reduction in the safety margin for the disturbance scenarios.

The expected effective dose for the human intrusion scenario is shown in Figure 8-14, page 208, Posiva 2012-12. The figure shows the expected peak annual dose of less than 0.01 mSv at the time of intrusion (1,000 years). The annual probability of human intrusion is taken as 10^{-7} (discussed later) for calculation of the expected peak value. The reason for choosing the time of intrusion to be 1,000 years is not given. YVL D.5 §316 states that the inadvertent human intrusion should be assumed to occur at time ≥ 200 years, when the existence of the waste can be assumed to be not known. STUK has requested additional information on this topic. Posiva did provide an analysis assuming human intrusion at 200 years; this information is discussed in Appendix A.

In constructing the scenarios, the declined performance of the safety functions is rationalized but not substantiated in the sense that it is not proven. It should be noted that most of the declined

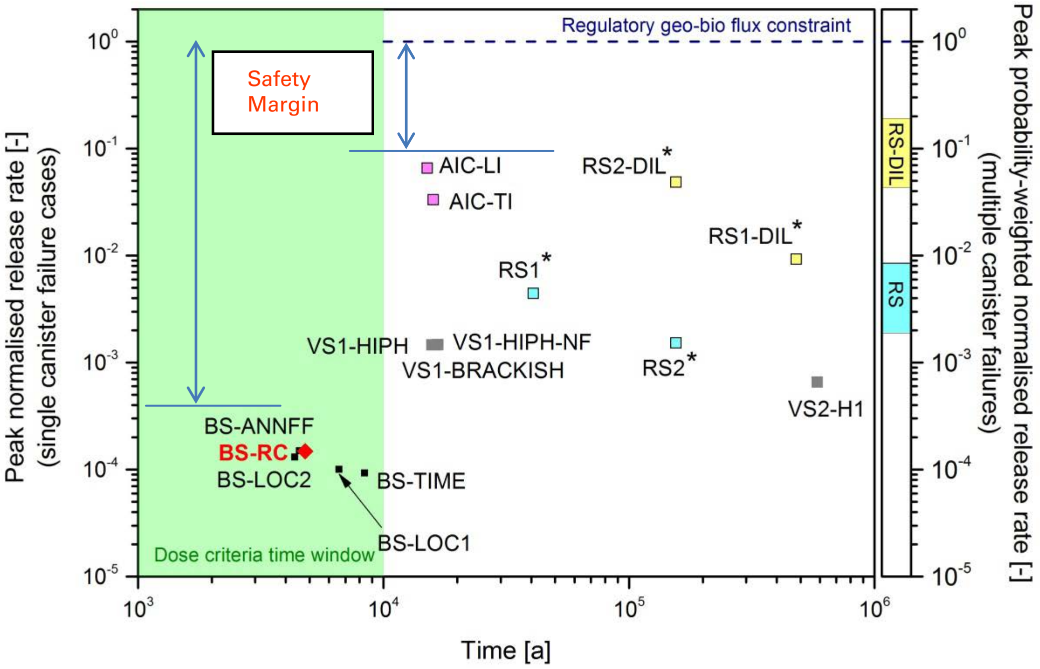


Figure 3. Calculated peak normalised release rates for various scenarios (Figure 15-1, page 358, Posiva 2012-09); the * indicates 1,000 year averaging; the yellow and blue bars on the right hand side show the range of probability weighted release rates; safety margin is shown with a blue arrow. [Adapted from Figure 8-18, page 217, Posiva 2012]

performance is based on assumptions or postulates and there is no way to prove these. It is for this reason that pessimistic assumptions should be made in defining the long-term evolution of the safety functions.

Time-dependent deviation and uncertainties in target properties is discussed in Chapter 9 starting at page 307, Posiva 2012-04. The significant deviations are: (1) creation of additional flow paths due to spalling, formation of excavation damaged zone (EDZ), and fracture reactivation, (2) transient flow conditions exceeding inflow to deposition holes of greater than 0.1 L/min, (3) anomalous sulphide levels of up to 12 mg/L, (4) potential unfavourable changes in host rock properties, (5) uncertainties in buffer saturation, (6) loss of bentonite material, and (7) asymmetric loads on canister due to uneven bentonite density and imperfection in deposition hole geometry. Based on these, Posiva has identified several topics for further RD&D on page 421 of Posiva 2012-04. We have proposed a potential topic for Posiva commitment regarding Posiva developing a prioritized list of the RD&D topics and relating the priorities to design, underground construction, engineered barrier fabrication, repository operation, and long-term safety.

To investigate what may truly challenge the proposed repository system, a member of our review team conducted a scoping calculation using a computer code different from Posiva's suite of codes. This calculation assumes that the seismic event occurs at 40,000 years. The results of this calculation are shown in Figure 4. Assuming failed canisters are emplaced in average deposition holes (relative to water inflow rates) the number of canisters that has to fail to exceed the annual NRR is greater than 1,000. However, if the flow assumption is changed to those assumed in the BS-RC case, the number of canister that has to fail to exceed the regulatory constraint is only about 200.

These results points to the importance of near-field flows once a canister has failed; greater the inflow to a deposition hole with a failed canister, greater is the radionuclide source term. This analysis still does not correlate higher inflow rates to canister failures. In the above analysis, canisters were assumed to fail due to rock shear. Posiva has estimated that at most 78 canisters can fail in a severe earthquake scenario and not all of these will face the flow conditions of BS-RC. Another independent calculation conducted by the same review team member shows that a large number of canisters can be impacted by dilute water if the post-glacial infiltration period is say 1,000 years

This independent analysis provides confidence that the repository system proposed by Posiva is reasonably robust.

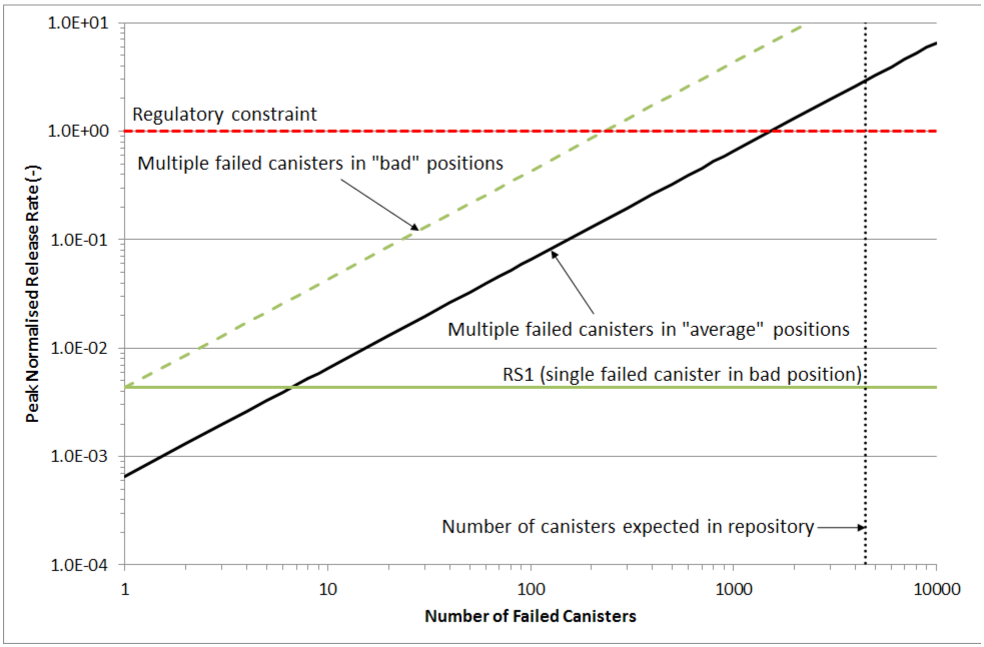


Figure 4. Results of an independent calculation conducted by a member of the core review team showing the effect of multiple failed canisters emplaced in deposition holes with either 'average' water inflow rates or 'pessimistic' water inflow rates.

Summary

(1) The external factors (climate change and seismic/tectonic processes) drive the definition of disturbance scenarios.

(2) Most known unlikely factors that have the potential to impair the post-closure safety have been considered.

(3) Combinations of unlikely disruptive factors have been considered within limits.

(4) Reasonable declined performance of safety functions has been postulated but it is not substantiated.

(5) Posiva should explain the reason for assuming the time of inadvertent human intrusion.

(6) The possibility of a large earthquake within the dose window should either be eliminated by reasoning or analysed (see also Appendix A).

(7) The possibility of dilute water penetrating for an extended period during the rock shear event should either be ruled out or analysed (see also Appendix A).

3.2.6 Review Topic 5: Declined performance of safety functions in variant and disturbance scenarios

It is difficult to say that the declined performance of "all" safety functions has been systematically and comprehensively considered in formulating the variant and disturbance scenarios.

The Safety functions and performance targets are defined in Posiva's Requirements Management System, called the VAHA system. The VAHA is designed to provide a rigorous, traceable method of translating the safety principles and the safety concepts to a set of safety functions, performance requirements, design requirements, and design specifications for the various barriers. However, we were not able to find a specific document on Posiva's web site that describes the VAHA system. Parts of VAHA are described in various reports. In the VAHA, requirements are specified at different level of detail (for example, see Appendix A of Posiva 2012-03). At the highest level (Level 1), 50 stakeholder requirements are defined. Following level 1, 12 requirements are defined for the overall system at level 2. Performance requirements are defined at the subsystem level in VAHA Level 3; canister (9), buffer (12), tunnel backfill and plug (9), closure (7) and the rock (19). The design requirements for the 5 subsystems are defined at VAHA Level 4; canister (22), buffer (10), tunnel backfill and the plug (9), closure (16), and the rock (22). (Table A-1 to A-12, pages 147 to 169, Posiva 2012-03). Finally, design specifications are specified at VAHA Level 5. Below, as an example of level of detail, we trace one requirement related to the canister.

At the stake holder level, requirement L1-STH-9 is, "Targets based on high quality scientific knowledge and expert judgment shall be specified for the performance of each safety function. … " Next, at the system level, L2-SYS-3 is defined, "The canister (is) to contain the radionuclides as long as these could cause significant harm to the environment." At the next VAHA level (Level 3 or Subsystem Requirements); the general L2-SYS-3 requirement is expanded into 9 requirements. At level 3, the requirements are still descriptive in nature, such as L3-CAN-4, "the canister shall initially be intact when leaving the encapsulation plant for disposal except for incidental deviations" and L3-CAN-5, "in the expected repository conditions the canister shall remain intact for hundreds of thousands of years except for incidental deviations." The L3 requirements are translated into design requirements at VAHA level 4. Again as an example, the L4-CAN-19 states, "the copper overpack is composed of a copper lid and a bottom welded into a copper tube or of a copper lid welded into a copper tube with an integrated bottom." At the next VAHA level (Level 5), the design requirements are converted into design specifications (e.g., the nominal wall thickness of the copper tube shall be 49 mm, etc.). As stated on page 29, Posiva 2012-05, "*Design specifications* are the detailed specifications to be used in the design, construction and manufacturing. They are defined so that the safety functions and performance targets are achieved initially and will be fulfilled in the expected conditions during the time that the spent nuclear fuel presents a significant hazard." The correlation between the design specifications and the performance targets is not as transparent as this statement seems to imply. The basic assumption is that the engineered components will meet their safety functions if they are manufactured following the design specifications. It is further stated on page 30, Posiva 2012-05 that, "The situations in which the system does not completely fulfil the (design) requirements, or there are significant uncertainties, or the future does not evolve according to the design basis scenarios, are taken into account in the performance assessment and analysed in the safety assessment. The performance targets are described at VAHA level 3 and are descriptive in nature. A quantitative description of a decline in these performance targets could be quite complex (e.g., for each requirement) a location and time along with the amount of reduction in performance could be defined. Considering that there are 56 performance targets defined for the canister, buffer, tunnel backfill and plugs, closure, and the rock, a very large number of possible combinations would have to be defined to be comprehensive. Posiva considers the performance targets as guidance for design although a clear one-to-one nexus between the performance targets and the design requirements is not transparent. Neither is the nexus between the subsystem performance targets and the overall safety measured in terms of either the human dose or the annual normalized release transparent. Some numerical performance criteria are defined by Posiva. Surprisingly, most of these are for the rock. The two most prominent ones in this category are the rock suitability classification (RSC) and rock suitability criteria and the layout determining features (LDF). A good description of performance requirements, design requirements, and design specifications related to near filed rock is given in Posiva 2012-24, Chapter 5. One has to wonder why it is acceptable to have numerical criteria for the rock but not for the EBS. Perhaps, that is just how the project evolved with lot more focus on the rock than on other parts of the system. Some of the numerical criteria, for example the RSC criteria for a deposition hole can be problematic to fulfill in practice. For example the RSC criteria for acceptance of a deposition hole are that the inflow be less than 0.1 L/min. The application of this criteria is expected to lead to a rejection of about 900 to 1,000 deposition holes out of a total of 5,500 (Posiva 2012-12, page 74). Yet, Posiva admits that a few (estimate of number is not provided) deposition holes will violate this criteria initially and in the long-term (for example see page 145, Posiva 2012-12). From a safety perspective and to gain confidence in the safety case, one needs to determine the effect on safety of such a violation. This could be done through a PSA. For example, the extent to which safety margins will be impacted by a flow rate into 10 % of the deposition hole that is say twice of the numerical criterion of 0.1 l/m. Posiva should provide a clear exposition of how the design specifications are derived and how they are related to fabrication, transport, emplacement, and to operational and long-term safety.

Posiva defines only a few variant and disturbance scenarios to account for decline in performance targets. The important question from the overall safety point of view is whether any important scenario is missing from Posiva's safety case. Our perspective on this has been given at several places in this review; a few additional views are outlined below.

The assessment would benefit from further information on the significance of the following features events and processes (FEPs): (1) melt water injection below a warm bottom glacier; (2) upwelling of saline waters from depth; and (3) drift seal failure in transmissive zones. Posiva assumes glacial melt water injection to occur during glacial retreat as the melt front transgresses the site (Posiva, 2012-09 Tables 10-1 and 11-1). Injection is assumed to occur for a period of 333 years. However, under glacial conditions the site could be overlain by a warm-based ice sheet and melt-water injection for many thousands of years. This expectation was based on other studies for similar situations (e.g. ice thickness up to 2500 m: Posiva, 2013-1 page 161) and latitudes, where it was concluded that glacial melt water injection historically occurred/may occur in the future, for timescales of tens of thousands of years [e.g. Boulton et al. (1996), NWMO (2011)]. Evidence for the absence of long-term melt water injection is derived from the hydrogeochemical conceptual model (Posiva, 2011-02 Section 7.7, and conclusions in 2012-11, page 68). Except for shallow, recent, meteoric water, the top 300 m of the geosphere contains sulphate rich waters that are considered to have been derived from sea water injection during the period ~8.5 to 2.5 thousand years BP (Posiva, 2011-02). The depth of injection was governed by the depth and salinity of the sea water (and hence driving head) and the permeability profile of the rock. Injection of sea water flushed out/overprinted older groundwaters, including glacial waters. However, there are a number of sources of evidence that these deep groundwaters are not completely 'stagnant', and flow and chemistry may evolve over assessment timescales: (1) the deep waters in the fractures contain a cold climate meteoric component and the fracture and matrix waters are of different composition so they cannot be truly stagnant, unless the difference is due to anion exclusion; (2) the fracture composition implies up flow from depth, and presumably therefore overprinting of older compositions; (3) there are no under or overpressures at depth, which suggests that these deeper waters have re-equilibrated following deglaciation, and therefore the deeper system is sufficiently permeable to allow the dissipation of any under or overpressures; and (4) The DFN model results suggest significant penetration of fresh meteoric water at the repository horizon over timescale of 10 to 50 thousand years (influenced by the extent of isostatic rebound, which affects the driving head). Although the DFN model may tend to overestimate penetration of fresh water to depth because it does not include variable density flow. We also recognize that it is possible that the chemical interaction between infiltrating water and the rock matrix can reduce dilution significantly that can buffer the pH and redox conditions (Posiva 2012-04, page 304), although stronger support is needed for such conclusions.

In the context of the safety assessment calculations, an extended period of melt water injection might be significant because it would lead to more rapid bentonite erosion, a greater number of disposal holes being affected by bentonite erosion, and more rapid transport of radionuclides. For example, the VS2 case considers full bentonite erosion followed by canister failure due to corrosion, taking into account enhanced flow and altered sorption for a period of 333 year associated with each de-glaciation event and injection of melt water (Posiva, 2012-09, Figure 10-1). Reasons for assuming the injection period of 333 years are not given. It can be pointed out that in a pilot reactive transport study at Palmottu, three recharge periods of 4,000 years were considered based on observations of uranium secondary mineralization in fractures at various depths and dating of pure U phases to estimate intervals of U mobilization (Hellmuth et al, 2011, unpublished report). In the RS1 scenario Posiva makes a non-conservative assumption that the buffer is not penetrated by dilute water and continues to fulfill its safety functions. The VS2 case considers that full bentonite erosion only affects 4 disposal holes, with only one hole being associated with a pathway to the biosphere, which is a function of the specific DFN model and associated realisation selected.

Performance Target L3-ROC-15 states that in the future expected conditions the groundwater salinity at the repository level shall be less than 35 g/l. Figure 7-2 in Posiva 2014-02 shows that the groundwater salinity increases with depth, and exceeds 35 g/l at depth of approximately 600 m. As noted above, it has been suggested that high salinity waters may have upwelled from depth since the preceding inter-glacial. Posiva 2012-04 Section 7.1.3, Figure 7-6 describe how short-term (100 years) transient upconing is possible during periods of glacier advance and retreat. It is not clear whether this is sufficient to explain the observed difference in the composition of matrix and fracture waters, or if the difference can only be explained by a longer period of upwelling. Therefore Posiva should consider whether a scenario that considers upwelling of waters with total dissolved solids >35 g/L be considered? This scenario has the potential to affect the buffer swelling pressure and hence performance in a significant number of disposal holes, if upwelling occurs over a long time period.

Performance Target L3-CLO-7 states that closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes. Corresponding criteria L4-CLO-7 states that sections in the underground openings intersected by highly transmissive zones… shall be hydraulically isolated from facility sections.

This raises the question of whether future rock movements might occur within the transmissive zones, thereby disrupting the drift backfill/seals through displacement (partial offset) and bypassing the sealing materials through enhancement of the EDZ. Additionally, could hydraulic erosion of fines from clay aggregate backfill or bentonite erosion from hydraulic seals result in reduced seal performance? This would not involve erosion of large volumes of clay aggregate backfill, but might involve 'opening' of interfaces between the rock and fill. It is not clear how vulnerable the disposal holes would be to damage of the backfill / seals in the transmissive zones.

Summary

(1) The declined performance of safety functions is considered in defining variant and disturbance scenarios. However, it is hard to say that all potential degradation of safety functions have been included. Posiva should show a clearer link between safety functions and scenarios.

(2) To understand what safety functions may degrade, it is important that the correlation between the design specifications of the EBS, the suitability criteria for the rock and the long-term safety is clearly explained. It would be helpful to document the iterations that led to the adoption of the current design specification.

(3) Posiva should consider analysing a scenario in which dilute water can penetrate the rock for an extended period.

References

Boulton, G.S., Caban, P.E., van Gijssel, K., Leijnse, A., Punkari, M. and van Weert, F.H.A. 1996. The impact of glaciation on the groundwater regime of Northwest Europe. Global and Planetary Change 12 (1996). pp. 397-413.

NWMO. 2011. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Geosynthesis. NWMO DGR-TR-2011-11.

3.2.7 Review Topic 6: Scenarios as a tool to manage uncertainties

The CLA demonstrates that Posiva has a good understanding of the role of scenarios in demonstrating compliance with STUK's safety regulations. Figure 3 of this report shows results of all the scenarios. Note that the results for the disturbance scenarios are probability weighted as is allowed by STUK regulations (YVL D.5 §316). The figure summarizes the Posiva conclusion that the proposed repository at Olkiluoto will comply with the safety standards.

The one scenario not reported in Figure 3 is the human intrusion scenario which is described in Posiva 2012-12, page 208 and also in Posiva 2012-31, page 195. Of the three human intrusion disturbance scenarios, DS(F)-HI-CANISTER, DS(F)-HI-BUFFER, and DS(F)-HI-BACKFILL, the scenario that assumes the drill penetrates the canister [DS(F)-HI-CANISTER] gives the highest dose. The dose depends on the time of intrusion which is assumed in Posiva's analysis to be greater than 1,000 years. The highest effective annual dose to most exposed people is found to be less than 0.01 mSv (see Figure 8-14, page 208, Posiva 2012-12). YVL D.5 Paragraph 315 states that the human intrusion event cannot occur before 200 years after repository closure. Posiva has been requested to explain the rationale for assuming intrusion at 1,000 years or later. Clearly, the estimated dose will be significantly higher if the intrusion is assumed to occur at say 200 years or shortly thereafter. The probability of such intrusion also needs a review.

Posiva 2012-12 Section 8.6.1 only presents the results for acute exposure of drill crew and geologists to abstracted core materials. Results for doses from medium-deep water well are presented in Figure 6-50, page 198, Posiva 2012-10. In this figure, the dose is based on the release rates calculated in the BS-RC scenario and the dose is estimated to be less than 10^{-5} mSv/year. Figure 6-51, Posiva 2012-12 however shows that the dose can be much higher (5×10^{-3} mSv/year) if releases from a scenario such as AIC-LI are considered, although such doses occur much later in time (e.g., 18,000 years).

We note that human intrusion might lead to chronic radionuclide releases, in addition to acute releases/exposures associated with the intrusion event. For example, groundwater flow and radionuclide transport up an abandoned, open, site investigation borehole, or chronic exposures due to a contaminated abandoned drill site. Posiva should consider assessing such chronic effects.

The Licensee does appear to understand the use of scenarios to manage key uncertainties in the disposal system. In the biosphere there remains a question of sufficiency of the ensemble of calculation cases that is the crux of the dose assessment.

Summary

(1) Posiva defines the calculation cases, including complementary cases to analyse the effect of uncertainties.

(2) Posiva should provide rationale for assuming the human intrusion to occur at 1,000 years and not sooner.

3.2.8 Review Topic 7: Scenarios as a tool to manage alternate assumptions

The key safety functions are summarized in Table 1-1, page 54, Posiva 2013-01. Much greater detail, where each safety function is broken into its components, is provided in Tables 2-1 through 2-5, pages 33–42, Posiva 2012-04. For the engineered barriers, the safety functions lead to defining design requirements and finally design specifications. For the host rock, the performance requirements are used to define the RSC and the LDF. In Section 3.2.5, we have already explained the safety functions in significant detail. As stated there, Posiva defines a large number of safety functions. Defining alternate assumptions about each of these safety functions is not even attempted in Posiva's safety case. One of the reasons for this state of affairs is that Posiva assumes full confidence in the success of its QA/QC program, to the extent that alternate assumptions are minimized. In the future, it may help to identify one or two key performance requirement for each of the 5 barriers and define alternate assumptions for those. For example, an alternate assumption could be that a certain percent of the buffer has a saturated hydraulic conductive an order of magnitude higher than assumed in the BS-RC. Similarly, it would be interesting to analyse a case in which the LDF is not fully implemented and a tunnel is located closer to a hydrologic zone than assumed in the base case.

From the safety case, it is apparent that containment in the near-field is the foundation of long-term safety. In this respect the spent fuel and the canisters are the two most important safety-significant components of the disposal system and Posiva makes few, if any alternate assumptions about them. These components are reviewed in much greater detail in a companion consolidated review report that is focused on engineered barriers.

Also, in the analysis of biosphere, there are emerging concerns that the scenario analysis does not consider alternate assumptions with respect to human behaviour and the interaction of potentially exposed groups with their environment. Posiva identifies agriculture as the type of land use that leads to dose. In practice this suggests commercial agriculture and therefore downplays the use of well abstraction for irrigation. The focus on commercial agricultural wells compared to domestic wells needs to be addressed. Commercial constraints on large scale irrigation mean that the water usage is kept to a minimum. In the case of high levels domestic autarky from the "kitchen garden" scenario irrigation application may be in excess of the plant needs and the commercial practice. This should be at least considered as a variant case, particularly as a domestic well (more likely to be shallow than deep) might be coupled with lower flow rates (i.e., lower dilution). The justification for ruling out such domestic well usage in the scenario analysis would appear to stem from insufficiently detailed background information on domestic practices in the region. There is a need to know more about domestic wells and the people who use them. This is true for contemporary lifestyles and those in the historical record. This could, in fact, define the most exposed group.

Summary

(1) Posiva investigates very few, if any, alternate assumptions regarding the evolution of the system. This is because of full confidence in the QA/QC system and built in safety margins in design.

(2) Just to demonstrate the robustness of the system, Posiva should explore a few 'out of the box' alternate assumptions.

3.2.9 Review Topic 8: Clarity of calculation cases

The reasons for defining the calculation cases are discussed in Chapter 7 of Posiva 2012-08. A reference case is defined for the geosphere base scenario (BS-RC) and also for the biosphere (BSA-RC). The assumptions regarding models and data in the reference case are "realistic" or moderately "cautious". That this is so is hard to accept. In the BS-RC, absolutely no safety function is even weekly challenged during the entire compliance period of 1,000,000 years.

Alternate models and/or data is considered in the sensitivity calculation cases but sensitivity cases remain within the scope of the base and/or variant scenarios. The four sensitivity calculation cases for BS-RC (Table 7-1a, page 86, Posiva 2012-08) contribute very little to expansion of system understanding. The same is true of the 3 cases for VS1 and 4 for VS2 scenarios (Table 7-1b, page 86, Posiva 2012-08). The information provided in Posiva WR 2012-25 is far more substantial than obtained from these arbitrary and somewhat artificial calculation cases. Posiva should consider more extensive use of the PSA in its next iteration of the performance assessment. It will, for example, be of interest to know how many canisters will have to fail before the NRR will exceed the regulatory limits and then provide reasons why this is close to an impossible scenario. Such analysis can provide a great amount of confidence in the robustness of the proposed system.

The what-if cases (Table 7-1c, page 87, Posiva 2012-08) are defined only for disturbance scenarios. Posiva states that the what-if cases are unlikely to be realized and are analysed only to enhance system understanding. The accelerated insert corrosion with a leaky insert (AIC-LI) has one what-if case and that is with a tight insert (AIC-TI). It is obvious to begin with that the AIC-TI is less pessimistic than the AIC-LI, so the purpose of it is not so clear. There would be considerably more information if the time of loss of transport resistance, assumed to be 15,000 years in both the AIC-LI and AIC-TI scenarios was varied instead. We have already commented on the RS1 and RS2 scenarios. To repeat, it would be more informative to vary the time at which the seismic shear occurs. The same is true of the RS1-DIL and RS2-DIL. The robustness of the system will be clearer if the RS1-DIL scenario, for example, was assumed to occur say at 100 years after repository closure (see Appendix A for some additional information).

In addition to the reference, sensitivity, and what-if calculation cases, there are also complementary calculation cases (Table 7-2 on page 92, Posiva 2012-08). According to Posiva, in the complementary cases, the models and or model parameters are not necessarily consistent with the base, variant, and disturbance scenarios. In the complementary cases, effects of (1) water type (acidic or alkaline compared to brackish assumed in the base case); (2) radionuclide inventory in the crud (zero assumed in the base case); (3) advective transport in buffer and colloid transport (ignored in the base case); (4) no matrix diffusion; and (5) C-14 release as methane gas, are analysed. Despite Posiva's explanation, these cases are no different from the sensitivity cases. Instead of CS4-H2, CS4-H3, and CS4-H4 (Section 7.4.4, page 94, Posiva 2012-08), in which transport paths are "forced" to enter geosphere, it would have been more reasonable to try other realizations of the DFN model or analyse deposition holes that do not fulfill the RSC criteria.

The biosphere modeling chain is made up of the terrain and ecosystem model (TESM), the surface and near-surface hydrology model (SHYD), the landscape model (LSM), the radionuclide transport model, and a model for radiological impact assessment. The radionuclide source term is of course obtained from the results of the geosphere calculation cases. The source term from BS-RC is propagated with all biosphere calculation cases; the source term from all other geosphere calculation is propagated with BSA-RC only (see table 8-4, page 103, Posiva 2012-08). Table 8-1, page 96, Posiva 2012-08 lists rather an extensive list of the TESM calculation cases.

Table 8-2, page 99, Posiva 20112-08 describes the calculation cases for biosphere variant cases. The primary objective of these calculation cases is to examine the effects of uncertainty in discharge locations, number of water wells, human diet, etc. Inadvertent human intrusion is the only biosphere disturbance scenario and the 'what-if' cases are tabulated in Table 8-3, page 100, Posiva 2012-08. In the biosphere, there is, a lack of clarity concerning what the calculation cases actually evaluated in time and space. That is to say the process of FEP review → scenario identification → calculation case definition does not lead to an unambiguous set of calculations. To aid clarity a "calculation case tree" diagram might be more informative than the simple tables shown in Chapters 7 and 8 of Posiva 2012-08.

In Chapter 9, Posiva 2012-08, Posiva's reasons that the set of scenarios and calculation cases is comprehensive. That may be so but the scenario presentation does not readily enable the reader to conclude that a reasonably complete set of calculation cases has been defined. The combination of deviations from the "normal" in defining the calculation cases seems to be based on the judgment of the analyst and not fully explained.

Summary

(1) The calculation cases do not have a firm logic underneath them; they seemed to be based on opinion of staff experts.

(2) The basic reasoning behind creating categories of calculation cases adds to confusion rather than clarity.

(3) There is no reasonable description that correlates the results of the calculation cases with their basic characteristic.

4 Post-closure safety assessment

4.1 Review Area I: Methodology (GD 736/2008 §14 and §15)

GD 736/2008 §14 require demonstration of compliance with safety regulations using, "… a numerical analysis based on experimental studies and complementary considerations..." and §15 requires that the input data and models used in the safety case, "shall be based on high quality research data and expert judgement." Posiva's safety assessment methodology is consistent with best practices. For example, the TURVA-2012 safety case portfolio (Figure 1-3, page 22, Posiva 2012-12) can be mapped to the major steps of the ISAM methodology (IAEA, 2004) and the IAEA Specific Safety Guide SSG-23 on the safety case and safety assessment for the disposal of radioactive waste (IAEA, 2012). It is also consistent with the basic requirements set in §14 and §15 of Government Decree 736/2008.

Posiva analyses repository performance in four time intervals: (1) the first 100 years of construction, waste emplacement, and operations; (2) the period from 100 to 10,000 years for which Posiva states that radiation dose to humans and the environment can be estimated and the current climate is assumed to prevail; (3) the period from 10,000 to approximately 150,000 years when the first glaciation cycle is estimated to end; and finally, (4) the period from 150,000 to 1 million years during which multiple glaciation cycles are repeated. The performance assessment methodology consists of modelling thermal, hydraulic, mechanical, and chemical changes in the system in response to external and internal loads and assessing impacts on performance targets. The impact of uncertainties in conceptual and numerical models is primarily analysed by defining a discrete set of variant and disturbance scenarios and also by conducting sensitivity analysis. Deterministic sensitivity analyses are conducted through calculation cases which are defined by varying assumptions pertaining to models and or their parameters. Probabilistic sensitivity analyses (PSA) are conducted by assigning probability distributions to uncertain parameters and conducting Monte Carlo analyses. POSIVA 2012-04 is the primary document describing the methodology although other reports also have descriptions of various aspects of performance assessment. Figure 2-4, page 47, Posiva 2012-09 is a good representation of the models and information flow in post-closure safety assessment. The specific approach for ground water modeling, a major part of performance assessment, is significantly influenced by the fractured nature of the host rock at Olkiluoto. The uncertainties in characterizing the fractured rock are managed by defining the RSC, LDF, and using the stochastic discrete DFN model.

As can be seen, the safety assessment requires many models and a large number of parameters. Posiva admits (see, for example, page 48, Posiva, 2012-09) that the challenge in safety assessment is to assign suitable parameter values to characterise evolving conditions. In general, Posiva uses a combination of "detailed process modelling and more qualitative argumentation."

Posiva has demonstrated (see Figure 6-7, Posiva 2014-02) that based on different DFN realisations; there is limited impact on the number of disposal holes that might be subject to higher flows. However, use of the DFN model does limit the radionuclide discharge points for use in the biosphere modeling. A PSA on human dose should be conducted to determine the impact of uncertainty in discharge locations generated by the DFN model.

The co-location of the encapsulation plant and a low and intermediate level waste (LILW) facility at the site is described in Posiva 2012-37. This facility is planned to be located at -180 m along

Summary

(1) Posiva's safety assessment methodology is consistent with best practices.

(2) Posiva should consider conducting a PSA of biosphere to identify important biosphere parameters and especially to determine the sensitivity of dose to discharge points obtained from the DFN model.

(3) Posiva should include the facility for disposing the low and intermediate level waste that is co-located with the spent fuel repository in safety assessments in an integrated manner.

the access tunnel to the spent fuel repository. All radioactive waste generated in the encapsulation plant, estimated to operate for 110 years and any decommissioning waste (that may take additional 3 years) will be disposed at this LILW facility. As stated by Posiva, this facility will be developed such that,"… the waste produced in the encapsulation plant can be disposed of in its own part of Posiva's disposal facility without compromising the long-term safety of the disposal of the spent fuel (Page 6, Posiva 2012-37)." The dose to a member of the most exposed group from this facility is estimated to be less than 10^{-2} mSv/year. The major contributor to this dose is Sr-90 (page 199, Posiva 2012-37).

Because this facility is located directly above parts of the spent fuel repository, we suggest that this facility should be included in the safety case for the spent fuel repository as an integral part. In other words, the dose estimates from the spent fuel repository should include the dose from the ILLW facility.

References

IAEA. 2004. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a coordinated research project. Volume 1: Review and enhancement of safety assessment approaches and tools.

IAEA. 2012. The Safety Case and Safety Assessment for the Disposal of Radioactive Waste; IAEA Safety Standards Series SSG-23.

4.1.1 Review Topic 1: Quality of models and input data [GD 736/2008 §15, and YVL D.5 §A107]

This review topic is concerned with the reliability of models and data used in building the safety case which according to GD 736/2008, § 15, "… shall be based on high quality research data and expert judgement. Data and models shall be validated as far as possible, and correspond to the conditions likely to prevail at the disposal site during the assessment period."

Models, data, assumptions, and uncertainties for the geosphere and engineered barriers (EBS) parts of the safety case are documented in Posiva 2013-01. Posiva 2013-01 is a detailed report that discusses models and data for external processes (Chapter 5), models and data used in performance assessment (Chapter 6), and models and data used in assessing radionuclide release scenarios (Chapter 7). Each section discusses the model, the key data, and provides an assessment of the confidence. Posiva discusses the sources for its parameter values on page 65 of Posiva 2013-01. These are (1) site-specific investigations, (2) data from international projects, (3) data from other national projects, most importantly from Sweden, (4) information from previous safety assessments, (5) data derived through expert elicitations, especially geochemical parameters such as solubility and sorption coefficients, and (6) data gaps filled by making cautious assumptions.

Over the last 25 years, Posiva has collected scientific data on the host rock, performed design of engineered barriers, gathered information on surface environment and conducted research and development activities. This includes evidence from the Onkalo underground rock characterisation facility, the results of tracer testing (undertaken by SKB and cited in Posiva 2013-01) and complementary considerations. Complementary considerations include natural analogues for relevant processes (Posiva, 2012-11), although natural analogues are not available for the disposal system as a whole. Posiva states that all such activities are conducted under ISO 9001: 2008 graded quality assurance program. Posiva has also engaged the Finnish National Laboratory (VTT) and other reputed organizations and experts in generating information. Therefore, it stands to reason to conclude that Posiva has collected significant amount of high quality scientific data from field investigations as well as from laboratory experiments. However, because of the large spatial (≈10 km^2) and exceptionally large temporal (1,000,000 years) scales, uncertainties persists and will continue to persist. Posiva makes assumptions to account for these uncertainties and uses a design that provides substantial safety margin. It is expected that Posiva will continue to conduct a RD&D program until repository closure, to confirm and improve the performance estimates. A commitment from Posiva is this regard should be sought. A process for decision making should be devised in case, (1) future RD&D identifies issues that may require major changes in design or (2) new RD&D results discovers new technology for significantly improving safety or reducing cost without impairing safety.

We assume that other reviewers who are conducting detailed review of a specific barrier or a component of a barrier or a specific FEP will review the data set related to it; in our review we have taken a broader view and focused on data affecting post-closure safety. For example, the bentonite buffer is an important barrier. The parameters and data on buffer that is used in safety assessment are described in Table E–1, page 705 of Posiva 2013-01. There, it is mentioned that for assessing safety, the upper value of saturated hydraulic conductivity for the buffer is set at 1.10×10^{-12} m/s while the experimentally measured value is 5.10×10^{-14}. These kind of seemingly cautious assumptions need to be checked carefully in performance assessment which uses hundreds of parameters. The higher saturated hydraulic conductivity assumed for buffer is considered pessimistic as it is expected to bias the calculated release rates to the higher side. Yet, the assumed hydraulic conductivity value will lead to an estimate of buffer saturation that is higher than the actual that would be obtained by using the lower measured value. This makes it desirable that the possible effects on performance of the actual delayed saturation of buffer should also be investigated (see Appendix A for additional information on this topic). There are too many models and parameters (and data) to be reviewed by any one person. A suitable audit approach should be considered for review of these aspects. That is, a small but critical set of parameters and models can be selected for detailed review. This selection can be based on the relative importance of the selected set to safety measures. Together with review of this set, one may also consider selecting one scenario that can be reviewed in detail from bottom to top. For example, the RS-DIL scenario may be selected because it has the highest release and also it has all the important processes involved for a detailed scrutiny. Special attention should also be paid to parameters obtained from literature or through expert elicitation and audit these to assure that unreasonable bias has not been introduced in them.

Further on page 424, Posiva 2012-04, Posiva states, “In making a statement of confidence, as to say that the performance targets and target properties will hold for most of the assessment time, and for most of the canisters containing the spent nuclear fuel to be isolated, we must be sure that:

1. The consideration of future evolution lines (i.e., scenarios) has been thorough and sufficient, meaning that the FEPs considered important for the evolution of the repository and the site have been taken into account.
2. The observations, models, experiments, and scientific background on which the statement is based are up to date.
3. There is a willingness and intent to answer any and all “did you think of this” questions in the context of evolution (i.e., through the formulation of scenarios).”

Posiva goes on to explain at great length (thousands of pages) that it meets these three criteria in its safety case. This and the other regulatory reviews are also focused on these aspects of the safety case in the CLA.

For TURVA-2012, the REPCOM code has been superseded by the GoldSim code, and FTRANS has been superseded by the MARFA code. GoldSim is widely used by waste management organisations in other countries for radionuclide transport calculations considering a wide range of repository host rocks and disposal concepts, and MARFA is also used by SKB for modelling geosphere transport through fractured rocks. Posiva has explained the benefits offered by the change of assessment codes, and have undertaken cross-comparisons against REPCOM and FTRANS (Posiva, 2014-02), thereby maintaining the link with earlier assessments. The parallels with SKB's safety case provide confidence in Posiva's assessment. There are, however, differences to SKB's assessment; in particular Posiva uses a primarily deterministic approach to assess a range of calculation cases, while SKB uses a probabilistic approach. The difference reflects the difference in regulatory requirements in the two countries. In reviewing the Posiva reports, we found some confusion regarding the use of MARFA code Version 3.2.3. Posiva 2014-02 references this version of the code but it does not include any discussion of the particle splitting algorithm despite the fact that it would have addressed some of the issues seen in the comparison with FTRANS code in Appendix B of Posiva 2014-02. However, this matter can be easily clarified.

The discrete fracture network model is the foundation of flow and transport modeling in Posiva's safety case. This model in particular but also other models should be used to "predict" the conditions that are expected to be seen during construction. For example, the DFN model should be used to predict the inflow rates into the tunnels and emplacement holes prior to drilling and such predictions compared to actual measurements. Such comparisons and subsequent improvement of the model(s) will generate significant confidence in the validity of the model(s).

A separate set of reports (Posiva 2012-28, Posiva 2012-29*,* Posiva 2012-30, Posiva 2012-31 and Posiva 2012-32*)* discuss the data and models aspects of the surface environment. Posiva's confidence in the models and data and the treatment of uncertainties is also discussed in these reports. Data sources for biosphere range from detailed site monitoring and measurement to published databases [e.g., IAEA (2010)]. The latter is used in the conceptualization of the elemental pools and fluxes for the typical biotopes of the system. The models so generated (e.g., page 197 of Posiva 2012-28 for croplands) are of great interest being a major step towards a quantitative transport model for the key radionuclides relevant to the dose assessment time window.

Overall, the modelling and input data in Posiva's safety case are based on expert judgment and high-quality scientific knowledge obtained through experimental studies, site investigations and evidence from natural analogues.

Summary

(1) In general, the modeling and data are high quality but to the extent possible, models, such as the DFN model should be verified by using them to predict conditions underground and then comparing those predications to measurements during construction.

(2) An audit of the data obtained using expert elicitations should be conducted to assure that divergent opinions were appropriately handled.

(3) Posiva should provide a clarification regarding how Posiva assured that sufficient number of particles was used to obtain converged results from MARFA.

(4) Posiva should commit that the RD&D program will continue with the aim of enhancing confidence in the safety assessment.

(5) STUK and Posiva should decide on a formal process for decision making in case, (1) future RD&D identifies issues that may require major changes in design or (2) new RD&D results discovers new technology for significantly improving safety or reducing cost without impairing safety.

Reference

IAEA 2010. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. Technical Report Series no. 472. International Atomic Energy Agency, Vienna.

4.1.2 Review Topic 2: Assumptions in models and data [GD 736/2008 §15, and YVL D.5, §704, §A107]

This review topic focuses on the selection of computational methods, performance targets and input data, which according to YVL D.5, §A107, "shall be based on the principle that the actual radiation exposure and the actual quantities of released radioactive substances shall, with a high degree of certainty, be lower than those obtained through safety analyses." In this regard, Posiva claims (page 63, Posiva, 2013-01) to use either models that are relatively complex which use realistic description of processes or relatively simple models that use "cautious" assumptions. This implies that the models and data used in safety assessment will tend to underestimate repository performance measured in terms of releases at the geo-bio boundary and radiation doses during the dose time window. Simplified models include buffer erosion and canister corrosion. The computational methods are reasonably standard in the sense that the same or similar methods are being used by other national programs. As stated elsewhere in this review, the two most important system components are the spent fuel itself (even if it is not deemed a barrier by Posiva) and the canister. For both of these components, the computational methods are rather simple (e.g., the method to calculate the corrosion rate of copper which is described starting on page 275, Posiva 2012-04).

For any safety-related consequence, it is clear that radionuclides have to leak from the canister. In Posiva's safety case, there are only three possibilities for this to happen: (1) an initial defect in the canister, (2) canister failure by corrosion, and (3) canister failure by rock shear. All of these three possibilities are considered unlikely even though an initially defective canister is included in the base scenario. Once the canister has failed, the slow dissolution rate of the fuel is a key barrier to release of much of the radionuclide inventory; including key radionuclides such as Cl-36 and I-129 (see radionuclide partitioning described in Table 7-6 of Posiva, 2013-01). Section 7.3.3 of Posiva 2013-01 discusses confidence in the partitioning and the fuel dissolution rate. The assumption on IRF is considered to be cautious, but the assessment results show that uncertainty in the IRFs of Cl-36 and I-129 can have a significant effect in the Reference Case, if the size of the defect increases and consequently the transport resistance of the defect decreases (Posiva, 2013-01 page 508). To help reduce this uncertainty, Posiva is participating in the EU project FIRST-NUCLIDES. This is one of a number of examples of where Posiva is participating in research projects to reduce uncertainty and conservatism, and improve confidence.

However, the assumptions regarding the size of the defect, the number of potential defects, and the transport resistance offered by the defect are not necessarily conservative. Similarly, justification for the timing of occurrence of an earthquake of magnitude capable of causing canister failure by rock shear at 40,000 years is not provided. That is, it is not explained why such an event could not occur sooner, especially before 10,000 years, the time period selected by Posiva to estimate radiation doses in the surface environment.

Posiva depends on its quality control and quality assurance measures to assure that the limits of applicability of input data are checked against the assumptions related to the scenarios and models (Posiva, 2013-01, page 66). Posiva depends significantly on analysing calculation cases and conducting sensitivity analyses to demonstrate that the selected parameter values are conservative and that the remaining uncertainties in their values do not affect the final conclusion regarding the safety. The conservativeness of all assumptions cannot always be ascertained. This is because an assumption (or parameter) that is conservative at one place may produce non-conservative results at another. In this regard, the results of the PSA described in Chapter 9 of Posiva 2012-09 and in Posiva 2013-25 are considerably more informative. Unfortunately, the PSA is limited to just two cases, the hole forever and the growing hole case. In those Monte Carlo calculations, all kind of combination of parameters is analysed. Figure 9-7 on page 187 of Posiva 2012-09 provides significant information regarding the effect of parameter uncertainties on calculated normalized release rates for the hole forever (the base scenario-reference case) and the "growing hole" (a variant scenario but with different assumptions regarding the growth of the defect). The sensitivity results in this figure are obtained by sampling the probability distribution functions assigned to the 160 (162 in the growing hole case) uncertain parameters, obtaining 10,000 samples and running the model repeatedly to obtained 10,000 realisations of results.

Two main observations from this figure are (1) the maximum value of the highest (among the 10,000 realizations) peak normalised release for the "growing hole" case ($\approx 10^{-1}$) is 500 times larger than the "hole forever case" ($\approx 5 \times 10^{-3}$) and (2) the peak releases can vary five orders of magnitude (between $\approx 10^{-6}$ to $\approx 10^{-1}$) within the 10,000 realizations because of the various parameter combinations analysed in the 10,000 realisations (variation marked as ΔNRR in the figure). Similarly the time when release begins can vary from 10 to 25,000 years (variation marked as ΔT in the figure). This shows that the calculated release rates are quite sensitive to the uncertainties in input parameters but that the peak normalized release rate remains below the regulatory constraint in all 10,000 realizations. In the hole forever case (upper figure), the deterministic result from the BS-RC scenario is also shown (the black curve). The figure shows that the deterministic peak normalized release rate lies between the 95th and the 99th percentile curves calculated by the Monte Carlo simulations. This provides the confidence that at least in the BS-RC, the assumed flow and transport parameters values are pessimistic. One must remember though that the only source of radionuclide leakage in the BS-RC is the assumed 1 mm hole in one canister.

Comparing the results of the "hole forever" case

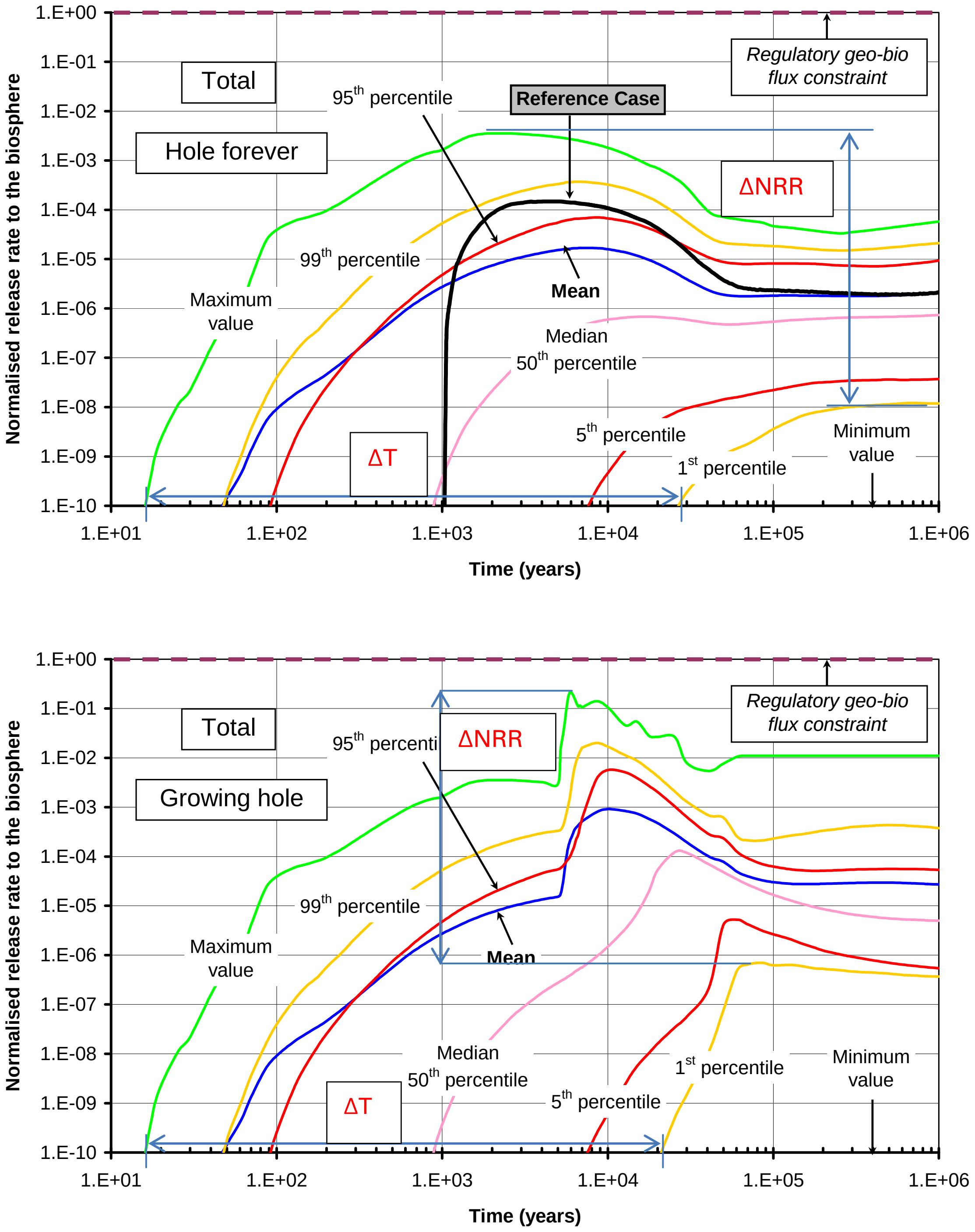


Figure 5. Total normalised release rate to the surface environment in 10,000 Monte Carlo realisations (hole-forever and growing-hole cases). The reference case release rate is also shown in the upper figure. ΔT = uncertainty in estimated time when release begins and ΔNRR = uncertainty in estimated annual normalized release rate. [Adapted from Figure 9-7, page 187, Posiva 2012-09]

with those of the “growing hole” case, we see that the peak of the mean annual normalized release rate in the “growing hole” case is about 100 times the mean of the peak in the hole forever case. In a later section, we will note that in both cases, the instantaneous release fraction of radionuclides in the spent fuel is identified by the PSA as the parameter of the highest importance. It is the IRF part of the radionuclide inventory that is released as soon as the transport path is established. The normalized release rate peak is higher in the growing hole case because the time to establish transport path is varied between 10 to 5,000 years and the time to loss of transport resistance is varied between 5,000 to 50,000 years in the growing hole case whereas in the hole forever case, it takes 1,000 years to establish the transport path and the hole never loses its transport resistance. Note that the growing hole case does not match the variant scenario VS1 in which the initial 1 mm defect grows up to 10 mm in 25,000 years. Earlier in Figure 2, the results of the VS1 scenario were reproduced. From that figure, the peak normalized release rate can be seen to be ≈ 10^{-3} which matches the peak of the mean (blue) curve in Figure 5, again providing confidence that the parameter values in the VS1 scenario are reasonably pessimistic. In a later section, we will further discuss the results of the PSA. Similar analyses for the other variant and disturbance scenarios will also produce important information and STUK has requested such analyses at least for one other scenario.

Posiva 2012-29 and Posiva 2012-30 provide key input to the dose assessment model in the form of (a) hydrological fluxes for representative biotopes in the landscape and (b) dimensions of super objects and biotopes within super objects; areal extent, thickness of soil layers and water depths. However, the details of how the landscape dose was estimated (e.g., input parameters, model equations, and intermediate results, such as water fluxes) were not found in the documents reviewed. Data related to dimension of super objects and biotopes within a super object has also been requested.

4.1.3 Review Topic 3: Model simplifications (YVL D.5, §704 and §A106)

This topic concerns simplifications of the models and the determination of the required input data, which according to YVL D.5, §A106, “shall be based on the principal that the performance of a safety function will neither be overestimated nor overly underestimated.” As stated by Posiva on page 64, Posiva 2013-01, “Simplified models are implemented in such a way that they do not overestimate the performance of the repository or underestimate the consequences of releases on long-term safety (e.g., by omitting processes that are beneficial to performance or safety, or by selecting pessimistic input data). Examples of simplified models are: mechanical erosion model for the buffer and the backfill (Posiva 2013-01, Section 6.10), chemical erosion models (Posiva 2013-01, Section 6.11) and canister corrosion models (Posiva 2013-01, Sections 6.12–6.22).” Similarly, with respect to input data, Posiva states, “If reliable data are not available, many of the assumptions are based on the likely/expected characteristics and evolution of the system, or on a reasonably expected range of possibilities, or defined to err on the side of caution. The aim is to overestimate the potential radiological impacts of the disposal facility but in a plausible way. The use of cautiously chosen model assumptions and parameter values is consistent with YVL draft guideline YVL D.5 STUK 2011a)…”

A state of the art model for simulating the hydrogeochemical evolution of the Olkiluoto site is described in Posiva WR 2014-09. Based on the

Summary

(1) In general, the assumptions and simplifications are appropriate for meeting the objective of safety assessment. However, it is not obvious that all the assumptions are cautious.

(2) We recommend that a Posiva commitment for greater use of the probabilistic sensitivity analysis in the next iteration of the safety assessment should be included in the list of commitments. In addition to continued use of deterministic sensitivity analyses, Posiva should commit to PSA for all scenarios and also inclusion of the biosphere in the PSA (see Appendix A for PSA analysis of RS-DIL scenario).

(3) Additional information has been requested with respect to landscape dose modeling which should include model equations, parameters, and intermediate results (e.g., water fluxes). Because of the rather complex and dynamic nature of the biosphere assessment models, such detail is necessary to reasonably understand Posiva calculations.

comprehensive site data on groundwater chemistry, rock matrix and fracture mineralogy, the processes comprising calcite and sulfide dissolution and precipitation, alumosilicate weathering, cation exchange and redox reactions are implemented in the numerical model. Although further clarifications are needed in order to make the outcome of this quantitative study more convincing, the results do not reveal any geochemical threats to repository safety during the operational and temperate periods. Critical issues are the potential for microbial sulfate reduction under different redox conditions, the role of different sulfide phases leading to different concentration of dissolved sulfide, and the role of Fe (II)-silicate minerals (chlorite, biotite).

Sorption is an important geosphere and biosphere process that is capable of controlling the transport of radionuclides in geosphere and their accumulation in biosphere. Posiva uses the simple concept of distribution coefficient, K_d which is based on the simplifying assumption of linearity and instantaneous equilibrium of concentrations in the solution and the solids (i.e., concentration of a radionuclide on a solid at location X and at time t = K_d x concentration in solution at location X and at time t). Posiva ignores any remobilization during climate change episodes. This is another example of where a seemingly conservative assumption (low sorption) will actually not be conservative because strongly sorbing radionuclides will have the opportunity to remobilize which process is absent for the non-sorbing radionuclides. The impact of this simplification and not using more physics-based models of sorption is probably minor on the overall safety. This is because, in Posiva's calculations, any radionuclide with even a small K_d never reaches the geo-bio boundary. This is illustrated in a PSA result presented in Posiva WR 2013-25. In that study, the K_d for I-129 in the unaltered rock (i.e., far-field rock) is assumed to vary between 10^{-10} to 3×10^{-3} m^3/kg. In all of the deterministic calculations, the K_d for I-129 is assumed to be zero. However, even this small value of K_d in probabilistic analysis is found to be the most important parameter in those Monte Carlo simulations resulting in the lowest NRR (see Figure 4-3, page 49, Posiva WR 2013-25). At an appropriate priority level, Posiva should continue to research the applicability of the K_d approach to complex evolving systems in general, and to fracture coatings in particular.

In contrast to the simplifications applied to the sorption phenomena at other places, the representation of water-conducting fractures in the models as heterogeneous, variably layered and variably coated features is surprising. This inclusion of complexity is not warranted but if included it would need specific, complementary calculations for clarification. Posiva should conduct separate simulations to illustrate, whether the application of a linear sorption mechanism in such complex structures with different altered and unaltered layers with different porosities and diffusivities and various mineralogical distinct coatings is realistic. The choice of sorption coefficient for the different transport classes (calcite, clay, other, and slikenslide), and mapping of the classes to the DFN model may be particularly important for Ni and Cs. Attenuation of Ni may be sensitive to the mapping of the 'clay' transport class in the flow pathways, while Cs may be sensitive to the mapping of the 'other' transport class to the flow pathways, since these fracture classes provide the greatest retardation of Ni and Cs respectively. Fortunately, the additional cases BS-RC-tc2 and BS-RC-tc3 described in Posiva 2014-02 show that the fluxes of Ni and Cs are not sensitive to bounding transport class realisations. This is a useful result and should perhaps feature more prominently in the assessment. The process of matrix diffusion which can also retard radionuclide migration, especially of non-sorbing radionuclides, in fractures is also found to be important but to a much lesser degree.

Although sorption in the geosphere is an important barrier for radionuclides such as Ni-59 and Cs-135, these radionuclides do not contribute significantly when the normalised near-field release rate is compared against regulatory constraints. Overall, the geosphere is not an important barrier from the perspective of retarding radionuclides because the key radionuclides (C-14, Cl-36 and I-129) have a K_d of zero. However, we note that the key role of the geosphere is to provide favourable hydraulic, geochemical, and mechanical conditions for the EBS and the host rock at Olkiluoto does serve this purpose very well. Both the retarding mechanisms (i.e., bulk sorption and matrix diffusion) are available in the far-filed should these be needed. One of our independent calculation demonstrated that even if Ni and Cs were not retarded in the geosphere, they would not contribute significantly to the normalised release rate. The C-14, Cl-35, and I-129 will be retarded by the process of matrix diffusion but the effect does not seem to be significant in Posiva simulations.

As stated above, in the calculations presented in Posiva's safety case, the sorbing radionuclides never enter the biosphere and therefore the possibility of accumulation in the biosphere is not considered. As has been suggested earlier in this review, if an earthquake/rock shear event is assumed to occur early in the life of the repository (say at t = 100 years), then there is a possibility of sorbing radionuclides to enter the geosphere and accumulate in certain biotopes. Such a scenario should either be ruled out on the basis of low occurrence probability or its consequences estimated.

Based on sensitivity analysis, Posiva concludes that the fuel dissolution rate is important to peak release rates of nuclides that are not solubility limited (Posiva 2012-09, Section 9.5.1). Posiva WR 2013-25 presents PSA results for Cl-36 and I-129, and concludes that while the fuel alteration rate is important for Cl-36 and I-129 in the long-term, yet for both radionuclides the long-term release rates are much smaller than the peak release rates which are due to the IRF.

Independent calculations related to the rock shear scenario, conducted by a member of the core review team, provided confidence that the probability weighted normalized release rates will not exceed the regulatory constraints.

In the biosphere, the main driver of radionuclide migration is the hydrology of the system. The overview of the detailed hydrology model (SHYD) is provided in Posiva 2012-30. From the detailed hydrology model the numerical values that are propagated to the dose assessment modelling are water fluxes averages over the entire modelled landscape surface. The appropriateness of this method is not explained. The average may not be a good representation of the characteristics of the ecosystem where the maximum doses arise. However, the bias introduced by this approach could be pessimistic or optimistic. Details of how the surface averaging has been carried out are not reported in the SHYD report, only the results. The attempt to use maximum and minimum values for the object specific flux matrix produce results which, we found, do not conserve mass and therefore could be problematic.

Summary

(1) Posiva's assumptions are generally pessimistic; that is, there is high likelihood that the safety measures are not overestimated.

(2) In its RD&D program, Posiva needs to continue to study, at a low priority, the applicability of the linear sorption mechanism.

(3) Posiva's analyses show that once the release occurs in the near-field, the far-field rock does not contribute significantly in delaying transport of radionuclides to the geo-bio boundary.

4.1.4 Review Topic 4: Robustness of technical arguments and evidence (GD 736/2008 §15/Paragraph 1)

Posiva's arguments in support of both models and data are most apparent in Posiva 2013-01 in which the confidence in data and models is discussed with respect to each major component of modelling. This discussion typically highlights important uncertainties; areas of ongoing research where cautious assumptions have been made; and the potential consequences of uncertainties, supported by the results of the deterministic and probabilistic sensitivity analyses. Overall, the technical arguments and evidence presented appear to be sufficiently sound, appropriate and adequate to support the results and conclusions. Some areas where further explanation, evidence or assessment would be beneficial are identified throughout this report.

In the process of describing their confidence level, Posiva has also stated potential short coming in their analyses. It may be helpful to the program to assemble all such statements and compare them to Posiva's future (2012-2015) plans described in Posiva YJH-2012 and perhaps even to longer-term (e.g., during the operational period) plans. In YJH-2012, Posiva states that, "The work to be undertaken under the programme includes verifying the conclusion of the studies of the Olkiluoto repository, design of the required plants and development of the deployed repository technology to the level required for disposal operations, as well as production of the safety case regarding long-term safety to be appended to the operating license application." This report points to the work that Posiva believes still needs to be done to strengthen the safety case included in the CLA. Selected items of work include: (1) testing of RSC at ONKALO, (2) quality control programs for canister production, (3) development of inspection techniques, (4) revision of buffer design and a full-scale test of buffer, and (5) elimination of any deficiencies and uncertainties that might significantly compromise the reliability of long-term safety assessment. The last point incorporates study of processes such as: (1) alteration of bentonite material, (2) formation of flow channels in and erosion of buffer, (3) impact of rock displacement on buffer, (4) microbial activity in buffer, (5) corrosion of copper in water, (6) creep of copper, (7) residual stresses after electron beam welding, (8) solubility of high burnup fuel, (9) verification of sulphide levels, and (10) impact of excavation damage zone on groundwater flow. Residual uncertainties in biosphere are also recognized by Posiva (see page 166, Posiva 2012-06).

It is obvious that Posiva has identified significant topics for its RD&D program up to 2015 and perhaps beyond. At one of the meetings with Posiva, the possibility of a full scale test of the canister was also brought up. Such tests could be the subject of plans for execution in the 100 years of operational period. It is also important that the studies proposed in YJH-2012 be fully coordinated with demonstration of constructability during the initial part of the construction phase. Thus, it is important that the ability to implement the RSC criteria, the LDF concept, the fabrication of the canister and buffer and their emplacement be fully demonstrated early in construction. Also, in-situ methods for characterizing (hydrologic, thermal, chemical, and mechanical) the rock volume designated for waste disposal should be designed, tested, and implemented throughout the construction period.

A major proof of robustness of the system is presented in the PSA (Posiva WR 2013-25). The results of the PSA clearly show that even assuming significant uncertainties in parameters, the possibility of exceeding the regulatory constraints is small. The PSA however is limited to just the “hole forever” and the “growing hole” cases. We have recommended that broader use of the PSA analysis to gain confidence in the robustness of the system even under disturbance conditions should be included in the list of Posiva commitments. Section 14 of WR-2013-25, presents the results of additional sensitivity analyses that have been undertaken to test the robustness of, and hence build confidence in, key aspects of the PSA: that a sufficient number of realisations have been used to obtain stable results; using uncorrelated distributions simplifies the PSA and does not change the results; and the results are not overly sensitive to the assumed shapes of distributions (i.e. results using log-normal and log-uniform PDFs are compared for selected parameters).

Regarding biosphere modeling, Posiva 2012-06 does not include a great deal of technical arguments regarding element-specific data. Indeed, as stated on page 166, “Little discussion of the results is provided here due to remaining uncertainties, particularly regarding the element-specific data, and due to their illustrative role in the biosphere assessment process.” It is not clear that this is a reasonable position, even if it is the first step in the licensing process.

However, because the radionuclide source term in the time window for calculating doses is so small that the overall conclusions will probably not change, even with the additional data.

Summary

(1) Overall, the technical arguments and evidence presented appear to be sufficiently sound, appropriate and adequate to support the results and conclusions.

(2) STUK should request a much broader PSA analysis to gain confidence in the robustness of the system even under disturbance conditions.

(3) Methods for characterizing the rock volume designated for spent fuel disposal should be thoroughly tested and implemented throughout the construction period.

(4) Tests to demonstrate the applicability of the RSC and LDF concepts in practice should be conducted in the early phase of construction.

(5) Tests that components of engineered barriers can be fabricated to design specifications and that appropriate non-destructive tests can be applied to check their integrity should also be carried out before the next licensing phase.

4.1.5 Review Topic 5: Technical presentation (GD 736/2008 § 15)

In general for the geosphere, the level of detail and manner of presentation of the performance assessment calculations is sufficient to allow a technically qualified individual to understand the development of the technical arguments, the scientific and mathematical methods used, and the results and conclusions reached without recourse to the author. This is not true of the biosphere calculations where some intermediate results are needed to fully understand Posiva calculations. We did not review the detailed mathematical formulation of complex models nor did we look at the implementation of the models in the form of computer codes. However, based on our independent modeling results, it is clear that Posiva has used generally accepted approaches in its safety case.

As stated before, Posiva's manner of presentation is such that certain aspects are repeated in many reports and yet no report is complete in itself. It is not possible to understand a topic by focusing on any one report but rather several reports must be consulted. This is necessary because of the complexity of the safety case and perhaps cannot be avoided entirely. There are also some circular referencing (report A refers to report B, report B, in turn refers to report A but the referred data is neither in report A nor in report B). Another difficulty was that even though reports were referenced, these were not published at the time of review. Posiva should be asked to adopt a document hierarchy that will aid in improving the clarity, accuracy, and transparency of the presentations and also a report should be referenced only after it is published. Ideally, all reports should be complete at the time the license application is submitted. Posiva 2012-12 provides a good summary of the safety case. It captures key information and assessment results from the underpinning reports. Nevertheless, there is scope to improve the synthesis of the information. For example, it would be helpful if results for the case with multiple container failures were included as is done in Figure 7-20, Posiva 2013-01. Another improvement would have been the inclusion of a clear exposition of key arguments supporting safety (e.g., the very long life of canisters, the very low dissolution rate of spent fuel, the stability of bentonite buffer and the insensitivity of surface discharges to the exact nature of rock fractures). In fact a shorter list of truly key safety functions would add to clarity.

One place the level of detail has remained somewhat obscure is the Discrete Fracture Network (DFN) model. It is difficult to understand the precise formulation of this model and its implementation in determining the flow fields used in the deterministic evaluations. From the performance assessment perspective, two issues are important in this respect: (1) assurance that 10 realizations of DFN model adequately sample the stochastic space with many uncertain parameters such as fracture orientation, location, intensity, hydraulic properties etc. and (2) assurance that the selection of one (ps_r0_5000) of those 10 realizations for deterministic compliance analyses is reasonable. The above question is posed primarily in the context of the effect of the DFN model on near-field flows. We believe that the effect of uncertainties in the DFN may not be very important in the far-field rock as all Posiva results show the far-field rock to not contribute much to either the slowing of the transport or the attenuation of the peak release. However, the far field DFN results are also important with respect to the discharge locations which affect the calculation of the dose in the biosphere. Similarly, the dose calculations depend greatly on the landscape (UNTAMO) model, yet it is not fully explained in the top-level documents reviewed by us.

The near-field, EBS, and in particular integrity of the copper canisters is the key barrier. Uncertainties such as dead end fractures, route dispersion, and selection of sorption coefficients for radionuclides that sorb onto fracture surfaces, etc. are not very important in terms of their impact on overall safety. Although the far-field rock is not very important as a barrier to radionuclide transport, it is very important in terms of providing mechanical stability, favourable environmental conditions (low flows in the near-field), and isolation of the near field from environmental change. It helps ensure that the EBS functions as intended.

Posiva's biosphere assessment model is fully dynamic and rather complex state-of-the-art model. However, its documentation is not adequate for a reviewer to fully understand the scientific basis of the dose calculations. Posiva has modeled the entire flow path from source location to discharge location in great detail but crucial information regarding the fate, distribution, and retention of radionuclides in the biosphere objects around the discharge location is missing. Characterization of the potentially contaminated objects in the landscape relies heavily on the UNTAMO model but details needed to understand this model are not available in the documents that we reviewed.

Summary

(1) Posiva's manner of presentation needs to be improved. It is fragmented, duplicative, and missing important information. A strict document hierarchy needs to be implemented that provides a reasonable explanation of a topic in one report. Also, the reports should be completed and delivered, preferably at the same time, or within a reasonably short period.

(2) The adequacy of 10 realizations of the DFN model and the selection of one realization for all analyses, defeats the purpose of the DFN model. Adequate explanation for doing this should be provided.

(3) The level of detail for the TESM and SHYD models provided in the upper level documents is not adequate for understanding the application of these models. STUK should request additional details on these models.

We recommend that Posiva provide sufficient detail on biosphere modeling in the next step of licensing process. As noted before, adequate details of the TESM and SHYD models were not available in the documents we reviewed. Without such details, an informed technical person will not be able to reproduce Posiva results.

4.1.6 Review Topic 6: Supporting methods

In the documents considered by this review, we have not found a specific discussion on how supporting methods were used, or reference to an overarching process or procedure. However, Posiva makes good use of supporting methods to support the conceptual models, the calculation cases, and the analysis of results, and they have been used appropriately. This includes useful quantitative discussions of key data underpinning the calculations, the calculation results and the confidence that can be placed in the models and data (Posiva, 2013-01). Scoping calculations are used less frequently than quantitative discussion, but examples include the impacts of colloids on fuel dissolution rates (Posiva, 2013-01 page 510) and the time for water penetration into a canister with a pin hole defect (Posiva, 2013-01 Appendix J).

Specific processes and procedures have been applied to data clearance and expert elicitation, which STUK includes under supporting methods. These are outlined in Posiva (2013-01, Section 1.7). The expert elicitation process has been applied to specific cases when the understanding or data basis is conflicting and consensus is needed for the selection of key data (e.g., solubility and sorption data – see Appendix L therein). QA of the elicitation process is controlled by the quality coordinator of the group responsible for production of the safety case (SAFCA).

Data sources and quality aspects of the sources are documented according to specific guidelines. Individual data and databases are approved through a clearance procedure, which is also supervised by the SAFCA quality coordinator. Posiva (2013-01, Section 2.3) describes the quality management measures applied to the models and data. That section describes eight QA measures and where they have been applied in the safety assessment. Therefore, there is evidence that specific data clearance and elicitation processes have been applied, which builds confidence, but we have not examined these processes or their application in detail since it is beyond the scope of the current review. STUK should consider if it is necessary to examine data clearance and elicitation approaches or their application in detail.

Summary

(1) Posiva has made appropriate use of supporting methods including applying procedures for data clearance.

(2) We assume that STUK audits periodically the application of Posiva's QA/QC system with respect to data clearance and also process for expert elicitation.

(3) Posiva should publish the details of its expert elicitations so that any bias introduced during the elicitation should become apparent.

4.2 Review Area II: Safety Analyses, Models and Data (GD 736/2008, §14, §15)

Chapters 5, 6, and 7 of Posiva 2013-01 describe models and data used in safety analysis. Our comments in Review Area II should be read as complementary to those provided in Review Area I because the two topics are intimately related. For that reason, the comments are duplicative at many places. We could have avoided duplication but in doing so, we found that the comments would not be as clear as they should be.

4.2.1 Review Topic 1: Appropriateness of conceptual models (YVL D.5 §704, §A106)

In YVL D.5 §704, STUK requires a safety demonstration to include, "…a functional description of the disposal system and a description of the conditions prevailing in the disposal site by means of conceptual and mathematical modelling, and the determination of necessary model parameters." Further in YVL D.5 § A06, the conceptual models are required to describe the release and migration processes and also the safety functions.

Future climate change and seismic activity are the two main external events that affect conditions at the disposal site. Of the two, climate change provides time-varying boundary conditions for the flow and transport processes to and from the repository and therefore has the potential to affect almost all safety functions. It also significantly affects the surface environment and therefore the estimated radiation dose. The seismic activity also can have broad impacts but in Posiva's safety analysis, its main impact is in failing the canisters by shear movement on fractures that intersect the deposition holes.

In addition to the external processes, there are processes occurring within the repository volume and the surrounding host rocks that present challenge to the safety functions of all components. Although the conceptual models relate to the safety functions, they have not been explicitly related to named performance targets and corresponding criteria (i.e., VAHA level 3, 4, and 5). For example the VS2 and RS2-DIL cases consider advective conditions in the buffer, but are not explicitly related to performance target L3-BUF-12 (i.e., the buffer shall be impermeable enough to limit the transport of radionuclides from the canisters to the bedrock). This is an opportunity for further integration and transparency in the next iteration of the safety assessment, although it does not affect the outcomes of the present assessment.

Except for the probabilistic sensitivity analysis, Posiva's safety analysis is deterministic in nature. In any case, all the conceptual models and the corresponding mathematical models are deterministic and are based on established principles of conservation of mass, momentum, and energy together with appropriate constitutive relations. The time variation of process rates are generally dealt with by defining time-windows. Spatial variation is considered at multiple scales through either appropriate spatial discretization or through stochastic representation, especially in representing the fracture network. For example, the climate change is primarily represented in a discretized manner through repeated glacial cycles (see Figure 5-2, page 121, Posiva, 2013-01).

The conceptual models of barriers do not necessarily explicitly describe their individual safety functions. Instead, the conceptual models are designed to predict the state of a barrier as it evolves in response to external and internal loads. Thus processes are modelled rather than safety functions. Because safety functions are also related to barrier state, one can of course derive conclusions regarding fulfilment of safety functions. The safety functions of the five barriers comprising the proposed repository system are described in very broad terms in Table 1-1,page 54, Posiva 2013-01. As an example, the safety function of the canister is stated as, "Ensure a prolonged period of containment of the spent nuclear fuel." During its life time, the canister will be subjected to thermal, chemical, and mechanical loads. These loads can impair the safety function by causing failures by corrosion, creep or shear (mechanical) failure. Therefore, Posiva discusses these processes although does not include them in a canister model.

The placement of conceptual models in the context of performance assessment is the central part of the safety case. As stated by Posiva on page 54, Posiva 2013-01, "A safety case for a geological disposal facility for spent fuel documents the scientific and technical understanding of the disposal system, including the safety barriers and safety functions that these are expected to provide, the results of a quantitative safety assessment, the process of systematically analysing the ability of the repository system to maintain its safety functions and to meet long-term safety requirements, and provides a compilation of evidence and arguments that complement and support the reliability of the results of the quantitative analyses."

Posiva admits that process knowledge is not perfect and data reliability is variable. It states on page 65, "If reliable data are not available, many of the assumptions are based on the likely/expected characteristics and evolution of the system, or on a reasonably expected range of possibilities, or defined to err on the side of caution. The aim is to overestimate the potential radiological impacts of the disposal facility but in a plausible way. The use of cautiously chosen model assumptions and parameter values is consistent with YVL draft guideline D.5 (STUK 2011a) …" This is reasonable at this stage of the licensing process.

Posiva uses two types of models as described on page 63, Posiva 2013-01:

1. Detailed models that aim at a realistic description of specific processes–sometimes termed "process models", and
2. More simplified models used for scoping the impact of key processes and for analysing radionuclide release, retention and transport in a cautious manner.

As stated by Posiva on pages 63 and 64, Posiva 2013-01, "Simplified models are used whenever processes are too complex to model or affected by significant uncertainties (in the process itself or in the data). In this case, cautious, simple calculations can be a more effective way to show that safety functions are preserved. Such simplified models allow the effort of data gathering and quality assurance to focus only on key parameters. Simplified models are implemented in such a way that they do not overestimate the performance of the repository or underestimate the consequences of releases on long-term safety (e.g., by omitting processes that are beneficial to performance or safety, or by selecting pessimistic input data). Examples of simplified models are: (i) mechanical erosion model for the buffer and the backfill (Section 6.10), (ii) chemical erosion models (Section 6.11) and (iii) canister corrosion models (Sections 6.12–6.22)." While the stated intent of focusing on key parameters is laudable, we note that the intent is not fulfilled; we did not find a clear exposition of the key parameters. We have recommended in our list, a Posiva commitment that in the next licensing step, it will provide a clear list of key parameters. Overall, Posiva discusses all relevant processes and provides arguments for the simplifications that it makes in the final analysis.

It is interesting to note that Posiva obtains data on solubility, diffusion and sorption via expert elicitation. Normally, one would assume that such data is measurable in the laboratory and on somewhat larger scales in underground laboratories. Such data should be reviewed for any potential biases as it is not uncommon to have such biases introduced if a formal elicitation process is not implemented. More detailed review of conservative assumptions made to fill data gaps should also be conducted as the "conservativeness" of some assumptions may not be always obvious.

The spatial and temporal scales are presented and fully discussed. Assumptions with respect to geometry, initial and boundary conditions, material properties, and relevant processes are presented wherever the models are described.

Conceptual model uncertainty or alternative conceptual models are not explicitly discussed by Posiva except the parameterization in different calculation cases. Parameter uncertainty in the corresponding mathematical models however is discussed throughout the safety case. The impact of parameter uncertainty is analysed by defining calculation cases. We recommend identifying important aspect(s) of a conceptual model and request through a commitment, potential alternate conceptual models.

The CLA is a complex set of documents. We have not read all of the documents. However, from the material assigned for review to the safety assessment review team, it seems that Posiva's documentation is both repetitive as well as non-local. That is, one will need to examine many documents to gather information on one topic, yet significant information is repeated in each report. But, overall, it seems that the reporting is sufficient to allow informed criticism in this first phase of licensing.

In the uncertainty assessment for radionuclide partitioning coefficients, Posiva does not discuss the general limitations of the linear K_d concept. In contrast, the SKB has identified and discussed the key conceptual uncertainties such as: (i) reactions other than ion exchange and surface complexation, (ii) changes of chemical and physicochemical conditions, (iii) the presence of ligands or colloids other than those in the K_d determination experiment. SKB has also clearly recognized that the key problem is not the random uncertainty which can be treated in a relatively straightforward manner, but is related to the lack of knowledge (SKB R-06-75). SKB state that the uncertainty stems from the use of crushed rock and other variables such as the groundwater composition, radionuclide speciation, etc. during the measurements and insufficient knowledge of the time dependence of the processes involved.

A key process that has only been assessed to a limited extent is gas-mediated release and transport in the AIC disturbance scenario. The release of C-14 in gas and subsequent transport through the geosphere in both water and gas can exceed the regulatory geosphere–biosphere flux constraint. 1,000 year averaging reduces the peak potential flux below the flux constraint for transport in both water and gas. It is anticipated that a sudden gas release would rapidly migrate through the geosphere with only limited dispersion, therefore, even though 1,000 year averaging is allowed by the regulations, it is not clear whether it is within the intent of the regulations for this case. Similar considerations apply to migration of dissolved gas in water for disposal holes where the geosphere travel time is much less than 1,000 year.

It is anticipated that the distribution of geosphere travel times for transport in gas will be much smaller than for transport in water, and for the majority of disposal holes transport of gas through fractures in the geosphere will be rapid. Therefore, the potential consequences of transport of C-14 in gas phase may be much more similar for different disposal holes than for transport of C-14 in water. Figure 12-8, Posiva 2012-09 shows that, even with 1000 year averaging, simultaneous gas release from four or more canisters could exceed the geosphere–biosphere flux constraint.

The majority of C-14 is present as an activation product in metal components and is released congruently with corrosion of the metal components. Anaerobic corrosion of the metal components results in the generation of bulk H_2 gas, which acts as a carrier for C-14 trace gases. It is assumed that a gas pathway is established once the gas pressure reaches the gas breakthrough pressure of the buffer. The gas breakthrough pressure for bentonite is very high, so it takes some time to reach this pressure. Recent studies (e.g., Graham et al., 2012) have shown that gas migration through bentonite can occur at lower pressures through dilation and gas piping. The peak pulse release occurs at 2,000 years (Figure 12-8, Posiva 2012-09), but is associated with cautiously high corrosion rates. Therefore early breakthrough associated with dilation and gas piping would likely not lead to significantly higher fluxes through reduced decay. More significantly, these processes might lead to a longer release period and a lower peak C-14 gas flux, perhaps similar to the 1,000 year average flux.

The chemical form of C-14, and any subsequent reactions that alter the form, are also important. We note that Posiva is participating in the EU research project CAST, which is investigating these issues (Posiva, 2013-01 page 542). Posiva admits that neither are all the processes completely understood nor all the data fully available. In this regard, Posiva will continue to conduct RD&D activities during the operational phase and continue to improve the assessment. However, the conceptual models and the corresponding models are sufficiently well formulated for a construction authorization decision.

A few samples of Posiva's statements regarding uncertainties in conceptual models are provided below.

Posiva 2013-01, page 119, in relation to climate modelling, "All the governing processes are not yet fully understood. The earth system modelling is therefore necessarily incomplete." And later on page 120, "As it is, Posiva is at this stage confident in the models and data used in and obtained from climate modelling, and they have been propagated to be used for permafrost modelling (Section 5.2), terrain and ecosystems development modelling (*terrain and ecosystem development modeling*), surface hydrological modelling (*surface and near-surface hydrological modeling*) and groundwater flow modelling (Section 6.1)."

In relation to modelling of seismic activity, Posiva states on page 140 of Posiva 2013-01, "Uncertainties in the model of future seismicity are related to the scarceness of earthquake data, especially on earthquakes with larger magnitude." Further, "A reliable study of brittle fault zones is not available at the scale of over 10 km long faults, which have potential to host an earthquake M > 6. Faults longer than 40 km have the potential to host an earthquake M > 7." Based on its model, Posiva concluded that, "… the average annual probability of an earthquake leading to canister failure is estimated to be low, in the order of 10^{-7}, given that there are around 5 zones that could host such an earthquake at any specific time."

This average frequency however ignores the potential larger frequency value for post-glaciation periods. STUK has requested Posiva to (1) consider occurrence of an earthquake before 10,000 years and (2) instead of using an average frequency number, to consider frequencies for the non-glacial periods and for the glacial periods, separately.

Another potential effect of seismic activity is the possibility of drift seal failures. Performance Target L3-CLO-7 states that closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels / deposition holes. Corresponding criteria L4-CLO-7 states that sections in the underground openings intersected by highly transmissive zones… shall be hydraulically isolated from facility sections.

This raises the question of whether future rock movements might occur within the transmissive zones, thereby disrupting the drift backfill/seals through displacement (partial offset) and bypassing the sealing materials through enhancement of the EDZ. Additionally, could hydraulic erosion of fines from clay aggregate backfill or bentonite erosion from hydraulic seals result in reduced seal performance? This would not involve erosion of large volumes of clay aggregate backfill, but might involve 'opening' of interfaces between the rock and fill. It is not clear how vulnerable the disposal holes would be to damage of the backfill/seals in the transmissive zones. Even though we believe that the effect on overall safety of this scenario will be small, for completeness sake, Posiva should include a discussion of it in its safety case.

The conceptual models for the surface environment relate mainly to the description of the surface landscape, geology, hydrology hydrogeology and biogeochemistry of the overburden, water bodies and soils. The influence of spatial and temporal scales is not readily apparent in the reviewed documents. The models are snapshots of typical system and although the pools and fluxes are normalised to object area it is not clear at this level of documentation that, say, a small mire behaves in the same way as a large mire allowing for a simple scaling.

Posiva 2012-29 and Posiva 2012-30 reports cover the relevant spatial and temporal scales but it appears as through potential useful and available data from the supporting models may have been combined in an inappropriate way for the dose assessment modelling. The spatial domain used in the averaging is too large and potentially important aspects of hydrology may well could be over looked. Initial and boundary conditions for the overall landscape are well calibrated but details of water balance within the biosphere objects of the landscape may not be well represented.

Release of radionuclides into the system is assumed to occur at a limited number of locations. The justification for this is not entirely clear. Additional information has been requested from Posiva on these topics.

Summary

(1) Although the conceptual models relate to the safety functions, they have not been explicitly related to named performance targets and corresponding criteria.

(2) In our list of commitments, we have included a commitment from Posiva that in the next licensing step, it will provide a clear list of key parameters. Overall, Posiva discusses all relevant processes and provides arguments for the simplifications that it makes in the final analysis.

(3) Posiva calculations show that there is potential for C-14 gas release to be rapid and possibly exceed the release constraint; the applicability of 1,000 year averaging should be reexamined for this case.

(4) Possible drift seal failure due to seismic activity should be considered.

(5) Additional details for the modeling of landscape dose have been requested.

Reference

Graham, C.C., Harrington, J.F., Cuss, R.J. and Sellin, P. 2012. Gas migration experiments in bentonite: implications for numerical modelling. Mineralogical Magazine, December 2012, Vol. 76(8), pp. 3,279–3,292.

4.2.2 Review Topic 2: Input data selection, justification and recording (YVL D.5 § 704, § A06)

Posiva's approach to selection of models and input data is described in Posiva 2013-01. The models are designed to describe the performance of the key safety functions of barriers. The circumstances that may potentially affect safety functions are described in general, but not necessarily explicitly for each safety function. The uncertainty ranges in both the models and their parameters are dealt with by defining calculation cases. It is in the calculation cases that the safety functions are degraded, generally one at a time. The degradation of the safety functions is justified but not always satisfactorily. However, there is such a large safety margin in all cases that minor changes in assumptions will likely not alter the final conclusion. Data and arguments are mostly consistent with few exceptions which have been noted at various places in this review.

Posiva divides key model parameters into three classes: (1) those that define the initial system state (e.g., repository layout, host rock properties), EBS design specifications, and properties of the spent fuel; (2) those that describe the space-time evolution of the system (e.g., rock damage, tectonic events, climatic conditions, etc.); and (3) those that describe radionuclide release and transport (e.g., fuel dissolution rate, diffusion, sorption, and advection, and geochemical reactions, etc.). The method for selection of parameters is explained on page 65, Posiva 2013-01 and is appropriate for the first stage of the licensing process. Input parameter values are based on (1) site-specific investigations; (2) international projects, such as LOT, FEBEX, EBS Task Force, LASGIT and MICADO; (3) data produced by other waste management programmes such as SKB (Sweden), Nagra (Switzerland), WMO (Canada), Enresa (Spain), and Andra (France); and (4) from expert elicitations such as solubility, diffusion and sorption coefficients of host rock. Because of the long compliance time frame, it is not uncommon that input parameters have to be either assumed or extrapolated. Posiva makes conservative assumptions in situations where there is lack of data. For example, for seismic parameters, Posiva states on page 135 of Posiva 2013-01, “With the scarce data in FENCAT it was not possible to establish statistically reliable seismic parameters for the Olkiluoto target area directly.” The solution to the problem is obtained by scaling parameters of larger regional seismic belts to represent the target area (region within a 100 km radius of Olkiluoto) as described in Posiva 2012-34.

Because of the importance of the source term to Posiva’s safety assessment, we decided to trace input data related to it. Data and models for the source term are described in Section 7.3, page 485, Posiva 2013-01. The ORIGIN-S code is used to generate the time-dependent inventory of about 1,000 radionuclides. The radionuclides are screened to select only those that are deemed to be safety-significant. The list of 41 selected radionuclides (see Table 7-5, page 494, Posiva 2013-01) contains all those mentioned in YVL D.5 and compare well to those selected by other waste management programs. In other words, no significant radionuclide is missing from the list. The radionuclide inventory is then partitioned into the four components of the source term (representative of all spent fuel in Posiva’s inventory) as described in Figure 7-3, page 486, Posiva 2013-01: (1) UO_2 matrix dissolution rate as 10^{-7}/year; (2) Zr-based alloy release rate as 10^{-4}/year; (3) release rate from other metal parts as 10^{-3}/year, and (4) instantaneous release rate (IRF). Of the four part inventory (see Table 7-6, page 495, Posiva 2013-01), the IRF part is probably the most important mostly because of Posiva’s pin hole scenario that does not allow the other parts of the inventory to exit the interior of the canister except at a much later time. The IRF of various nuclides is discussed in Table 7-8, page 500, Posiva 2013-01 and the rationale of values used in the deterministic compliance calculation is provided. However, uncertainties are not explicitly discussed.

Posiva 2013-01, Section 1.8 states that an important purpose of the models and data report was to bring forward quality assurance aspects of the models and data handling process. Posiva assures the consistency of input data by the application of its QA/QC program. On page 66, Posiva 2013-01, eight quality management measures applied to the models and data are described. These include validation of models, verification of computer codes, justification of input parameters, and adequate documentation of calculations. To keep track of, and to archive, the results of safety assessment calculations, Posiva has developed an electronic system called *docgen*. We recommend an audit this system to gain assurance in its effectiveness. There is scope for Posiva to improve the QA of its assessment calculations. Posiva anticipates that the data checking undertaken during production of the models and data report (Posiva 2013-01), and learning from experience, will provide important inputs into improved QA processes for updates to the safety assessment in support of the operations licence application, for example to facilitate setting up a data freeze. Such a data freeze should greatly improve QA of, and confidence in, the safety assessment calculations

As part of the current review, a few of Posiva’s calculations were reproduced with independently

Summary

(1) Posiva's approach for selection of input parameters is reasonable and it is appropriately documented.

(2) Posiva's QA/QC program is designed to assure consistency and correctness of data. However, the assumption that it will forever function without any violations is not practical.

(3) Our limited independent checks of calculations did not point to any consequential errors.

developed models. A number of minor errors, inconsistencies and uncertainties in the data and calculations were noted as result of these calculations but overall the independent calculations match those of Posiva. Such reproduction of Posiva's results helps build confidence in Posiva's calculations despite the minor discrepancies that were identified.

4.2.3 Review Topic 3: Mathematical models (YVL D.5 §704, §A106)

The mathematical models should be (YVL D.5 §A106)," … derived from the conceptual models, normally by way of simplification." Posiva appropriately derives the mathematical models from the respective conceptual models. The simplifications in models are adequately described. However, there is little discussion of alternate models and approaches but this is to be expected as the approach is mature and uncontroversial. There is a useful discussion of alternative modelling assumptions in Appendix E of Posiva 2012-09 and alternative models are discussed for some of the details, such as for the deposition hole damaged zone in Appendix C of Posiva 2012-09.

One detail where the explanation of the mathematical model is not clear is in the derivation of the equivalent flow rate (Q_F) from the pathway to a fracture intersecting a deposition hole. This is expressed in terms of flows through the damaged zone (as modelled in the DFN by some additional fracture planes), except for the case with no damaged zone when a diffusion-based approach is used. This relates to the conceptualisation of the damaged zone as a mixing zone. It appears that this approach implies that there is no release unless there is flow through the damaged zone; what happens if there is flow through the fracture but none deviates into the damaged zone? This is also an area where alternative models have been considered (Appendix C of Posiva 2012-09). This shows that the assumptions made are important, but the higher release alternatives are dismissed on the basis that they are unrealistic, but no evidence is presented to allow the reader to judge what really happens at this interface. Posiva should provide an explanation of the assumptions made in deriving the equivalent flow rate and its assumptions on the damaged zone.

To trace one model and the data required to execute it, we picked a simple but important example. The example relates to Posiva's model for transport from the 1 mm defect in the canister. Posiva's model is discussed in Posiva 2012-09, Chapter 3.

Transport of radionuclides from inside the canister through the defect to the buffer outside is assumed to be by molecular diffusion which assumes that a continuous water phase exists between the canister and the buffer. Posiva's terminology here is somewhat confusing for naming a factor in the equation flow rate; even when transport is by diffusion (we believe that this terminology is borrowed from SKB). In any case, the mass transport by diffusion is proportional to concentration gradient. If the concentration inside the canister is $C_{canister}$ and the concentration at the buffer-canister boundary, $C_{boundary}$, then the mass flux rate, J_{defect} is given by,

$$J_{defect} = \frac{\pi r^2 D_{defect}}{l_{defect}} \left(C_{canister} - C_{boundary} \right) \tag{1}$$

where r is the radius of the defect, l_{defect} is its length, and D_{defect} is the diffusion coefficient. Note that the hole is not assumed to have any clay in it. The next leg for mass transfer is in the buffer where mass is assumed to diffuse radially in the pores and the mass flux, J_{buffer} is

$$J_{buffer} = 2\pi r \varepsilon_{buffer} D_{buffer} \left(C_{boundary} - C_0 \right) \tag{2}$$

where, ε_{buffer} is the diffusional porosity and D_{buffer} is the diffusion coefficient. C_0 is the concentration at say the buffer-rock interface.

Posiva connects the two diffusional legs in series and obtains an expression for mass transport rate, J, from inside the canister to the buffer-rock interface as

$$J = Q_c \left(C_{canister} - C_0 \right) \text{ where}$$

$$Q_c = \left(\frac{l_{defect}}{\pi r^2 D_{defect}} + \frac{1}{2\pi r \varepsilon_{buffer} D_{buffer}} \right)^{-1} \tag{3}$$

Note that the units of Q_c are (l^3/t) and therefore, SKB and Posiva calls it "equivalent flow rate". Because an initial defect in the canister is the only reason that there is any release of radionuclides in the base case and also in the variant scenarios, the Q_c term controls all the results and it therefore is of primary importance.

Sample values of the parameters in the above equation are listed in Table 13-5 on page 340 of Posiva 2012-09. That is

$l_{defect} = 0.05$ m,
r = 0.0005 m,
$D_{defect} = 10^{-9} m^2/s$ in water
$\varepsilon_{buffer} = 0.08$ for I-129, and
$D_{buffer} = 7.8E \times 10^{-12}$ m^2/s for I-129.

Substituting these values in the above equation, one gets $Q_c = 8.72 \cdot 10^{-15} m^3/s$, or $2.75 \cdot 10^{-7}$ m^3/a.

Assume about 2 tU per canister (see Table 3-2 on page 78 of Posiva, 2012-12 for mass of U in a spent fuel assembly and Table 3-4 on page 81 of Posiva 2012-04 for number of assemblies in a canister).

The mass of I-129 in spent fuel is given in Table 7-7 on page 496 of Posiva 2013-01 as, 1.87 mol/tU. In terms of radioactivity, it is given in Table 7-6 on page 495 of Posiva 2013-01 as 1.91 GBq/tU. Therefore the initial content of I-129 can be estimated as, 2 tU/canister × 1.87 mol/tU × 1.64×10^4 gm/mol = 6.13×10^4 gm/canister or alternatively 3.82 GBq/canister. Of this 5% is instantaneous release fraction. That amounts to 3.06×10^3 gm or 0.191 GBq, the remaining (5.83×10^4 gm or 3.629 GBq) is in spent fuel matrix.

The solubility of I-129 is unlimited (Table D-5 on page 703 of Posiva, 2013-01). However, the dissolution rate of spent fuel matrix is, 10×10^{-7}/year (page 486 of Posiva, 2013-01). The concentration inside the canister is determined by adding the instantaneous release fraction to the amount that dissolves from the spent fuel and dividing it by the volume of water inside the canister.

Posiva's conceptual model for release inside the canister is that water seeps into the canister through the defect in the weld at the top lid and that radionuclides start seeping out once the canister is full so that a continuous water path between the canister interior and the buffer is established. Posiva estimates that it takes 1,000 years for the canister to fill the 0.7 m^3 interior void space. For a rough estimate, we can assume the mass available for dissolution is ½ to that dissolved in 1,000 years (not all spent fuel is in contact with water for 1,000 years) (i.e., 2.91×10^{-3} kg). Adding the IRF and dividing by water volume gives us the concentration as 4.358 kg/m^3 or 0.273 GBq/m^3. Assuming C_0= 0, the source term of I-129, J can be estimated to be 1.2×10^{-6} kg/a or 7.5×10^{-8} GBq/year which is orders of magnitude below the regulatory limit of 1×10^{-1} GBq/year. The source term will increase with time as more and more I-129 becomes available but it is easy to see that in the pin-hole scenario, there is little chance of it exceeding the regulatory limit. In fact another independent calculation performed indicated that even if all the canisters are assumed to have the pin hole defect, the NRR will still be less than the regulatory constraints. This release rate decreases significantly by the time the contaminant front reaches the buffer-rock interface as shown by Figure 7-1, page 147, Posiva 2012-09 where the peak release rate for I-129 is about 100 Bq/year (figure reproduced below). Posiva's result 100 Bq/year is comparable to our calculated value (without the use of a computer code) of 75 Bq/year. In Figure 4-12 on page 107 of Posiva 2012-09 the maximum value of Q_c is given as 4.9×10^{-7} in the reference case while the maximum value is 4.3×10^{-4} in Monte Carlo simulations. Also, note that while the solubility of I-129 is unlimited, the concentration of other radionuclides inside the void space is also constrained by their solubility. The point of this calculation is to show that the Q_c term controls the source term and therefore also any transport downstream through the host rock to the surface environment. Our simple calculation confirms the low value of Q_c.

Figure 13-11, page 342, Posiva 2012-09 also illustrates this point. As can be seen in this figure, the fractional mass transfer rate from the canister to the buffer is the lowest of all the mass transfer rates. In some sense, this reduces the safety impact of, for example, the DFN model in the base scenario because advection in fractures is important only if material is available for transport such as in the RS

Summary

(1) Posiva should clarify how the damaged zone affects the estimate of the equivalent flow Q_F.

(2) The release in the base case is controlled by the rate of diffusion in the defect, Qc, which is very small, nothing else (including DFN results) really seem to matter.

(3) Posiva should consider conducting complementary analysis of dose using simpler biosphere models to enhance confidence in its calculations done using the current complex model.

(4) Posiva should provide additional description of how it calculates the fate of radionuclides released to the surface environment.

and RS-DIL scenarios.

In Posiva 2012-29 alternative calculation cases are presented. These are suitably justified. The range of results presented in Posiva 2012-30 regarding near surface hydrology are not so well justified. There is one case that describes the surface average for the water fluxes in different classes of biosphere object and for which mass balance is consistent. Other cases deal with the maximum and minimum flows in the biosphere object but for these, mass balance is not achieved and it is not clear what aspect of reality these situation are intended to represent (see Section 4, Posiva 2012-30) in relation to the drivers of radionuclide migration.

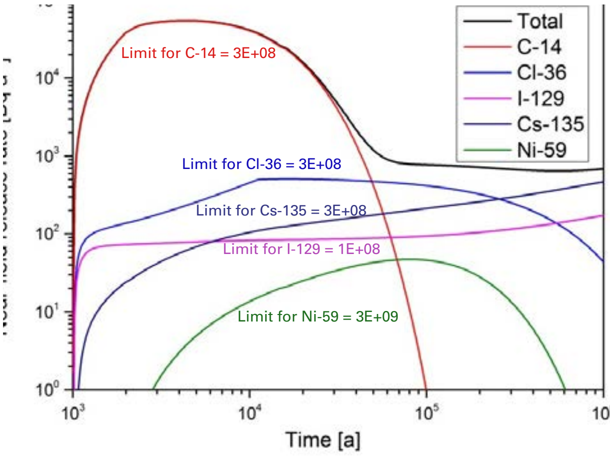


Figure 6. Near-Filed release from the pin-hole. The five radionuclides presented in this figure make up most of the total release. Regulatory release limits (Bq/year) at the geo-bio boundary are shown. The releases are estimated to be 3 to 8 orders of magnitude below the regulatory constraints. [Adapted from Figure 7-1, page 147, Posiva 2012-09]

One area where the dose modelling appears to be lacking is in the use of simple models to investigate and support aspects of the dose assessment. In part this is carried out using simple models in the radionuclide screening process but this is not carried through to the real site data. A complementary analysis using simple models would be welcome addition and it will enhance confidence. Mathematical details underlying the TESM and the SHYD models are inadequate in the reposts that we reviewed. In the SHYD report (Posiva 2012-30) water balance is not maintained when the maximum and minimum flows in the biosphere objects is used. Posiva should clarify the use of such maximum and minimum fluxes. Posiva should also provide a reasonable description of the fate of radionuclides released to the surface system.

The lack of alternate conceptualisation for near surface hydrology and terrain and surface models is something of a concern. The main obvious lack at the current stage of the review relates to the identification and justification of the biosphere objects into which the releases might occur.

4.2.4 Review Topic 4: Consistency of calculation cases, models and data (GD 736/2008 §15, YVL D.5 §A107)

Selection of the calculation cases is described in Posiva 2012-08, Section 7. In general there is adequate discussion of the selection of input data, and uncertainties are typically managed by erring on the side of caution, which provides confidence that data limitations will not 'hide' potentially significant impacts. Posiva depends on the success of its QA/QC program to assure consistency of calculation cases, models and data. Posiva's QA/QC procedures include (1) validation of input data for the scenarios and models and checking the limits of applicability of the input data against the assumptions (Posiva 2012-12, Section 2.5.3); (2) a version management system to keep track of any changes in input files and thus maintain the reproducibility of calculation results; (3) an assessment database for the storage, checking and exchange of input data, intermediate results and final results (Posiva 2012-12, Section 2.5.3); and (4) creation of purpose-specific databases to manage the data clearance procedure in a structured way and to ensure the controlled use and traceability of input data used as input to safety related assessment calculations

(Posiva 2012-12, Section 2.5.4). Therefore, while we have not examined model input files, there is good evidence that appropriate QA procedures have been applied. We leave it to STUK to audit aspects of this process to gain reasonable assurance about its effectiveness.

The PSA Monte Carlo simulations were undertaken using GoldSim and the sensitivity measures were calculated using Matlab The PSA considers two cases: 'hole forever' which can be compared with the Reference Case, and 'growing hole'. The growing hole case considers that the initial defect will become enlarged over time and the transport resistance, associated with migration through the hole, is instantaneously lost after a period that is varied between 5,000 and 50,000 years. It is not clear why this assumption was made, compared with the more realistic assumption of a gradually enlarging defect in the VS1 case. Further, Posiva do not draw any conclusions about the relative likelihoods or significance of the two cases, which leaves some uncertainty regarding the conclusions to be drawn from the PSA.

Posiva (WR_2013-25, WR_2013-61) describe the probability density functions used in the PSA. For most parameters upper and lower bound values can be identified with reasonable confidence. However, in most cases there are not sufficient data to describe the shape of the probability density function, and log-uniform distributions are generally assumed primarily because the range of values spans several orders of magnitude. Exceptions are probability density functions for solubility limits and distribution coefficients, where there are sufficient data to describe them by log-normal distributions, and the distribution of near-field and geosphere flows which are taken directly from the DFN model.

The PSA shows that radionuclide fluxes are sensitive to the mass of clay in the cavity. However, the PSA report does not include a discussion of this parameter (which is zero for the deterministic Reference Case) and therefore it isn't entirely clear how buffer intrusion within the cavity was modelled (the deterministic variant case CS3-FILL considers buffer intrusion into the defect, but not the cavity itself), and whether the calculation case, models and data are consistent. Posiva (2012-09, Section 9.6.2) indicates that buffer intrusion into the cavity reduces radionuclide fluxes, so the reference case is cautious, and therefore this is a relatively minor omission.

The rock shear scenario resulting from future seismic activity is of special interest for performance assessment as it is the scenario in which the largest numbers of canisters (35 to 78) fail and it results in the highest NRR. However even in this scenario, all the other EBS barriers (especially the buffer) are assumed to fulfill their safety functions and the spent fuel is assumed to be undamaged. Such assumptions reduce the realism of this scenario. It is only in the RS-DIL scenario that the buffer safety functions are assumed to be partially impaired.

In relation to modelling of seismic activity, Posiva states on page 140 of Posiva 2013-01, "Uncertainties in the model of future seismicity are related to the scarceness of earthquake data, especially on earthquakes with larger magnitude." Further, "A reliable study of brittle fault zones is not available at the scale of over 10 km long faults, which have potential to host an earthquake M > 6. Faults longer than 40 km have the potential to host an earthquake M > 7."

Based on its model, Posiva concluded that, "… the average annual probability of an earthquake leading to canister failure is estimated to be low, in the order of 10^{-7}, given that there are around 5 zones that could host such an earthquake at any specific time." Also, according to Section 7.2.4 of Posiva 2012-04, the number of canisters that could potentially fail in the event of a large earthquake, denoted by N_{crit} , is between 35 and 78 [i.e., 1.2% of the total of 4,500 canisters when applying the full perimeter intersection (FPI) criterion rock suitability criterion and 0.4% when applying the modified FPI criterion].

The average frequency however ignores the potential larger frequency value for post-glaciation periods; no historical data exists for such conditions. In its next iteration, Posiva should consider (1) occurrence of an earthquake within the dose time window and (2) instead of using an average frequency number, to consider separate frequencies for the non-glacial periods and for the glacial periods.

On page 284 of Posiva 2012-09, Posiva states, "The expectation value of the normalized radionuclide release rate from the geosphere in the rock shear scenario is taken to be the weighted average of all values that the release rate could take, given the uncertainty in the timing of the earthquake giving rise to canister failure due to rock shear and in the number of canisters affected. The weights used to evaluate this average correspond to the probabilities of a given value of normalized release rate arising at a given time." This complex concept is explained in Figure 11-9, page 287, and Equation (11.2-1) on page 288, Posiva 2012-09. Although it is not clear how many earthquakes are considered in calculating the probability weighted mean, the process seems reasonable.

Posiva states that the likelihood of a large ($M \geq 5$) earthquake occurring during periods of glacial retreat is higher. The length of the glacial cycle is assumed to be 120,000 years which is assumed to include three glacial retreats. In Section 7.2 of Posiva 2012-04, justification is provided for assuming the existence of 5 fault zones around and within the area of the repository that could host a $M \geq 5$ earthquake. If p is the annual probability of occurrence of an earthquake of $M \geq 5$ during a glacial cycle per fault, then the probability of such an earthquake occurring at the site during a glacial cycle is given by

$$P = p \cdot 120{,}000 \text{ (glacial cycle length)} \div 3\text{(retreats)} \cdot 5\text{(capable faults)} \qquad (4)$$

Posiva estimates p based on historical data in various seismic zones in the region. The seismic zones are shown in Figure 5-8, page 136, Posiva 2013-01. However, one should note that no data is available for the glacial cycle. Therefore, any value assigned to p should be regarded as an extrapolation.

Posiva estimates (Page 286, Posiva 2012-09) the average annual probability, p, of a large earthquake occurring on any one of these faults as between 2.3×10^{-8} to 4.7×10^{-8} (a wrong reference to Table 7.2 rather than 7-3 in Posiva 2012-04 is made here). Applying the above equation then gives $P = 0.0048$ to 0.0096.

The probability number is important for estimating the expected value of NRR. Therefore, we believe that alternate models such as the simple Poisson model should be examined. This model provides the probability of n earthquakes in time t as

$$P_N(n) = prob\{N = n\} = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \qquad (5)$$

where λ is the occurrence rate (1/year) or frequency. Then, $P_N(0) = e^{-\lambda t}$. Assuming $\lambda = 1 \times 10^{-7}$/year/fault, the probability that no large earthquake occurs in a period of glacial retreat (about 40,000 years) is 0.9801. Or the probability that at least one large earthquake will occur during the first glacial retreat is 1–0.9801 = 0.020 compared to 0.0048 to 0.0096 obtained by Posiva. If λ is assumed an order of magnitude higher during the glacial cycle (i.e., $\lambda = 1 \times 10^{-6}$) then the probability of at least one event is 0.181. If the higher probability number (0.181) is used, the peak NRR will be about 40 times higher than calculated by Posiva which is still below the regulatory limit. This topic has been reviewed in greater detail by seismologists and their review is reported in the Site Consolidated Review Report. See also Appendix A for review of additional information on this topic.

The site descriptive models for the surficial deposits and the biosphere system are extensive. Of particular interest is Chapter 5 of the Posiva 2012-06 where the transport and fate of the selected elements (in terms of pools and fluxes) is set into a detailed ecological context. It is not clear how much or indeed how this information is translated into the dose assessment modelling.

The apparent aim of the Posiva 2012-30 is to determine a practical means of expressing the water fluxes in the future landscape. At the small scale and for the present day the details provided in Posiva 2012-30 are of high quality. There is, however, a large descriptive gap between the calibration data and the numerical results discussed in Chapters 4 and 5 of the report. There is a lot of textual description but the numerical details are sketchy and these only appear as fully developed values for the average cases in Chapter 4. In this respect the description does not provide a sufficiently detailed description of the derivation of the object-specific water fluxes in the landscape context.

Nevertheless the larger scale landscape is used to evaluate doses to the broader population. In this way the focus of the dose assessment modelling is on the description of doses at low dose rates to a larger population with less emphasis on the description of particular human activities that are possibly close to the release where the highest environmental concentrations would occur.

While addressing regulatory requirements, this approach effectively reverses the emphasis in traditional reference biosphere models where the "critical group" is the focus of all attention. It is possible that analyses described in Posiva 2012-10 and Posiva 2012-31 may actually underestimate doses to the most exposed group of individuals.

Although Posiva 2012-12 has a section dealing with biosphere – geosphere interactions (page 133) and the effects of changes in hydrogeochemistry are identified as being important "very near the surface at Olkiluoto", it is far from clear how these matters are taken forward into the dose assessment and neither is the description given at the same level as purely separate biosphere and geosphere descriptions. Geosphere-biosphere interface issues are not addressed in Posiva 2012-30 except insofar that average fluxes are carried into TESM with limited discussion of dispersion in the overburden. This is not to say that the discussion of the geosphere-biosphere interface will lead to deficiencies in the dose modelling; it is certainly true that it is not so well integrated into the overall treatment of FEPs as other parts of the system. How these matters are handled in the modelling will therefore be an issue of some concern.

Posiva 2012-29 report also generates the super objects seemingly independently of the hydrological model so that the hydrology of the contaminated areas are not well linked to the objects they describe, and this could lead to considerable uncertainty. Were it to be reasoned that these matters are of no consequence then there would be no real justification for the complexity of the TESM.

There is adequate discussion of the scientific rationale and mathematical basis for the selection of models. Mostly, the models are appropriate for their intended use. Posiva states on page 597 of Posiva 2013-01, "The main outcome (of this report) is that models and databases are fit-for-purpose (i.e., models incorporate relevant FEPs and models and data used within their applicable ranges of conditions). However, improvements could still be made to reduce uncertainties and improve overall system understanding."

Posiva also notes on page 598 of Posiva 2013-01, "Uncertainties in the source term (both radionuclide inventory and release rate) have a large impact on the radionuclide release and transport calculation results, most notably uncertainties in the fuel dissolution rate and the labile fractions of radionuclides (IRF). Further planned work to reduce uncertainties in the source term includes:

1. update of the radionuclide inventories based on updated spent fuel data from TVO and Fortum,
2. evaluate spent fuel dissolution rates in natural groundwater and UO_2 surface reactions (EU project REDUPP or REDucing the uncertainty in Performance Prediction),
3. perform short-term leaching tests of high burn-up fuel to justify lowering of the assumed release rates of the labile fraction of the inventory …

Modelling work concerning scenarios potentially leading to criticality events in the long term continues throughout the 2013–2015 research period."

We note that despite spent fuel not being identified as a barrier, Posiva does understands that the source term is probably the most critical part of post-closure safety assessment. Similarly, future work topics related to the canister, buffer, backfill etc. are also identified in Chapter 8 of Posiva 2013-01. As we have stated before, such topics for future RD&D should be gathered for identification of potential license conditions/requirements/commitments and for defining a future RD&D program – see Table 1 at the end of this report for a summary of our recommendations.

In the biosphere, "models for the evolution of the site" is understood to mean supporting models–TESM and SHYD. The dynamic nature of the state of the surface system means that changes therein are expected to have more significant effects. This is confirmed in the use to which the TESM is put in the assessment modelling. Starting from the topography of the present day–including the bathymetry of the bays, UNTAMO is used to identify changes due to uplift, sedimentation, gyttja formation, development of mires, infilling of lakes, maturation of forests and the most favourable locations for agricultural land. In practice much of the potential variation in the development of the site has little overall impact in the first 10,000 years (and much of the variation presented in TESM is not carried forward to the dose assessment modelling. It would be of interest to see how UNTAMO would represent the evolution of, say, 100,000 years. For other site contexts, outside Fennoscandia this might be of considerable interest. However, the integration of SHYD into this framework remains unpersuasive, lacking in detail.

In the time period for the dose assessment modelling the two main impacts are land uplift and climate evolution. Climate change and sea-level scenarios are well described with detailed and informative documentation giving range of options. Implications of global climate warming are investigated suggesting that, in the longer term, sea levels will be outpaced by land rise. The role of tectonics in the dose assessment window is of some concern.

Regarding data use, Posiva states on page 597 of Posiva 2013-01, "The compilation of the present report helped to identify which data have been used in the modelling chain, clarify input/output data flow and identify discrepancies in the use of the data. Appendices C through I provide a component-wise view of the various input data and point out whenever there were discrepancies in data use for different models. For example, the performance assessment modelling chain was implemented by groups (or individuals) who worked independently from each other or ran their models in parallel and used different input data for the same parameter (e.g., porosity of the buffer and backfill) or used provisional data, where only this was available at the time of model compilation (e.g., layout)."

Further, "Some discrepancies originated from miscommunication among modelling groups (or individuals) (e.g., transport parameter values in the near field) in spite of the quality control measures implemented for the assessment of radionuclide release scenarios for the repository system modelling chain (see Section 2.3). Those discrepancies that had a potential impact on the results of *Assessment of Radionuclide Release Scenarios for the Repository System* were selected and additional calculations have been done using the updated data and the results compared with those presented in *Assessment of Radionuclide Release Scenarios for the Repository System* (see Appendix M). None of these discrepancies led to significant differences in the total releases. Other discrepancies (e.g., rounding errors) were discovered in the compilation of this report and reported in the relevant sections but they were not deemed sufficiently significant to require additional calculations."

Based on our reviews, it is impossible to reach a conclusion about the proper use of data. We recommend some detailed reviews of selected topics and also some audits to confirm that the data quality is appropriate and that the data has been appropriately used. In general, Posiva has provided sufficient discussion to justify the data used in safety assessment.

The calculation cases are defined for the Base, Variant, and Disturbance scenarios, primarily to analyse the effect of uncertainties. The calculation cases are summarized in Table 7-2 on page 169 of Posiva 2012-12. For example, the BS-RC assumes (1) RSC criteria are applied successfully, (2) performance targets for the host rock and the EBS are met except for a 1 mm hole in one canister, (3) the spent fuel dissolution rate is very low (1×10^{-7}/year), and (4) the canister with the pin-hole defect is placed in a deposition hole that produces the greatest release at the geo-bio boundary (pessimistic location). The Base Case calculation cases include (1) location of the initially defective canister at alternate locations, (2) selected radionuclides (Ag, Mo, and Nb) are assumed to migrate as anions (meaning at a rate faster than in the BS-RC case), and (3) the time for establishing the transport path in the defect is increased from 1,000 years in the BS-RC to 5,000 years in the calculation case.

Of course, there could be other calculation cases. In fact, the calculation cases where the initially defective canister is located at less pessimistic locations and the one in which the establishment of the transport path takes five times longer will produce consequences smaller than the BS-RC and therefore do not add to the risk information. Posiva may argue that the calculation cases are more realistic and that the BS-RC case is pessimistic. However, the greatest uncertainty in the Base case is in the size of the defect, the number of possible defects, and the possibility of a defect at the bottom weld (if Posiva choses to have the base plate welded). As an extreme calculation case, one may assume that one canister completely fails.

Posiva is correct in stating that the likelihood of placing the defective canister in a bad location is low (1/number of deposition holes or 2×10^{-4}) assuming it to be random. Therefore, in a probabilistic analysis, it may not matter much even if one canister is considered to be completely failed initially.

The variability and uncertainties in parameters is adequately described by Posiva. The assumptions are also properly stated. Posiva has also described its assessment of confidence in its modelling. We see nothing obvious missing but only a detailed review of selected important topics can lead to a firm conclusion in this regard.

Summary

(1) STUK may request Posiva to (1) consider occurrence of an earthquake within the dose time window and (2) instead of using an average frequency number, to consider separate frequencies for the non-glacial periods and for the glacial periods.

(2) We recommend a detailed review of C-14 modeling in dose assessment as it dominates doses in almost all cases.

(3) Topics for future RD&D should be gathered for identification of potential license conditions / requirements / commitments and for defining a future RD&D program (see Table 1 at the end of this report for a summary of our recommendations).

(4) To gain confidence, we recommend some detailed reviews of selected topics and also some audits to confirm that the data quality is appropriate and that the data has been appropriately used. In general, Posiva has provided sufficient discussion to justify the data used in safety assessment.

(5) Posiva should explain more clearly the processes considered at the geosphere-biosphere boundary.

4.2.5 Review Topic 5: Random variations (GD 736/2008, §15, YVL D.5 A107)

Heterogeneity and random variations in the geosphere dominantly occur due to fractures and their connections, and consequently at the intersection of the natural and engineered systems. The nature of the fracture network not only controls flows, but also affects spatial evolution of the groundwater chemistry in response to changing conditions (repository construction and dewatering, climate and landscape change including sea level rise, isostatic rebound and glacial melt-water injection). At the interface of the natural and engineered systems, different disposal holes may be subject to different flow rates, and will exhibit different vulnerabilities to changing conditions. The geosphere fracture network and associated heterogeneity cannot be fully characterised. Sample data is used to estimate parameter distributions and develop a Geo-DFN model, which in turn feeds into the Hydro-DFN model. The scenarios, conceptual models and radionuclide transport calculations are underpinned by the Hydro-DFN model. Therefore there is very strong reliance on the results of the DFN model, and in particular the DFN model description of heterogeneity and random variation. Posiva has explored, in a limited way, sensitivity to different groundwater modelling assumptions, DFN realisations, and different realisations of mapping the fracture transport classes to Hydro-DFN. However, due to the size and complexity of the DFN model, there are limitations on the number of groundwater flow modelling assumptions and DFN realisations that can be explored, and only a specific case is carried forward for radionuclide transport calculations for each scenario. The rationale for picking the specific realization and the demonstration that the selected realization is pessimistic is lacking. The question of how only 10 realizations can be representative of the stochastic field should also be examined by evaluating the sampling scheme.

Posiva does conduct a probabilistic sensitivity analysis (described in Chapter 9 of Posiva, 2012-09 and in much greater detail in Posiva WR 2013-25) in which it assigns probability distribution functions to various uncertain parameters. Parameters are either assigned a truncated lognormal or a loguniform distribution. Most, but not all, of the uncertainty intervals are such that the reference value is in the middle of the range. In some however, the interval is biased to one side or the other. Reasons for such a bias are provided in most cases in WR 2013-61. Generally, a bias is introduced to accommodate the "pessimistic" nature of the reference value. This means that if the pessimistic reference value was high to begin with then the upper end of the uncertainty interval is closer to the reference value than the lower end and vice a versa. In the deterministic analysis of the hole forever case, a delay time of 1,000 years is used. This rules out any possible consequences due to the two fission products with large inventories: Cs-137 and Sr-90. In the PSA, the probability density function for delay time is Log-Uniform (10–5,000 years). This uncertainty interval is biased towards the low value which is good for the sensitivity analysis. Cavity water volume (reference value 700 kg) is also biased in the right direction with the distribution Log-Uniform (90–900 kg) and the same is true for the clay in the cavity for which a distribution Log-Uniform (1–1,000 kg) is used.

All parameters are assumed to be statistically independent of each other which may not be strictly true but is acceptable for the PSA at this stage. Simple random (in contrast to stratified or other complex schemes) sampling is used to draw 10,000 samples of each uncertain parameter. Thus, the PSA is based on 10,000 parameter vectors, each vector having 160 (in the case of hole forever) or 162 (in the case of growing hole) values in it. Table 3-19, page 42, WR 2013-25 lists the various parameters used in the PSA.

Inventory and half-lives of radionuclides are considered fixed at the values of the deterministic reference case (see Table 3-1, page 16, Posiva WR 2013-25). Various data reported in WR 2013-61 shows that the inventory of various radionuclides vary by less than a factor of 3 even considering high burnup rates. The probability distributions of instantaneous release fraction are based on fission gas release data and leaching tests (WR 2013-61, page 10). For instance, IRF (I) for iodine, the upper limit is set at 0.15 in order to explore the potential effect of high burnup PWR fuel (such as OL3) and the lower limit is arbitrarily set at ten times smaller or 0.015. The reference value used in the deterministic calculations is 0.05. The distribution for IRF (I) is Log-Uniform (0.015–0.15). The Log-Uniform distribution means that $\log_{10}$ of IRF (I) varies randomly between −1.824 [$\log_{10}$ (0.15)] and −0.824 ($\log_{10}$ (0.15).

As described in WR 2013-61, page 63, only a single realization (ps_r0_5000csv) of the DFN model in ConnectFlow is used to simulate flow. Posiva has determined that 4,718 holes out of a total of 5,391 are expected to fulfill the RSC criteria. These 4,718 holes are used to sample near field flows, Q_F, Q_{DZ}, and Q_{TDZ}. In 1,017 of these holes, one of the near field flows is zero; therefore, corresponding far field geosphere pathway is not defined for these holes. This leaves 3,701 hole locations that satisfy both the RSC criteria and also define the far field flow paths. The probability density functions of the 9 geosphere parameters are based on values at these 3,701 deposition hole locations. The PDFs are sampled without reference to the specific hole location. For example, in a realization of the PSA, WL/Q for the F-path may belong to one hole, WL/Q for the DZ-path to another, and the WL/Q for the TDZ-path to yet a third one. Thus, variation from hole to hole is represented as uncertainty over all holes.

In the Posiva analyses, space-variability is considered in formulating the conceptual flow model. The fracture properties (e.g., transport resistance) are considered to be uncertain. Such treatment complies with YVL D.5 §A107 which states “Whenever the input data used in modelling involves random variations due to (e.g., heterogeneity of rock, stochastic models) may be employed.” At all other places, to the best of our knowledge, distinction between variability and uncertainty is not made and parameters are treated as simple random variables rather than stochastic processes. In other words, the mean, variance, and other statistical measures are assumed constant. Even though the input parameters are not stochastic, the results of Posiva’s PSA are stochastic as the normalized release rate is calculated as a function of time. In the PSA analysis, only one sample of the DFN model is used for all 10,000 realizations. Thus, the stochastic variability of DFN is effectively not used in PSA.

In the deterministic analyses of the hole forever and growing hole cases, the defective canister is assumed to be emplaced in a depositional hole with relatively large water inflows (but still less than 0.1 l/m which is one of the rock suitability classification (RSC) criteria). In the PSA, placement of the defective canister in any of the deposition holes is considered as equally likely and location is sampled. This makes the sensitivities presented in WR 2013-25 somewhat difficult to interpret because a large percentage of the deposition holes have little or no flows.

Posiva uses several sensitivity measures in PSA. These include a parameter’s mean rank (higher the mean rank, more sensitive is the result to that parameter); contribution of a parameter to the mean of a selected sample of the output (higher the contribution, higher the sensitivity); rank correlations (higher correlations mean greater sensitivity); regression coefficients; and contribution of a parameter to the variance (variance decomposition) of the output. Each measure produces useful information.

Many useful results are described in WR 2013-25. Here, we provide a summary of the selected few. Figure 7 (reproduced from Figure 4-3, page 49, WR 2013-25) shows the mean rank of parameters for the growing hole case.

From the red curve in Figure 7, we can conclude that for the growing hole case, high values of instantaneous release fraction, IRF (I), diffusion coefficient, D_e (anions) in buffer, near-field flow rate in the damaged zone, Q_{DZ}, and near-field flow rate in fractures intersecting deposition holes, Q_F (in that order) and low values of resistance to far-field flow, WL/Q for DZ-path, WL/Q for F-path, and D_e in unaltered rock (in that order) produce higher peak normalized release. Similarly, the blue curve indicates that high values of sorption coefficient, K_d(I), D_e, and maximum penetration depth in unaltered rock, WL/Q for DZ-path and WL/Q for F-path and low values of fuel alteration rate and IRF (I) produce lower normalized release. The extreme values (high or low) of normalized release are not significantly affected by the remaining parameters. The important point to note is that only about 10 parameters from a total of 162 are capable of defining both the highest and the lowest values of the output. One caution to be kept in mind in interpreting these results is that the conceptual and mathematical models have to be pre-judged to be appropriate.

There are two apparent surprises in results of Figure 7: (1) none of the parameters related to canisters appear among the important and (2) fuel alteration rate does not appear to affect the peak normalized release at the geo-bio boundary. It is easy to understand why none of the canister parameters show up as important: the canisters, except for the initial defect in one, never fail. Having canisters that maintain containment for a long period is a positive attribute of the Posiva design. However, use of such a dominant barrier makes it difficult to understand the performance (or capability) of other barriers. It may be worthwhile for Posiva to consider some analysis to show the capability of individual barriers. A “one-off” analysis may provide important information in this regard. To figure out the reason for the fuel alteration rate not showing up as important in Figure 7 may require some additional thought. Also, the non-zero value for K_d in unaltered rock (far-field) for I-129, albeit small makes the highest contribution to realizations with low peak normalized release. It is interesting to note that K_d for I-129 in the buffer is fixed at zero in the PSA (Table 3-11, page 25) otherwise none of it will likely show up in the far-field.

As an example of different sensitivity measure, we point to figure 4-7, page 65, WR 2013-25 which is based on a regression fit. The first order sensitivity indices calculated by regression measure the extent to which a parameter explains the variability of the output. This figure shows that for the hole forever case, the fuel alteration rate, the diameter of the defect, the diffusion coefficient in the defect, and the volume of water in the cavity explain almost all of the variability in the calculated normalized release rate. In effect, hardly any of the safety functions of any barrier play a role in this scenario.

Figure 16-2, page 501, WR 2013-25 is probably the best description of the effect of rock damage

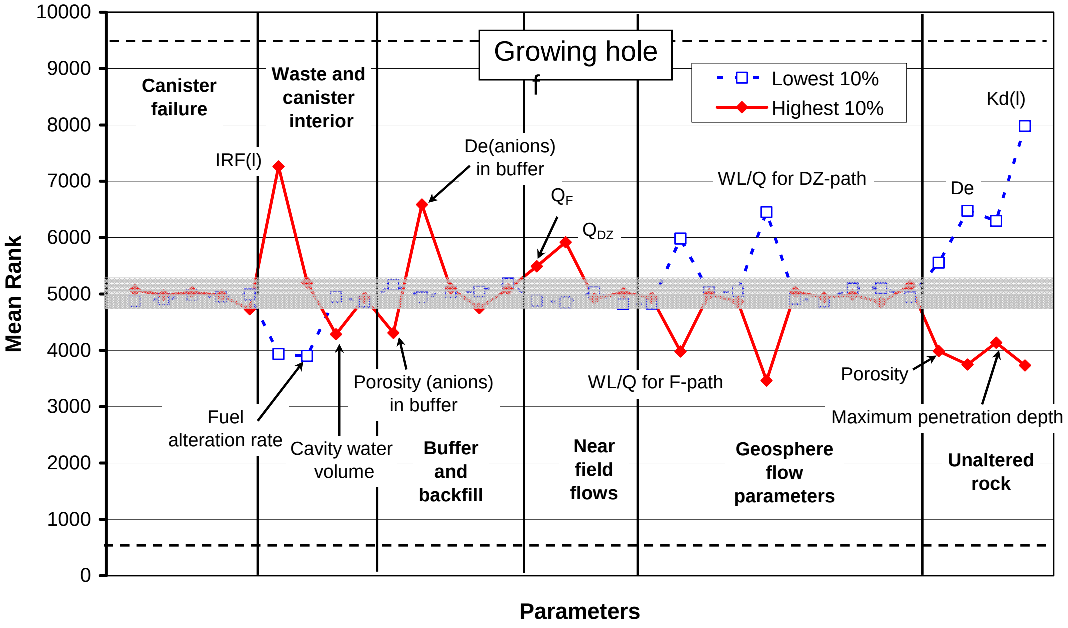


Figure 7. Mean ranks of all (162) random parameters in 1,000 realisations that have the largest normalized release rate (the red curve) and also 1,000 realisations with the lowest (the blue curve) normalized release rate of I-129. [Reproduced from Figure 4-3, page 49, WR 2013-25]

Summary

(1) In the deterministic compliance demonstration, random variations are considered only in defining the fracture network, but only one realisation of the DFN is used in modeling.

(2) The limited probabilistic sensitivity analysis uses up to 162 random parameters and provides very useful information regarding important parameters.

(3) Because the PSA is limited to the case of a pin-hole, no canister parameters show up as important although it is probably the most important barrier in the system.

(4) While continuing to use calculation cases as part of the deterministic sensitivity analysis, Posiva should expand the PSA to cover all scenarios.

(5) Posiva should use the PSA to show the links between design specifications of engineered barriers and rock suitability classification criteria and the overall safety (see also Appendix A).

on near-field releases. This figure is a scatter plot between NRR without rock damage on the y-axis and NRR with rock damage on the X-axis. Overall, this figure shows that the inclusion of a damaged zone around the deposition hole leads to lower peak normalized release rates (more dots below the diagonal in Figure 16-2) more often than higher values (fewer dots above diagonal). Somewhat counterintuitive, this result needs to be verified using an alternative model. Figure 16-8, page 505, WR 2013-25 shows the effect of a continuous damaged zone along the length of the tunnel. On page 507, WR 2013-25, Posiva concludes that a continuous tunnel EDZ produces, in general, slightly greater peak release rates than in the central case, although, for many deposition hole locations, the peak normalised release rate with a continuous tunnel EDZ is smaller than with a discontinuous tunnel EDZ (central case). Results also show that on average, the assumption of continuous tunnel EDZ produces only a factor of 1.12 (1.22) of increase in the values of the peak total normalised release rate from the near field the hole forever (growing hole) case compared with the central case (discontinuous tunnel EDZ). These results should also be verified using alternate models or assumptions as the future work related to characterization of the rock damage zone can be guided by these results.

Posiva should consider extending the PSA with higher values for the Q_F parameter and analyse the case by including a model for mechanical erosion of the buffer. This type of analysis will quantify the effects of the inflow to (or water velocity in) the deposition hole. Our recommendation to extend the use of PSA is not meant to reduce the use of the deterministic calculation cases, rather it is meant to drive the analyses towards a balance between the two. Review of additional sensitivity analyses provided by Posiva in response to STUK request is documented in Appendix A.

4.3 Review Area III: Uncertainty assessment (GD 736/2008 §15)

The licensee has clearly described its approach to developing the safety case, including uncertainty assessment. The approach consists of adequately characterizing the site, appropriately designing the engineered barrier components to meet the intended safety functions/targets, conduct operations that would meet the RSC and the LDF, identify and characterize uncertainties, conduct analyses to demonstrate compliance with regulations, and provide other supporting arguments to enhance confidence.

The regulatory requirements and Posiva's approach to treating uncertainty are described in Section 2.3.8 of Posiva 2012-12. Section 2.4 of Posiva 2012-12 describes Posiva's systematic approach to the management of uncertainties in the safety case. This provides a clear account of how uncertainties have been assessed. The overall approach is based on identifying, avoiding, reducing and assessing uncertainties. Although specific approaches are not described for different types of uncertainty (e.g., aleatory, epistemic, irreducible, etc.) overall a very large number of uncertainties have been identified and explored appropriately.

Description of the uncertainties of each FEP is commensurate with the description of the FEP. The regulatory framework (e.g., constant climate for the dose assessment window) helps to reduce some of the uncertainties. The inventory of uncertainties appears to be complete and it is a question of how these are used firstly to determine the calculation cases and secondly to inform the model descriptions (with associated data bases) that will determine the adequacy of the utilisation of the FEP descriptions.

As a complementary review, for the biosphere, it might be useful to carry out a simple assessment using traditional “reference biosphere” type methods to assess the doses arising from the concentrations around the release location. This would be similar to the Tier 2 screening calculations but would be based on the calculated radionuclide releases from the bed-rock fractures. A wider range of radionuclides should be included with site-specific rather than generic data. This would go some way to ensuring that the balance between the “critical group” and wider population doses is addressed.

There are a number of examples where Posiva is involved in ongoing research, including international programmes, to further reduce uncertainty and build confidence. Posiva (2012-09, Section 15.5) describes how the outputs of the safety assessment feed into Posiva’s RD&D programme. Key areas of ongoing technical development are rock suitability classification (RSC) criteria, better understanding the process of chemical erosion of the buffer and detection of canister defects.

Posiva (2013-01, Section 8) describes the activities that are being undertaken during 2013-15 to improve confidence in the models and data. A substantial range of activities are identified. Importantly this includes full-scale and/or *in situ* tests on the components of the repository system to demonstrate that the repository can be implemented according to the assumptions in the safety case.

A potentially important issue raised by RD&D programme is that the DFN models do not take into account density effects. However, ignoring density effects is likely to be cautious because the models will tend to underestimate the stability of the deep groundwater, and overestimate penetration of meteoric and glacial waters.

The results of the safety assessment and uncertainty analyses have been fed into the RD&D programmes (Posiva 2012 Section 15.5, and 2013-01 Section 8). However, collation and integration of the results of all the different uncertainty analyses is not presented within the documents considered in this review. Such an integration processes could not only collate and describe the relative significance of all the uncertainties, but also describe which uncertainties cannot be reduced, and which uncertainties should be the subject of further research. This integration process would highlight the key uncertainties and their potential significance, and demonstrate that the most important uncertainties have been fed into the RD&D programme where relevant. Such an analysis could usefully be linked to a description of the relative importance of different barriers.

Some uncertainties are managed by defining rules, such as, “The deposition holes with inflow above 0.1 L/min will not be accepted for canister emplacement (Posiva, 2012-04, page 113).” The licensee realizes that the implementation of this rule cannot be guaranteed, therefore, in its sensitivity analysis, it considers a certain percentage of deposition holes to violate this rule. Such rules however can be expensive to apply and their basis should be firmly derived from design, construction, or safety considerations.

There is no evidence that the licensee has distinguished between different kinds of uncertainties or that different kinds of uncertainties have been treated differently. There are large amount of aleatory variability/uncertainty (natural randomness) in the description of both the climate change and the seismic activity which will perhaps require an expert elicitation to quantify. Aleatory uncertainties are largely irreducible and these are usually dealt with by providing adequate safety margins in the design of EBS components or by devising rules for selection of waste deposition holes and selecting other features of the site. Because of rather short climate and seismic data sets, there is also a large amount of epistemic uncertainties which Posiva has tried to reduce by considering data from analogous areas and by scaling down data obtained at a much larger scale. Posiva does follow the normal engineering practice to set performance targets that are expected to provide safety margins in case the uncertainties in longer term processes (climate change and seismicity) come into play. An example of this is that the EBS components are designed to maintain their safety functions in a broader range of pH values than is “expected” at the site. The adequacy of the safety margins, however, is difficult to assess without first getting a sense of the aleatory randomness. Because, Posiva demonstrates that it meets the regulatory criteria (normalized release or dose) with a margin spanning several orders of magnitude, we believe that there is a good chance that uncertainties will not alter the overall conclusion regarding safety.

The separation of uncertainties into aleatory and epistemic groups will require significant effort and probably will require expert elicitations. It is not clear to us whether such an effort will greatly improve the safety case or confidence in the safety case. However, in the next licensing phase, Posiva should make an effort at more comprehensive description of the uncertainties.

Posiva does not provide any explicit relationship between time and uncertainty. The initial conditions summarized in Chapter 3 (page 45) of Posiva 2012-04 probably are the least uncertain. The initial state is the starting point for the performance assessment. Posiva asserts that, "The target properties for the host rock (see Section 2.1.5) are fulfilled at the initial state when suitable RSC criteria are applied." However, the initial properties of the engineered components are attained at different times depending on the sequencing of construction activities.

It is common to think that the far future is far more uncertain than the near future, that is, the uncertainties increase with time. Fortunately, the repository system is a passive system, i.e., it has no moving parts that can easily malfunction. Under expected conditions, both the engineered barriers and the host rock evolve very slowly in response to external stresses (primarily climate change and tectonic/seismic activity) and internal stresses (primarily thermal, water flow, and rock-water interactions). Seismic event is the only event at proposed repository site that is capable of causing sudden damage but its probability of occurrence is small.

Posiva has made an effort to define the residual uncertainties and has made statements that it intends to conduct a research and development program (for example see YJH-2012, Posiva 2012 for the proposed 2013-2015 RD&D program) to characterize, reduce, and manage these uncertainties. STUK may add topics for future research to Posiva's list based on its reviews of the CLA.

In Posiva 2012-04, page 27, Posiva states that it implemented a graded quality control system according to which, "… the main safety case reports are subject to stricter quality demands than general research activities." Further it states that, "The purpose of this enhanced process control is to provide full traceability and transparency of the data, assumptions, models, calculations and results." Posiva also conducted internal and external reviews of all TURVA-2012 reports. From the description provided in the reports, it seems that Posiva has an established and mature quality assurance/quality control program. One way to verify traceability is to conduct an audit and trace back values of important parameters (e.g., radionuclide solubility) to source data. It may also be important to audit the expert elicitation process to confirm that the data/parameters obtained through this process are reasonably unbiased.

There are two methods Posiva uses to assess the significance of uncertainties: (1) deterministic calculations by defining calculation cases with parameters different from the expected case and (2) through probabilistic sensitivity analysis or PSA described in Chapter 9 of Posiva 20112-09.

Posiva ignores the possibility of common cause failures of EBS components due either to undetected malfunctioning of machines/ processes during the fabrication stage or due to human errors in fault detection or both. Thus, the creation of initial defects and their detection may not be entirely random. This may not be of great concern because independent calculations by a member of our review team show that the likelihood of exceeding the regulatory constraints even if all the canisters are assumed to have a defect is very small.

On page 178 of Posiva 2012-09, Posiva states, "The results of Monte Carlo simulations can be used to determine both the uncertainty in the model outcome (uncertainty analysis) and the input parameters primarily responsible for that uncertainty (sensitivity analysis)." Posiva conducts 10,000 Monte Carlo realizations. Two cases are analysed, the hole forever case and the enlarging hole case. Some of the model assumptions are different from those in the deterministic cases which may result in some confusion in comparing the results. Table 9-2 on page 180 of Posiva 2012-09 lists the parameters treated stochastically.

On page 182 of Posiva 2012-09, Posiva states that, "The PDFs are chosen to provide a reasonable representation of the full ranges of uncertainty and variability in the input data. The input data used and the process followed to create the PDFs are presented in WR 2013-25. Posiva seems to lump uncertainty and variability together when these are two very distinct characteristics of data. Variability usually describes changes with time or location in space while uncertainty is the lack of knowledge

Summary

(1) Posiva's approach for handling uncertainties is based on identifying, avoiding, reducing, and assessing; "avoiding" plays a big part because Posiva assumes an almost flawless implementation of its QA/QC program. Posiva should consider more uncertainties due to potential human errors.

(2) Posiva does not differentiate between aleatory and epistemic uncertainties; this is reasonable in this first phase of licensing but greater attention should be paid to uncertainties arising from 'lack of knowledge' or epistemic uncertainties.

(3) Uncertainties are handled in compliance demonstration by defining various types of calculation cases; this approach is reasonable but greater use of the PSA should be made.

(4) Posiva should consider using a traditional reference biosphere calculation, using local data, to enhance confidence in the dose calculations.

about the value at any given time and location. For example, does Posiva develop probability density functions representing the flow paths (F, DZ, and TDZ) deposition hole by deposition hole or does it develop one single density function for each of these paths that represent all deposition holes? We assume that latter is the case. If so, then it would be interesting to determine how the sampled paths are assigned to each deposition hole. STUK should consider a detailed review of this topic.

It should be noted that peaks of releases very likely occur at different times in different realizations. We assume that percentiles shown above are at fixed times. An alternative would be to plot a distribution of the peaks. In this case, one could determine the mean of the peaks. Thus assuming that the peak release is of interest (irrespective of when the peak release occurs), this statistic can provide a distribution of the peaks, including the mean of the peaks. Posiva already has the results of the Monte Carlo runs; therefore this can be done easily without any new calculations. The distribution of peaks provides additional information about the impact of uncertainties on peak release.

In biosphere, the approach to uncertainty management is essentially deterministic with scenario identification and variants thereon determining alternative calculation cases. This is applied at the system identification and justification level in the TESM so that there is, effectively, a screening level of uncertainty analysis. In the SHYD report there is also an attempt to propagate some estimates of uncertainty to the dose assessment modelling. This appears to be less successful.

4.4 Review Area IV: Complementary considerations (GD 736/2008 §15)

4.4.1 Review Topic 1: Identification of complementary considerations

Posiva describes the objective of complementary considerations in Posiva 2012-11, "The main emphasis in Posiva, 2012-11 is on the evidence and understanding that can be gained from observations at the site, including its regional geological environment, and from natural and anthropogenic analogues for the repository, its components and the processes that affect safety. In particular, the report addresses diverse and less quantifiable types of evidence and arguments that are enclosed to enhance confidence in the outcome of the safety assessment. These complementary considerations have been described as evaluations, evidence and qualitative supporting arguments that lie outside the scope of the other reports of the quantitative safety assessment."

Complementary considerations include comparisons of the disposed activity and radiological hazard compared with background over time, evidence for responses to climate and landscape change, analogues for relevant processes, and the impacts of discrete events such as seismic events. Appendix C therein provides a useful summary of processes for which there are analogues, and whether the analogues are of direct relevance and provide qualitative or quantitative information.

Posiva, 2012-11 Chapter 13 provides a descriptive link between the natural analogues, important processes for safety and high level safety functions, although there is not a figure or table that explicitly shows the mapping to safety functions. Complementary considerations are not explicitly mapped to requirements described in the VAHA management system, such as performance targets (VAHA Level 3). Posiva could improve mapping to safety functions, relative importance of barriers and key processes. The complementary considerations could have been linked more effectively to show how much complementary support there is for safety, the key safety functions and key processes.

There are no unique scenarios that are analysed by complementary considerations only. As stated above Posiva's objective in bringing forth complementary considerations is to enhance confidence in the quantitative analyses developed in performance assessment.

One of the useful complementary considerations is that of radiotoxicity index. Posiva defines (page 249 of Posiva, 2012-11) a radiotoxicity index or RTI (t) as the hypothetical dose at time t resulting from ingestion of the activity A_j (t) [Bq] of radionuclide j, divided by 0.1 mSv (derived from the Finnish regulatory dose constraint for the most exposed person):

$$RTI\left(t\right)=\frac{A_j\left(t\right)D_j}{10^{-4}} \qquad (6)$$

In the above equation, D_j [Sv/Bq] is the dose coefficient for ingestion (see Appendix B, Posiva 2012-11 for a table of these coefficients). Based on the activity level as a function of time, the RTI is estimated as shown in Figure 3-3, page 33, Posiva 2012-11. From this figure, it is apparent that the toxicity of spent fuel decreases significantly with time and at 100,000 years, the RTI of 9,000 tonnes of spent fuel is similar to that of the Cigar Lake Uranium ore body. Because the canisters are estimated to last (except for the possibility of an initial defect), for several hundred thousand years (see page 56 of Posiva 2012-11), then from this kind of complementary information, one can have high confidence in the safety of the repository.

Posiva provides enough caution in interpretation of such results. For example, on page 35 of Posiva 2012-11, Posiva states that, "… such comparisons need to be used with caution. This is not only because the isotopic compositions of natural systems will differ from those of the initial spent nuclear fuel, the eventual repository releases and the remnants of the spent nuclear fuel in the repository at long times but also because the assumption should not be made that natural occurrences of uranium ore are necessarily harmless. …"

Similarly, the Kronan cannon archaeology analogue study is discussed on page 91 of Posiva 2012-11 to support the low corrosion rate of copper. In that study, a corrosion rate of 0.15 µm/year was calculated under oxidizing conditions. This provides confidence regarding the even lower corrosion rate under repository's reducing conditions.

Long-term stability issues of bentonite are also addressed based on observations in natural occurrences. These include thermal, mechanical, chemical alteration, hydraulic properties, freezing and chemical erosion. The existence of intact bentonite layers in near surface environments under thin soil cover gives qualitative evidence of bentonite stability over geological time periods. However, no convincing evidence is given for the mechanical stability of the buffer, say under rock shear conditions. While many examples are given for illustrating the efficiency of the buffer as a hydraulic barrier, the same is not true with respect to its resistance to chemical erosion.

In the biosphere, the complementary considerations are highly relevant since they describe aspects of more mature lakes and mires not present in ecosystems in the biosphere model area. Four lakes are selected but in the report there is no discussion of the ages of the lakes (relative to the coastline) and so it is difficult to judge if the range is sufficient. Similar comments apply to the selection of the mire areas. It is also notable that there is no discussion of forests of different ages.

Taking into account the overview found in the Posiva 2007-10, the complementary considerations are relevant in respect to the evaluation of the overall radiological impact of the disposal. As discussed above, there is a need to provide a clearer, more direct, assessment of the potential impact on the most exposed group. Complementary methods would be appropriate as one way in which this could be addressed. This would say (1) what is special about Posiva's approach (for example realism in comparison to conservatism) and (2) indicate areas where additional reasonable conservatism might be incorporated in future revisions of the methodology.

Reference

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Summary

(1) Posiva's objective in bringing forth complementary considerations is to enhance confidence in the quantitative analyses developed in performance assessment.

(2) Complementary considerations are not explicitly mapped to requirements described in the VAHA management system; Posiva could improve mapping to safety functions, relative importance of barriers and key processes.

4.4.2 Review Topic 2: Use of complementary considerations in reducing uncertainties

By their very nature, the complementary considerations are not suited to reduce uncertainties in performance assessment. That is because, the analogous evidence presented in the complementary cases is not precise and also, it doesn't exactly match the repository conditions. However, complementary considerations reduce uncertainties to the extent these enhance understanding of the phenomena that would then be factored into the models used for safety assessment. Complementary considerations are discussed in Posiva 2012-11.

Regarding the earthquake risk, the statement that the density and magnitude of earthquakes in Finland is generally much lower than in other areas is justified. However, the special feature in Scandinavia is the enhanced risk immediately after retreat of the ice sheet. A large number of events have been dated in Sweden by Mörner (1996), Sjöberg (1994) and E Tröften (1997) based on observations in Quaternary clay sediments. The focus in Posiva's complementary considerations is very much on the accelerations measured during earthquakes at different depths, based mainly on recent experiences from Japan. It should be emphasized that the main risk with respect to the performance of the engineered barrier system is caused by the associated rock displacements. Maximum displacements at Olkiluoto are suggested to be 0.005 m [0.5 cm]. A closer look on the data attached to Posiva WR 2007-05 shows that displacements of about 10–20 cm have been observed near Olkiluoto (only some were postglacial related to the last glacial advance). Further southwards near Kustavi, more spectacular displacements of near 30 cm were documented. Posiva should explain how these shear displacements are related to known tectonic features and rock structures. The significant displacements in sea bottom sediments as observed by Hutri et al, (2004, 2007) should be included in the argumentation as well to justify Posiva conclusion of "limited impact of earthquakes."

Summary

(1) Complementary considerations provide a measure of confidence but are not suited to a quantitative reduction of uncertainties in performance assessment.

(2) Care has to be exerted that the choice of complementary considerations does not include intentional bias. We did not find such a bias in Posiva's discussion of natural analogs.

(3) In general, Posiva uses the complementary considerations effectively, to enhance confidence in the safety case

Consideration of complementary evidence can introduce bias. For example, in the case of metal artefacts, one can focus on specimens which did not corrode much, on the other hand, in the treatment of the hydrogeochemical site evolution one can hardly leave out results of laboratory or field investigations etc. It is understandable that the authors may feel that they have to present examples of positive, confirming evidence in more detail and in a more emphasizing way. At most places, there is no bias in selecting examples or in interpreting the data. However, there are a few known cases where evidence from natural systems might seemingly conflict with argumentations in the safety case, but the knowledge bases of these cases are often weak.

The radionuclide transport in geosphere calculations only make limited use of complementary considerations for processes (e.g. matrix diffusion and colloids are considered in Posiva, 2013-01), although Posiva (2012-09) does make use of complementary indicators (e.g., comparison of calculated radionuclides fluxes from the wastes with natural radionuclide fluxes). We previously noted the potential significance of release of C-14 labeled gases. Posiva 2012-11, page 226 provides a very useful complementary indicator, whereby it is noted that C-14 gas released from the repository is small compared with uptake of natural atmospheric C-14 by plants and animals.

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4.5 Review Area V: Compliance with the regulatory criteria (GD 736/2008 §4, §5 and §14)

4.5.1 Review Topic 1: Compliance with dose constraints

In Chapter 6 of Posiva 2012-08, the surface environment scenarios are described. Much greater detail of the surface environment is provided in Posiva 2012-10 and other biosphere-related documents. Key regulatory requirements applicable to the biosphere are summarized in Table 1-1 on page 14 of Posiva 2012-10. On page 27 of Posiva 2012-10, Posiva acknowledges past STUK comments, "As a general observation, STUK noted that Posiva already has a lot of information from several safety areas, but the knowledge is somewhat sporadically presented and difficult to trace. Therefore, STUK felt unable to form a view about Posiva's own estimate of the current status for demonstration of long-term safety. In addition, STUK considered that the preliminary application had some shortcomings in demonstrating the fulfilment of the requirements, necessary conclusions, reasoning and analysis." Regarding transparency, it further states, "The feedback has also been taken into account in the systematic structuring of the safety case and the reports included in the TURVA-2012 portfolio. In particular, *Formulation of Radionuclide Release Scenarios and Features, Events and Processes* constitute a significant improvement regarding transparent documentation of the biosphere assessment and the management of uncertainties. The formulation of surface environment scenarios (see *Formulation of Radionuclide Release Scenarios*) follows a systematic approach to identifying an envelope of credible lines of evolution for the surface environment from the emplacement of the first canister until at least several millennia later. The scenario formulation is driven by uncertainties in features, events and processes of the surface environment, determined by external geological and climatic processes, and to some extent by future human actions (*Features, Events and Processes*, Chapters 9 and 10)." Our opinion is that the transparency and comprehensiveness of Posiva's safety case remains imperfect. For example, it would not be possible for a reviewer to reproduce the doses from the descriptions in the BSA 2012 portfolio.

Just as for the geosphere, Posiva defines the three categories of scenarios – Base, Variant, and Disturbance along with calculation cases to analyse the effect of uncertainties and alternate assumptions. In the biosphere assessment (BSA) scenarios, present day human practices are assumed to continue, the climate is assumed static at today's climate, and sea-level changes are assumed to change the land scape by submergence of more land around the site in the Baltic Sea. Seven variant scenarios (VS) are considered: (1) radionuclide discharge locations varied depending on the location of the defective canister; (2) climate changes from the static climate assumed in BSA; (3) varied crops are considered; (4) number of wells are varied; (5) alternate radionuclide transport paths are assumed; (6) human diet is varied; and (7) the sea level is assumed to decrease (see Figure 6-3 on page 80 of Posiva, 2012-08). The calculation cases for the surface environment are described in Chapter 8 of Posiva 2012-08; see Table 8-2 on page 99 and Table 8-3 on page 100 of Posiva 2012-08 for a summary.

Posiva estimates doses for the first 10,000 years after repository closure. Figure 8 (a) and (b) below provides the results of calculations for BSA-RC.

As can be seen the earliest and the greater dose is from C-14 which is assumed to be released instantaneously once a transport path is established. The effect of uncertainties in estimating the instantaneous release fraction of C-14 and I-129 is discussed on page 508 of Posiva 2013-01. The IRF of C-14 is assumed to be 5.5 percent while that of I-129 is 0.1 percent (Table 7-6 on page 495 of Posiva, 2013-01). The probabilistic sensitivity analysis showed that the very large uncertainties in C-14 IRF (1- to 100%) did not much affect the peak release but that the uncertainties in IRF of I-129 did significantly influence the peak. Posiva states that further studies of IRF inventory of I-129 are required.

Posiva shows results of its dose calculations that meet the regulatory standards with ample margins. We emphasize that in safety assessment, the biosphere is at the downstream end of the calculation chain. If the source term (amount of

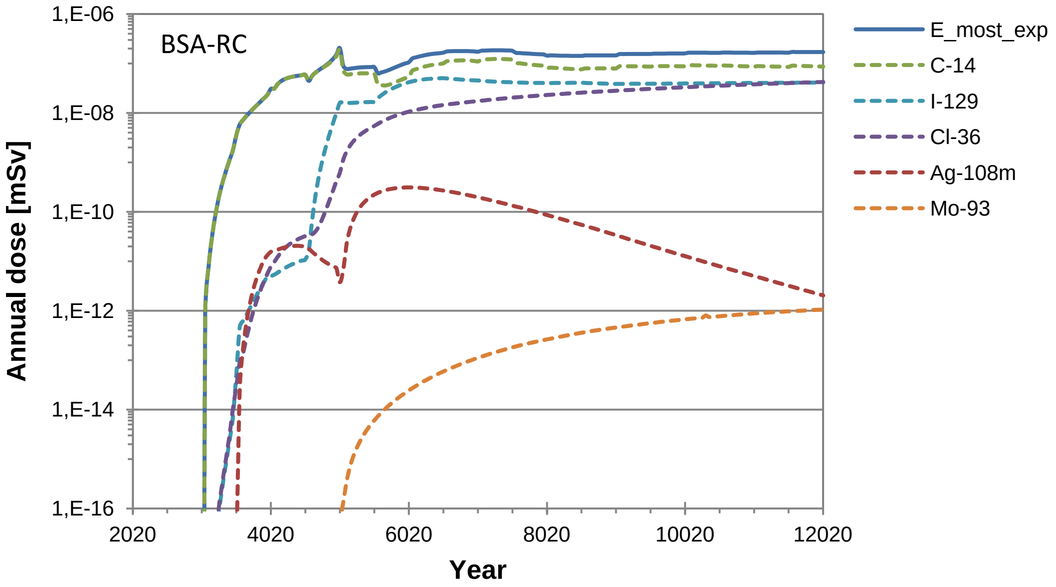

Figure 8a. Contribution to annual dose to a representative of the most exposed group from various radionuclides. [Adapted from Figure 8-19, page 192, Posiva 2012-12]

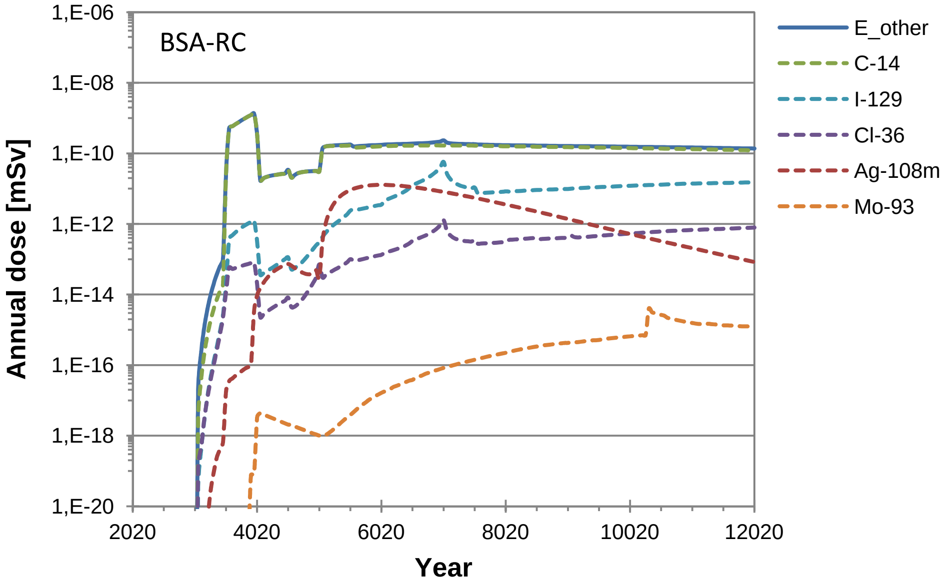

Figure 8b. Contribution to dose for a representative of group other than the most exposed group of various radionuclides (adapted from Figure 8-5 (b), page 192, Posiva 2012-12.

radionuclides emerging from failed canisters) is small to begin with, then variations in biosphere characteristics are not going to materially affect the peak dose unless there is some mechanism for accumulating or concentrating the radionuclides in some biotope or unless the basic definition of the “most exposed group” is varied.

Posiva does not assign the biosphere any safety functions, although it states that delay and dilution may be thought of as its safety functions. Any unacceptable dose estimates will eventually lead to making changes to engineered barriers to reduce the source term. Given that Posiva’s Base Scenario postulates a small pin-hole defect in one canister, there is little possibility of decreasing the source term any further. The one scenario in which the source term can be much larger is the earthquake scenario during the dose time window in which many canisters can experience shear failure.

The annual dose maxima for a representative in the most exposed group are provided in Figure 9. This figure shows that, in a relative sense, the discharge points determined by the DFN model can have a significant effect on the estimated dose but the dose is so far below the regulatory limit that it doesn’t matter in the absolute sense because the probability of it exceeding the limit is quite low. A scoping calculation conducted by a member of the review team indicated that alternate assumptions can lead to dose estimate that is 10 times the estimate by Posiva but even with that, the dose is significantly below the regulatory constraint.

The specified exposure pathways are all part of the system description. As noted above, there is concern that the scenario formulation has played down the possibility of domestic irrigation using well water for home-grown produce. In part this is because of the limitations in the characterisation of human behaviour in the present day sampling.

The regulatory framework has been taken seriously by Posiva to the extent that the evolutionary modelling seems to be designed to meet the stated requirements. However, the new material incorporated into the assessment has had the effect of overshadowing the more traditional approach to estimating critical group dose, so that the wider population dose takes precedence over the description of the “critical group” dose.

All of the required exposure pathways have been addressed. However there seems to have been a very literal interpretation of these to the extent that potentially important related exposure routes (e.g., the kitchen garden scenario) have been overlooked.

Posiva identifies three key factors affecting the evolution of surface environment: (1) climate change, (2) sea-level change in the Baltic Sea, and (3) the ongoing land (crustal) uplift after the retreat of the last Weichselian ice sheet, 115,000–10,000 years before present. All three of these factors affect the hydrologic balance of both the aquatic and the terrestrial ecosystems. Models for estimating changes in surface environment are discussed on pages 121–128 of Posiva 2012-12. Projected future environment in 12,020 (10,000 years from now) is shown in Figure 8-4a on page 189 of Posiva, 2012-12.

Posiva acknowledges the existence of large uncertainties in both the climate change and the sea-level change. In the BSA-RC, Posiva assumes that the current climate prevails and that the sea-level can gradually rise due to global climate change. The net sea-level rise would be less due to the effect of the crustal uplift which is assumed to continue at the current rate (about 6 mm/year-see page 67 of Posiva, 2012-10). For the BSA-RC, present day practices regarding crop type, irrigation proce-

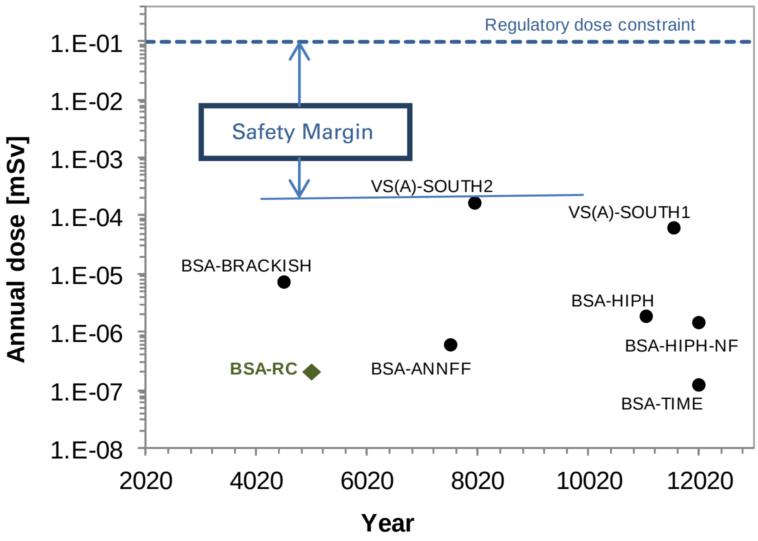

Figure 9. Estimated maximum annual dose to a representative of the most exposed group in the nine cases described in the safety case. [Adapted from Figure 8-19, Page 219, Posiva 2012-12]

dures, animal husbandry, Forestry and peatland management, and well construction are assumed to continue. Similarly, the site is assumed to continue to be sparsely populated as it is now.

In summary, Posiva does consider the change in sea-level in defining the evolution of the surface environment. Posiva admits that the estimation of sea-level change is highly uncertain. Some of these uncertainties are explored in variant scenarios.

Posiva states its understanding of the first two of these pathways on page 69 of Posiva 2012-08, "Posiva understands this paragraph to mean that, if it is plausible, crop-producing farms, using surface or well water for irrigation, and livestock farms using surface or well water for animal watering should be features included in the base scenario." Regarding the third pathway, Posiva states, "Posiva understands this to mean that, if it is plausible, at least one small lake and one shallow water well should be features included in the base scenario."

Posiva doesn't state but we assume that household water in all three pathways also mean water used for drinking, cooking, and other activities such as bathing.

Posiva has certainly considered the pathways enumerated above and has shown that estimated

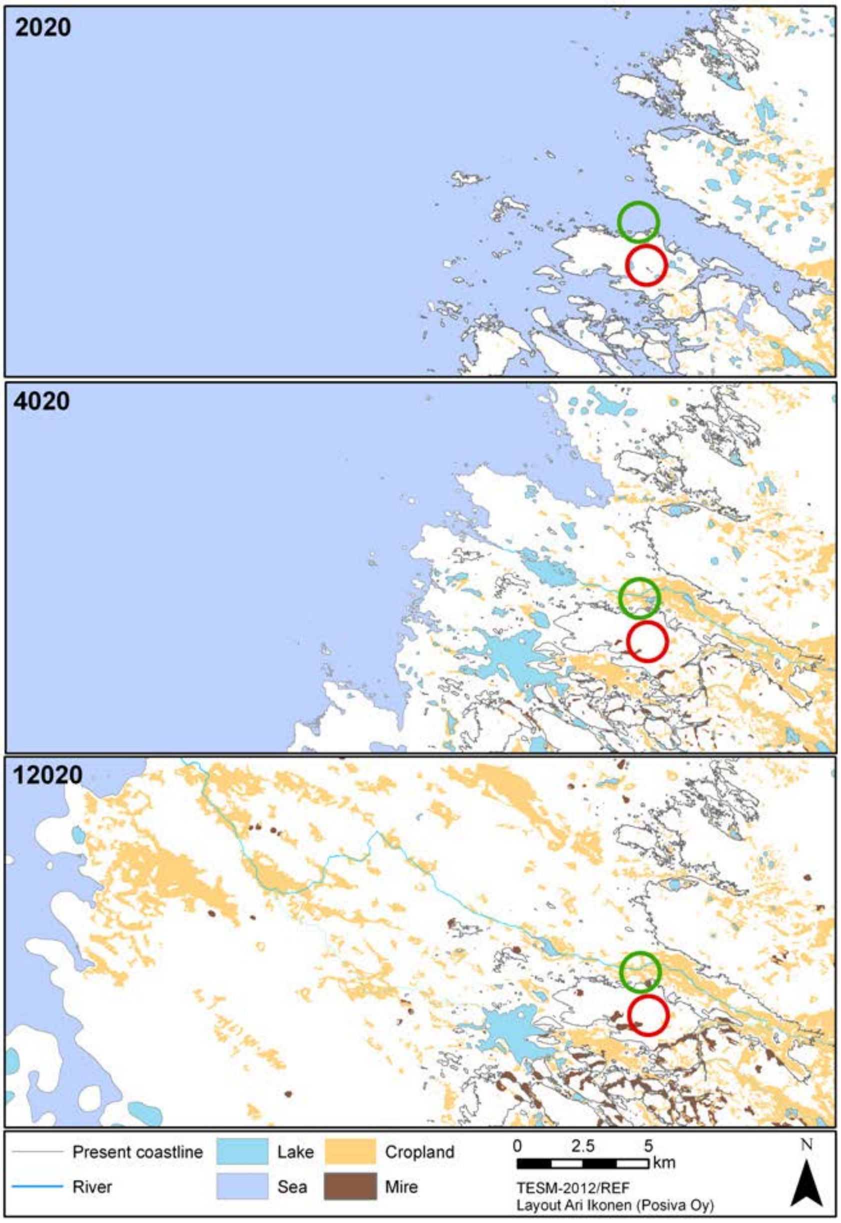

Figure 10. Estimated surface environment up to the year 12020 (the end of dose window); the effect of the land up-lift is clear. The red circle is the location of the repository and the green circle is the discharge point. [Adapted from Figure 8-4a, Page 189, Posiva 2012-12]

Summary

(1) Posiva has developed an advanced and elaborate biosphere model that is state-of-the-art; however its documentation is not transparent.

(2) Posiva should identify the important parameters for the biosphere; we recommend conducting a probabilistic sensitivity analyses.

(3) Because of the very low source term during the dose window, Posiva estimates a very high safety margin; we believe that uncertainties in the biosphere models will not change the basic conclusions.

(4) The effect of uncertainty in DFN predicted discharge locations should be examined.

(5) Posiva should examine alternate assumptions for dose estimation.

effective dose to the most exposed and the average person will be below the limits stated in GD 736/2008 §4. With respect to human habits and diet, Posiva followed the guidance in YVL D.5.

Posiva estimates radiation dose for up to 10,000 years. During this period, the present day climate prevails but the land mass has changed due to land uplift. However, there is only one source of radionuclides. This source is a canister (or up to four) with a small initial defect. Without this assumption of an initial defect, the dose will be zero. It is also to be noted that the host rock contributes little to the delay of radionuclides once the release occurs from the canister. Therefore, it is the canister, the spent fuel, and the buffer that contribute the most to overall performance. This is true in all scenarios.

4.5.2 Review Topic 2: Compliance with flux constraints (GD 736/2008, §4)

The nuclide specific constraints for the radioactive releases to the environment (average release of radioactive substances per annum) are specified in YVL D.5 as follows.

- 0.03 GBq/a for the long-lived, alpha emitting radium, thorium, protactinium, plutonium, americium ja curium isotopes
- GBq/a for the nuclides Se-79, Nb-94, I-129 and Np-237
- GBq/a for the nuclides C-14, Cl-36 and Cs-135 and for the long-lived uranium isotopes
- GBq/a for the nuclide Sn-126
- GBq/a for the nuclide Tc-99
- 10 GBq/a for the nuclide Zr-93
- 30 GBq/a for the nuclide Ni-59
- 100 GBq/a for the nuclide Pd-107.

YVL D.5 further states that the averaging shall be made at most for a period of 1,000 years. The sum of the ratios of the nuclide specific activity releases and the respective constraints shall be less than one.

Chapter 15, Posiva 2012-09 summarizes Posiva's conclusion in regard to meeting the activity flux constraints. As stated on page 357 therein, "To obtain the normalised release rates, the release rates for each calculated radionuclide have been normalised by dividing by the corresponding nuclide-specific constraints for the radioactive releases to the environment (Table 2-1). The peaks of the normalised release rates, summed over all radionuclides, have then been calculated. For calculation cases RS1, RS2, RS1-DIL, and RS2-DIL, 1,000-year centred moving averaging has been applied to the geosphere release rates to smooth the sharp pulses that occur at the times of peak release. Such averaging conforms to Finnish regulations." The results are shown in Figure 15-1 on page 358 of Posiva 2012-09. This figure has been reproduced in this report as Figure 4. As can be seen, there is a significant safety margin estimate for all calculation cases. The only scenario not included in the above mentioned figure is the human intrusion scenario.

1,000 year averaging has been applied to the RS and RS-DIL scenarios, and for gas mediated release and transport in the AIC disturbance scenario. Posiva (2012-09 Figures 11-8 and 11-12) transparently show the consequences of 1,000 year averaging on the normalised releases, which are quite significant for the RS2-DIL scenario. The RS2-DIL scenario is the type of situation where 1,000 year averaging is within the intent of the regulations, and where heterogeneity and variability that is not accounted for in the assessment calculations might result in dispersion of the contaminant flux. While consistent with the regulations, it is less clear whether this is within the intent of the regulations.

As can be seen in Figure 3, the Base Scenario releases are more than three orders of magnitude smaller than the regulatory limits specified in GD 736/2008 4 §. Note that only in the RS scenario (RS in the figure), does Posiva apply the 1,000-year

Summary

(1) Posiva's demonstration of its compliance with the normalized release rate regulatory constraints is acceptable.

(2) The disruptive scenarios are the only ones that challenge the capabilities of the engineered barriers and in these scenarios; the estimated safety margin reduces from four orders of magnitude in the reference case to one order of magnitude in the rock shear case.

(3) In the next phase of the licensing process, Posiva should focus on common cause failures of the engineered barriers; this may be a low probability event but it may be the constraining scenario.

(4) Posiva should define a more illustrative reference case than the pin-hole scenario.

averaging and also apply probability weighting. The 1,000 year averaging seems to smooth (i.e., reduce) the peak by a factor less than 5 (see the yellow and blue colour intervals on the right side of the figure). The probability weighting is much more significant as the annual probability of an earthquake per square kilometer per capable fault is taken as 1×10^{-7}. In the RS scenario, multiple canisters fail resulting in high source term. The other scenario with higher normalized release is the AIC or accelerated insert scenario. In this scenario, one container fails completely because of the corrosion product from accelerated corrosion of the cast iron insert. It is apparent that complete failure of one container (in contrast to a pin-hole defect) can increase the normalized release by 2 to 3 orders of magnitudes. Again note that the releases in the AIC scenario are not probability weighted which Posiva could do as per the regulation.

4.5.3 Review Topic 3: Compliance with dose constraints during unlikely events (GD 736/2008 §5; YVL D.5 §314 and §A105)

Inadvertent human intrusion is the only disturbance scenario giving rise to dose in the 10,000 year dose window. Seven calculation cases, from DS(A) to DS(G), are defined to consider the unlikely events. These are summarized in Table 6-2 on page 81 of Posiva 2012-08. The unlikely events considered are: (A) sudden rise in local sea level, (B) no crop grown at the site, (C) the Lapijoki river changes direction, (D) constant occupancy of plants and animals in the most biotopes leading to the highest dose rate, (E) lower sea level resulting in larger land area, (F) inadvertent HI in the form of a borehole drilling hitting the repository, and (G) drilling of a deep well intercepting water that has passed through the repository.

We note that Posiva does not consider the unlikely occurrence of a large earthquake (capable of shearing the canister) during this period (10,000 years) and it does not provide adequate reasons for this omission.

We did not see any consideration of rock displacement in defining unlikely scenarios in the surface environment. However, a deep well (depth > 300 m) is considered in DS (G) scenario. The deep well scenario considers two cases, one in which the well supplies drinking water and the other in which the well supplies both the drinking water as well as water for agriculture. The well is assumed to intersect a water-conducting feature that has a hydrologic connection with the repository volume. Obviously, the dose in this scenario will depend upon the location of the well relative to the discharge points and the shallow ground water hydrology.

In the inadvertent human intrusion scenario, Posiva considers drilling within the footprint of the repository. In the main DS (F) scenario, Posiva also assumes that the drill penetrates into contaminated buffer or backfill material but does not penetrate the waste canister. However, Posiva analysed 6 calculation cases related to DS (F). These are summarized in Table 7-9(b) on page 178 of Posiva 2012-12. As can be seen from this table, the calculation cases cover the important potential conditions during human intrusion.

The results for the human intrusion scenario are provided in Figure 8-14 on page 208 of Posiva 2012-12 and reproduced below. Note that the dose values in this figure are expected values meaning that Posiva has multiplied the calculated dose by the probability of intrusion (drilling). This is allowed by Posiva regulations.

A discussion of probability of inadvertent human intrusion is provided in Posiva 2012-10, page 191. Based on historical drilling frequency in Finland (Table 6-17, page 191, Posiva 2012-10), drilling of 10 drill holes per year to a depth > 400 m is estimated to be a reasonable value. Dividing this number by the land area of Finland and multiplying by the foot print area of the repository, Posiva obtains the annual probability of drilling into a canister as 10^{-7}. Of the 82 radionuclides that Posiva estimates maybe brought up to the surface during a drilling event, only 44 for which the dose conversion factors are available are considered. Posiva admits that this leads to an under estimation of the dose but states that the error is small because the radionuclides not considered contribute less than 5% to the total activity in the first 10,000 years (page 192, Posiva 2012-10). Am-241 and Pu-240 contribute most to dose. Posiva assumes that intrusion will not occur before 1,000 years and at that time, the expected dose is estimated to be < 10^{-2} mSv; Figure 8-14, page 208, Posiva 2012-10. We admit that it is difficult to estimate the probability of human intrusion and the time of intrusion. The probability of intrusion may vary from location to location within Finland and the frequency may be smaller or higher in the Olkiluoto area than the national average. Also, it is not clear why human intrusion is not assumed to occur sooner than 1,000 years. Therefore, the conservativeness of these estimates are questionable.

Posiva (2012-12, Section 8.6.1) only presents the results for acute exposure of drill crew and geologists to abstracted core materials. Section 7.3.4 states that doses from a medium-deep water well are assessed but the results are not presented in that report. We note that human intrusion might lead to chronic radionuclide releases, in addition to acute releases/exposures associated with the intrusion event. For example, chronic exposure may result from groundwater flow and radionuclide transport up an abandoned, open, site investigation borehole, or due to a contaminated abandoned drill site. Such chronic effects have not been assessed by Posiva.

Summary

(1) Inadvertent human intrusion is the only disturbance scenario giving rise to dose in the 10,000 year dose window; Posiva does not consider the possibility of a large magnitude earthquake during the dose window.

(2) In the human intrusion scenario, Posiva only considers acute exposure of drill crew and geologists to abstracted core materials. We note that human intrusion might lead to chronic radionuclide releases, in addition to acute releases; Posiva should consider such a calculation case.

(3) Posiva should consider the possibility of a large earthquake event an early time and analyse the dose impacts from that case.

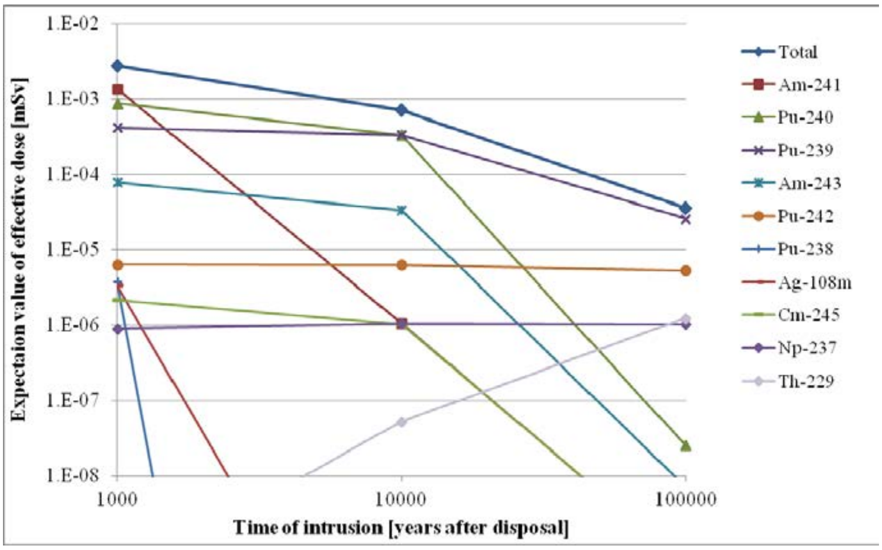

Figure 11. Radionuclide dose contribution in the human intrusion scenario occurring at 1,000 years; Cs-135 and Sr-90 can be expected to make major contributions if the event is assumed to occur say at 200 years. [Adapted from Figure 8-14, page 208, Posiva 2012-12]

Summary

(1) Posiva uses a state of the approach for estimating the absorbed dose rate for various species of flora and fauna

(2) The absorbed dose rate is estimated to be below the acceptable limits.

4.5.4 Review Topic 4: Compliance with constraints on flora and fauna (GD 736/2008 §14)

GD 736/2008 § 14 requires," … possible impacts on flora and fauna shall be analysed." Posiva has assessed the effects on fauna and flora and as reported on page 219 of Posiva 2012-12, "The (typical) absorbed dose rate maximum for plants and animals is 2.6·× 10^{-7} microGy/hour in the BSA-RC, for Pike in freshwater environment. The dose rate maximum for plants and animals in all the calculation cases presented in this report is 1.3·× 10^{-4} microGy/hour, for Mallard in freshwater environments in the calculation case VS (A)-SOUTH2." Figure below show results in greater detail.

4.5.5 Review Topic 5: Confidence level with regard to compliance (YVL D.5 §A109)

YVL D.5 § A109 requires," The safety case shall include an assessment of the confidence level with regard to compliance with the safety requirements and of the uncertainties with the greatest impact on the confidence level." Posiva's safety case does include an assessment of the confidence level with regard to compliance. The statement of confidence is provided in Chapter 11 of Posiva 2012-12. On page 235, Posiva states, "Inevitably, uncertainties remain. The impact of these uncertainties has been assessed through a number of scenarios and quantitative analyses that cover a broad range of conditions and uncertainties. Identified remaining uncertainties are such that they do not have an immediate impact on safety for the construction phase of the repository and thus on the CLA. These uncertainties will be addressed through further research and technological development activities to either resolve them through a modified design or gather further data to better understand their long-term safety impact. So far, no uncertainties have been identified that cannot be adequately resolved before the operational license application. As yet, unidentified issues cannot be excluded and their early detection is a key aim of a programme of demonstration and pilot activities as well as a monitoring programme."

We note that in Posiva 2013-01, Posiva describes data and models for individual components of the repository system and makes confidence statements

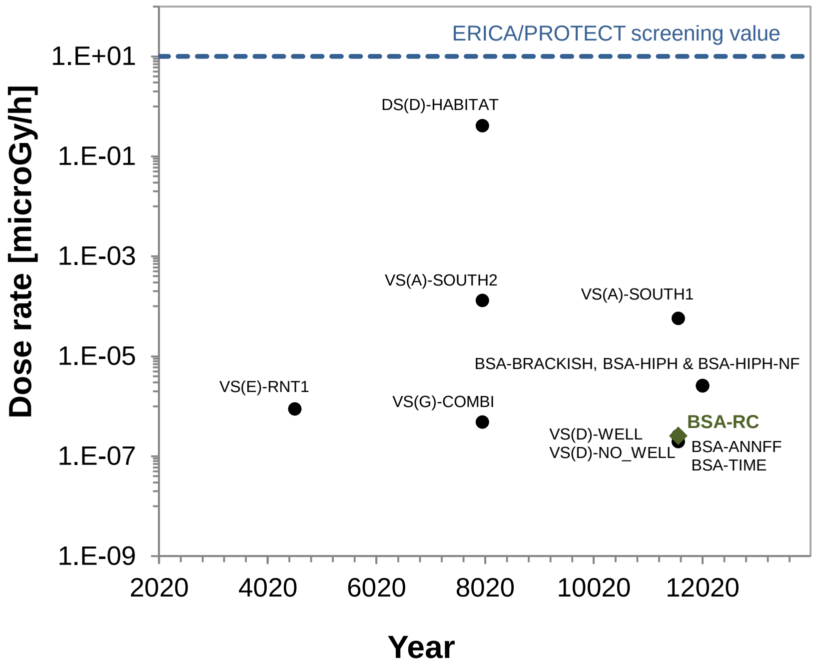

Figure 12. Maximum annual dose to flora and fauna. [Adapted from Figure 9-3, page 227, Posiva 2012-10]

Summary

(1) Posiva makes a 'conditional' statement regarding confidence (Chapter 11, Posiva 2012-12, page 235), "Inevitably, uncertainties remain. The impact of these uncertainties has been assessed through a number of scenarios and quantitative analyses that cover a broad range of conditions and uncertainties. Identified remaining uncertainties are such that they do not have an immediate impact on safety for the construction phase of the repository and thus on the CLA. These uncertainties will be addressed through further research and technological development activities to either resolve them through a modified design or gather further data to better understand their long-term safety impact. So far, no uncertainties have been identified that cannot be adequately resolved before the operational license application. As yet, unidentified issues cannot be excluded and their early detection is a key aim of a programme of demonstration and pilot activities as well as a monitoring programme."

(2) Reduction of uncertainties should be a commitment in the construction license.

(3) STUK should review the programme of demonstration and pilot activities; this is especially important for demonstrating constructability of the underground structures and the fabrication of engineering components.

(4) STUK should develop a regulatory process for assessing the impacts of any design change and/or technological advances.

on each. At several places, Posiva emphasizes the phased nature of the repository project and concludes that while it had adequate confidence in models and data for getting a construction license, it also had confidence that it would be able to resolve some of the remaining uncertainties by the time an operating license is sought. Posiva also identifies several topics for further investigations in the longer term. For example, these are identified in report YVJ-2012.

4.6 Review Area VI: Reliability of the post-closure safety case (GD 736/2008 §15)

For decision making, it is important that reliability of the post-closure safety case is established adequately and that uncertainties are clearly identified. As stated in GD 736/2008 §15, "Data and models shall be validated as far as possible, and correspond to the conditions likely to prevail at the disposal site during the assessment period." The methodology used by Posiva is transparent, it includes identification of the key safety functions, and it brings out the key issues and uncertainties. We consider the conceptual models, mathematical models and data to be adequate and appropriate for the first phase of licensing. A suite of scenarios has been assessed through a large number of calculation cases, supported by complementary calculations and a probabilistic sensitivity analysis. Posiva has used relevant data management and QA procedures to help ensure the reliability of the safety case. A number of discrepancies have been identified by Posiva, but these have been evaluated and found to be insignificant by Posiva (2013-01, Appendix M). Therefore overall the reliability of the data and models is considered to be good and we have been able to largely reproduce a number of key calculations, using models and computer codes developed independently of Posiva, although there are some minor differences for the rock shear scenario case

Although the safety analysis is of good reliability, there is scope for improved synthesis of information including: (1) a more comprehensible (simpler) description of the anticipated geosphere evolution preferably via conceptual figures; (2) identification of the key safety functions, key safety-important parameters, and relative importance of different barriers; (3) collation of the results of uncertainty analyses, comparison of the results to identify the key uncertainties and selection of uncertainties to be considered in the RD&D programme; and (4) an adequate description of components of landscape dose models, including SHYD and TESM.

In addition to the potential enhanced quality assurance procedures identified by Posiva, that would enhance reliability of the safety case as it continues to be developed further, we have suggested that there should be a restructuring of the reports. The reports would be more transparent, if each report tackled a topic in detail. To the extent possible, large amount of duplication that is currently present should be avoided. Also, in the next phase, Posiva should complete all reports prior to submitting them for regulatory review, thereby reducing duplication and the potential for discrepancies, but also reducing the total volume of material that has to be read in order to get a good understanding of the safety assessment.

Posiva asserts that the input data is adequately verified and confirmed. It may not be possible to check each and every data point but a well-designed audit can provide the required confidence. One way to design this audit is to select one or two topics that are most important for conclusions regarding regulatory compliance. It will be appropriate to select a case which incorporates calculations of radiation dose at 10,000 years and if there are resources available, another which may be a disruptive scenario (we suggest the rock shear scenario). For the selected cases, the audit team should pursue bottoms up audit, that is start at the bottom and follow through all details up to the final result. This auditing process may be called a "vertical slice" approach in contrast to a "horizontal slice" (e.g., check all the geochemical parameters). The vertical slice will examine, the data (experimental, theoretical, and that obtained by expert elicitations), the derivation of parameters for a specific model from the data, verification of the model, and verification of the model output. This kind of audit will provide confidence in the overall quality of the safety case.

Posiva's philosophy for developing models (see page 83 of Posiva, 2013-01) is to incorporate applicable FEPs in models. The models are then executed to determine if the safety functions are fulfilled during various time periods. The best description of the state of the safety functions is provided in Posiva 2012-04. For example, the state of components with regard to safety functions and performance targets during the excavation and operational phase is discussed on page 189 of Posiva 2012-04. Based on model results, Posiva draws the conclusion that during the construction period (assumed to be 100 years) all repository barriers will conform to the performance targets with a few possible incidental deviations. These deviations include (1) the flow rate in a few deposition holes exceeding 0.1 L/minute, (2) a few canister positions having water chemistry outside the target range for a short period, and (3) 4–5 canisters out of 4,500 may have an initial manufacturing defect. Similar explanation is provided for 10,000 years after closure on page 384 of Posiva 2012-04. Again Posiva concludes that all components will conform to their performance targets with some incidental deviations, such as (1) transport resistance may decrease to as low as 1×10^{-4} year/meter for some deposition holes during the period when the repository is under the ice sheet, (2) a few canister positions may experience dilute ground water, (3) a few tens of canisters may fail due to seismic activity but the probability is low, (4) up to about 3 canister positions may experience chemical erosion of buffer, and (5) between 1 to 3 canisters may fail due to sulphide corrosion during the first glacial cycle. Finally, in Chapter 8 of Posiva 2012-04, fulfilment of performance targets and target properties is discussed during one million years. The model results show that after 8 repeated glacial cycles, (1) about 300 deposition holes (Table 8-1 on page 387 of Posiva 2012-04) may experience advective conditions, (2) copper corrosion depth will be less than 3 mm for all canisters (Figures 8-1, 8-2, and 8-3 on page 388 of Posiva 2012-04), (3) under the worst conditions of high sulphide concentration and advective conditions due to buffer erosion, 150 to 200 canisters may fail (Figure 8-4 on page 391 of Posiva 2012-04), (4) repeated earthquakes will not degrade repository's performance, (5) periodic isostatic pressure load from ice sheet formation will not increase creep strain, and (6) fuel will stay sub-critical but even criticality occurred in a single canister, the consequences will be low. Some of these incidental deviations will occur simultaneously, others will occur in isolation. While the safety case presented by Posiva does not provide a full probabilistic analysis including the above deviations, because of the large safety margins estimated by Posiva in its calculation cases, we believe that the system as designed will meet the regulatory safety constraints.

Fulfilment of individual targets for the host rock and the EBS are summarized in Chapter 9 of Posiva 2012-04 in considerable detail. Based on this discussion, we conclude that Posiva developed conceptual and mathematical models are capable of estimating the state of safety functions of the components.

As explained in various Posiva reports (e.g., 2012-04, 2012-12, 2013-01), models are based on incorporating all relevant FEPs that are expected to be operative during the one million year assessment period. To the extent possible, Posiva has used data and models that propose to represent conditions that are anticipated to prevail including potential deviations. We have noted a few deficiencies in this regard in other parts of this review.

Some idea about the relative importance of parameters can be developed from the probabilistic sensitivity analysis. Figure 9-10 on page 193 of Posiva 2012-09 provides some specific information. But we didn't see a list of safety significant parameters in Posiva's safety case. Posiva should include such a list in the next phase of the analysis. Looking at the red curve in this figure, one can identify the small hole diameter, and fuel alteration rate as the two most important parameters that lead to higher release rates in the reference case. Similarly, the mass of buffer in the cavity (Posiva allows clay to enter the defect in its PSA analyses), and sorption coefficient of the buffer and backfill are the two most important parameters that lower the release rate. One can also see that geosphere transport/retention parameters are not so important mainly because the barrier properties of the far-field rock are not called upon to play much of a role in the scenarios analysed. Other scenarios may provide different results. In any case, Posiva should develop an analysis that establishes the capabilities of individual barriers, including the far-field rock.

The uncertainties are documented in Posiva 2013-01. Data sources should be reviewed to determine if the uncertainty ranges are adequately defined. We believe that it would have been difficult for Posiva to include every detail in the main reports or even in the supporting reports of the CLA. Overall, Posiva has done a good job of providing critical information even though the reader has to go to many reports to understand a topic reasonably well.

Summary

(1) The methodology used by Posiva is transparent, it includes identification of the key safety functions, and it brings out the key issues and uncertainties. We consider the conceptual models, mathematical models and data to be adequate and appropriate for the first phase of licensing.

(2) STUK should consider doing a "vertical slice" audit of selected calculation cases to check the reliability of the entire calculation chain.

(3) To further enhance confidence in the reliability of the safety case, Posiva should provide (1) a list of top 10 parameters affecting post-closure safety, representing all scenarios, not just the Base Case, (2) descriptions of uncertainty ranges on these parameters and justification for the ranges, (3) references that provide the source of data on these parameters, and (4) plans for reducing the uncertainties in these parameters.

As stated before, Posiva closely follows the Finnish regulations and STUK guidance in constructing its safety case. It demonstrated compliance with quantitative regulatory standards by deterministic calculations. Deterministic sensitivity analyses are conducted via calculation cases by varying one or two parameters at a time.

We recommend that to further enhance confidence in the realiability of the safety case, Posiva should provide (1) a list of top few (5 to 10) parameters affecting post-closure safety, representing all scenarios, not just the Base Case, (2) descriptions of uncertainty ranges on these parameters and justification for the ranges, (3) references that provide the source of data on these parameters, and (4) plans for reducing the uncertainties in these parameters.

5 Proposed conditions, requirements and/or commitments

STUK will continue its regulatory oversight role during the future phases of construction, operations and ultimate closure of the repository and decommissioning of the site. As a regulatory management tool and to assure resolution of important uncertainties and enhance safety, STUK may propose some work or actions to be taken by Posiva during the future phases of licensing. In our review, we have identified some issues that are candidates for inclusion in such a proposal.

STUK plans to define a hierarchy of provisions as follows.

1. **Government License Conditions:** These are the highest or policy level provisions and relate essentially to the scope of the facility. STUK may identify license condition in its safety evaluation and upon approval by the Ministry of Economy and Employment (the Finnish Government Ministry responsible for granting the license); the conditions may be included in the license.
2. **STUK Requirements:** STUK requirements are of administrative or technical nature and would be addressed between STUK and Posiva following an agreed to process (that may include review and discussion) and will follow an agreed to schedule. STUK may request Posiva to submit a plan for addressing an issue for review and also conduct inspections and audits to assess progress of issue resolution. Regarding schedule: (a) certain STUK requirements will require actions prior to underground construction, e.g., before excavation of disposal tunnels/panels/boreholes or drilling into the proposed disposal rock volume or (b) prior to fabrication/manufacture of the engineered barrier components, e.g., canister, buffer, backfill, or closure components or (c) prior to the Operating License Application is submitted and the results of such work will be expected to be included in that license application.
3. **Posiva Commitments:** Posiva commitments are technical in nature and are focused in further development of the safety case and longer term RD&D. The work related to such commitments will be initiated at an appropriate time and progress reported as appropriate but included in the Operating License Application. The purpose of the Posiva commitments is to continue to enhance understanding of processes related to, design, operations, and long-term safety, improve models and conduct verification and validation activities, and improves data bases for use in safety assessment.

In the following table, the issues identified in our review are summarized in categories as explained above and related to topics for future work.

Summary

(1) None of the issues in Table 1 are of a nature that can alter the bottom line conclusion that Posiva has adequately demonstrated compliance with regulatory safety constraints.

(2) However, residual uncertainties remain and need to be resolved during the following licensing phases.

(3) STUK should consider developing a prioritized consolidated list of items/topics and seek Posiva's commitment to respond to these in a timely manner.

Table 1. Categorization of topics into potential license conditions, STUK requirements and Posiva commitments.

<table>
<tr><th colspan="4">Potential Topics for License Conditions</th></tr>
<tr><th>Issue No.</th><th>Brief Issue Definition</th><th>Suggestions for Issue Resolution</th><th>Proposed Schedule for Resolution</th></tr>
<tr><td>1</td><td>**Integration of Intermediate and Low Level Facility Safety Assessment:** The small facility for the disposal of intermediate and low level waste emanating from the encapsulation plant is co-located with the spent fuel repository. Posiva has not integrated the safety case for it (Posiva 2012-37) with that of the spent fuel repository.</td><td>Posiva should fully integrate the safety assessment of the co-located intermediate and low level waste facility with that of the spent fuel repository, i.e., incorporate interactions between the two facilities, for example the possibility of an alkaline plume from the intermediate and low level waste facility.</td><td>An integrated safety case should be presented in the Operating License Application or earlier.</td></tr>
<tr><th colspan="4">Potential Topics for STUK Requirements</th></tr>
<tr><td>1</td><td>**Demonstration Activities Prior to and During Construction and Fabrication:** Posiva has not provided a plan for demonstrating that the EBS components can be fabricated to design specifications; that the rock suitability classification criteria can be met during underground construction; and that the waste can be emplaced as described in the CLA.</td><td>Posiva should (a) present a reasonable and verifiable plan to demonstrate that (i) engineered barrier components can be fabricated to meet design specifications; (ii) the underground construction will be able to meet the rock suitability classification criteria; (iii) waste can be transported and emplaced as described in the CLA; and (b) that it has on its disposal suitable methods to adequately characterize (geologic, hydrologic, thermal, geochemical, and mechanical) the rock volume designated for waste disposal.</td><td>The plan should be presented before EBS fabrication or underground construction begins; the actual demonstration tests may be conducted early during the fabrication and construction stages; plans for rock characterization should be presented before construction begins.</td></tr>
<tr><td>2</td><td>**Calculation Cases and Sensitivity Analysis:** Posiva's choice of calculation cases in its deterministic sensitivity analyses (geosphere, engineered barriers and biosphere) does not follow a systematic approach. The use of the probabilistic sensitivity analysis is limited in the current safety case.</td><td>Posiva should (a) more clearly and in an integrated manner, explain the formulation of the calculation cases and the lesson learned from each; (b) consider achieving an appropriate balance between the use of deterministic and probabilistic sensitivity analyses to demonstrate the robustness of the system; (c) conduct a probabilistic sensitivity analysis of biosphere to identify important biosphere parameters and especially to determine the sensitivity of dose to discharge points obtained from the Discrete Fracture Network model; (d) clearly identify processes, models and parameters that most influence the safety measures (annualized normalized releases and radiation doses); (e) establish a clear link between the identified important parameters and the plans for future RD&D; and (f) document in greater detail, the models, parameters, and processes that significantly influence estimates of safety measures.</td><td>Recommended for (a) future iterations of safety assessment; (b) inclusion in the plan for safety assessment for the Operating License Application.</td></tr>
</table>

Potential Topics for STUK Requirements			
Issue No.	Brief Issue Definition	Suggestions for Issue Resolution	Proposed Schedule for Resolution
3	**Derivation of Design Specifications and Rock Suitability Criteria:** We were unable to find a clear description of the link between the engineered barriers design specifications and the rock suitability classification criteria to construction, fabrication, and operational or long-term safety. While a relationship is alluded to, it is obscure in the current safety case. Similarly, the capability of each barrier is not clearly described. The descriptive safety functions and performance targets are good as a guidance tool but these do not provide a clear picture of the capabilities of the individual barriers.	Posiva should (a) provide adequate rationale for the engineered barrier design specifications and rock suitability criteria based on their relationship to fabrication, construction, transport, emplacement, and operational and long-term safety; (b) devise a modeling approach to clearly describe the capability of each barrier, even if the capability will not be called for during the assessment period; and (c) conduct a few 'what-if' analyses with extreme conditions. Such analysis should clearly show the built-in robustness in the system.	Recommended for inclusion in the Operating License Application.
4	**Turva-2012 Documentation:** Posiva's current CLA documentation is voluminous and extensive. However, as reviewers, we found that it lacks consistency, clarity, and transparency. There is much duplication in documents and yet important information is missing from the top-level documents. A significant number of the documents were not even published at the time the review began, even though these were referenced.	Posiva should (a) develop a more cohesive documentation hierarchy; (b) to the extent practical, submit all documents simultaneously; (c) decrease duplication by developing a summary document containing basic and essential system description that should not be repeated in other documents; (d) as far as possible, provide detailed information about topics significant to safety, design, construction, or fabrication in one place; (e) better implement the QA/QC process to avoid editorial and referencing errors; and (f) include bookmarks in PDF documents.	A plan for documentation of the Operating License Application should be developed in consultation with STUK and implemented.

Potential Topics for Posiva Commitments			
Issue No.	**Brief Issue Definition**	**Suggestions for Issue Resolution**	**Proposed Schedule for Resolution**
1	**Base Scenario:** The fixed pinhole defect in one canister base scenario obscures the real effectiveness of the multiple barriers of the repository system. From the safety case, we get the overwhelming sense that Posiva believes that the design-basis (or expected) scenario will have zero release during the entire compliance period. It seems that the inclusion of the pin-hole defect is in deference to the regulations.	Posiva should (a) state that the "expected" case is zero release for 1,000,000 years; (b) construct and analyse an illustrative "reference" case that modestly challenges the safety functions of the barriers; (c) analyse illustrative scenarios to define the vulnerability of the system, for example the number of canister that have to fail before the normalized release rate will exceed the regulatory limit.	This recommendation should be implemented in the next safety assessment.
2	**Prioritization of Future RD&D:** In Turva-2012, Posiva proposes a large number of topics for future research, development and demonstration (RD&D). However, no prioritization of the topics is provided.	Posiva should (a) establish a priority for the topics for RD&D based on the significance of these topics to design, construction, and operational and long-term safety; (b) prepare a plan for performance confirmation that would include monitoring underground during construction, monitoring of surface environment, testing of engineered barriers at suitable-scales, and model validation using site data and data on engineered barriers, as it becomes available; (c) RD&D topics suggested by us and other reviewers should be evaluated for inclusion in the list. these include (i) impact of cast iron insert corrosion, (ii) potential failure modes for the canister, e.g., creep, embrittlement, and stress corrosion cracking; (iii) variation in buffer evolution as a function of space and time; (iv) potential of mechanical erosion of buffer under varying fracture flow conditions; (v) spent fuel dissolution rates; (vi) resistance of closure components (seals and plugs) to piping and (vii) potential higher probability of large earthquakes in the post-glacial period.	This should be done prior to development of the next RD&D plan; Posiva may have to conduct additional sensitivity analyses to implement this recommendation.
3	**Consideration of Human and Machine Errors:** Posiva's assumption that its QA/QC program will be implemented flawlessly has not been justified in Turva-2012.	Posiva should (a) document the effectiveness of the QA/QC system with special attention to potential random and systematic human errors; (b) consider the possibility that its implementation of quality assurance/quality control system will not be flawless; (c) consider the potential for human errors during construction, fabrication of engineered barrier components, waste emplacement, and closure; and (d) analyse, in much greater detail, 'what-if' scenarios that include common cause failures of the barriers.	Observations should be made, recorded, and analysed during the time that tunnels or deposition holes are constructed and during fabrication of engineered barrier components.

Potential Topics for Posiva Commitments			
Issue No.	**Brief Issue Definition**	**Suggestions for Issue Resolution**	**Proposed Schedule for Resolution**
4	**Scenario Methodology:** The methodology used for definition of scenarios in Turva-2012 is sufficient for the first phase of the licensing process but it is difficult to assure that most scenarios have been included in safety assessment.	Posiva should (a) develop a more systematic approach for scenario definition; (b) relate more closely the scenarios to performance targets; (c) consider additional scenarios – (i) a kitchen garden scenario, (ii) multiple defects in one canister and multiple canisters, (iii) longer-term infiltration of dilute water during temperate period and during post-glaciation period affecting performance of buffer; (iv) human intrusion soon after repository closure and the possibility of chronic exposure during such an event, (v) occurrence of a seismic event causing rock shear early during temperate period, (vi) possible failure of drift seal failure due to seismic activity; (c) provide a mapping of barrier performance targets and scenarios.	This recommendation should be implemented in preparing the Operating License Application.
5	**Consideration of Uncertainties:** In general, the modeling and data used by Posiva in Turva-2012 are high quality but the treatment of uncertainties could be improved.	Posiva should (a) to the extent possible, verify models such as the DFN model by using them to predict conditions underground and then comparing those predications to measurements during construction; (b) use probabilistic sensitivity analysis more extensively than used in Turva-2012 to demonstrate system robustness; (c) construct deterministic sensitivity cases that would define the "failure" limit of Posiva's robust system; (d) discuss in some detail the partition of the uncertainties into aleatory and epistemic categories; (e) differentiate better between uncertainty and spatial and/or temporal variability; (f) formalize its process for expert elicitation; (g) resolve uncertainties regarding dissolution rate of spent fuel; and (h) resolve uncertainties regarding instantaneous release fraction of I-129 and C-14.	This should begin during construction and continue during the project life.
6	**Alternate Assumptions:** Posiva does not analyse many alternate assumptions in its safety assessment.	Posiva should (a) include broader analysis using a variety of alternate assumption both related to external factors (earthquakes and climate change) and internal factors (non-fulfilment of safety targets of barriers); (b) analyse alternate assumptions in fracture flow in the DFN model; (c) provide a rationale why only one sample of the DFN is used in calculations.	This should be implemented in the next iteration of safety assessment.

APPENDIX A Review of Posiva responses to requests for additional information on post-closure safety assessment

Based on reviews conducted by STUK staff and by STUK consultants, requests for additional information (RAIs) were prepared and transmitted to Posiva for responses. One such request was related to post-closure safety assessment. The review of the additional information provided by Posiva on this topic is provided in the following.

A.1 Analysis of early earthquake

In response to a request for additional information, Posiva provided results of calculations for the case in which a large earthquake is assumed to occur 200 years after repository closure. In the deterministic calculation, one canister is assumed to fail in the event. Cs-137 (8 GBq/year) and Sr-90 (3 GBq/year) dominate the near-field release at about 100 years after such an event. C-14 follows with 0.3 GBq/year. Cs-137, however sorbs to the rock surface/decays and doesn't reach the geo-bio boundary. Sr-90 (1 GBq/year), C-14 (0.1 GBq/year), and Ag-108m (0.01 GBq/year) dominate the release rate at this boundary. The peak of releases occurs soon after canister failure, before 300 years) both for near-filed and the at the geo-bio boundary. Posiva also provides a rough indication of dose rates for this case. Based on a household well, the annual dose rate is estimated to be roughly 3 mSv/year primarily from Sr-90. The release or dose in this case is not multiplied by the low probability of the earthquake. Posiva acknowledges that some phenomena such as incomplete saturation of buffer, increasing temperature due to decay heat, incomplete biosphere data for radionuclides such as Sr-90 and Ag-108m which were screened out in the main safety case makes the analysis approximate. Obviously, the deterministic assumption of one canister failure is not realistic as all canisters in the critical positions can fail. However, not multiplying the estimate dose with the probability of the event is a very conservative assumption. The probabilistic calculations provided by Posiva may be considered as more representative of the case requested in the request for additional information.

In the probabilistic calculation, expected value of dose is estimated for the case of a household well and agricultural well, by taking 100 Monte Carlo samples of 'time of canister failure' from a uniform distribution between 200–50, 000 years. For each of the 100 sampled canister failure times, the probability is calculated in the manner already explained above.

Sampled times, t_i, i = 1, 2, …, 100; $200 \le t_i \le 50{,}000$ years; $\Delta t = 50{,}000–200 = 49{,}800$ years. Samples are from uniform distribution, therefore they are equally probable with probability = 1/100. Posiva uses a simple model for assigning a probability to an earthquake at any of the sampled times, Probability of Earthquake at any of the sampled times = pi = $(\lambda \cdot \Delta t)/100$ where λ is the average frequency of earthquakes. If N canisters located in critical positions fail, then the expected value of dose is simply

$$E\left\{D(t)\right\} = \frac{N \cdot D_c \cdot \lambda \cdot \Delta t}{100} \sum_{i=1}^{100} R_i(t) \qquad \text{(A–1)}$$

In the Eq. (A–1), D_c is the dose conversion factor (mSv/Bq) and $R_i(t)$ is the release (Bq) from an earthquake at the sampled time t_i. Considering the potential 5 fault zones, close to the repository that is capable of hosting an event M > 5, the annual probability is taken as 2.4×10^{-7}. For this case, the expected annual dose is estimated to be 2 orders of magnitude below the regulatory constraint. If the probability is based on a greater number of potential capable faults lying within the 5 km radius then the annual probability is increased to $1.5–10^{-5}$. With this assumption, the annual dose is still below the regulatory constraint but not by much. Expected value of dose is dominated by C-14, I-129, and Ag-108m in the dose window and by Ra-226 beyond the dose window. Posiva has made a number of conservative assumptions in these calculations, so it is reasonable to assume that the system is robust enough to withstand a large earthquake in the early period of the repository's life. However, we believe that Posiva needs to conduct more data gathering and analyses to get a better handle on the probability of the earthquakes. In Appendix 1B of its response, Posiva explains the difficulty inherent in estimating the frequency-magnitude relationship for seismic activity because the observed data is considered sufficient for events with magnitude $M < 4$ only. There are no observations of large magnitude earthquakes and most of the estimates are based on extrapolating the observed data for $M < 4$ events using the Gutenberg-Richter equation relating magnitude and frequency.

A.2 Probability-weighted multi-canister failure

This information was requested because the approach explained in Posiva 2012-09 was not clear. The explanation given in response to the RAI is still not clear; for example the index k in equations 5 and 6 makes little sense; we believe a summation on k is missing from these two equations. However, it seems to us that the approach for the probability-weighted multi-canister failure is very similar to the probabilistic approach for an earthquake during the temperate period explained above. The average rate of occurrence of large earthquakes during a period of ice retreat was calculated as explained earlier, as varying from $\lambda = 0.0048$ to $\lambda = 0.0096$. The expected value of release rate of a radionuclide j at time t due to failure of N canisters is then estimated by

$$E\left\{R_j\left(t\right)\right\} = N \cdot \lambda \cdot \frac{1}{24}\sum_{i=1}^{i=24} r_{i,j}\left(t\right) \tag{A–2}$$

where $r_{i,j}$ (t) is the release rate from failure of a single canister and i represents the 24 periods of ice retreat during which an earthquake can occur. The interest is in calculating the peak release rate which occurs soon after the event and then in subsequent high flow periods during ice retreat. Therefore the above equation is modified to,

$$E\left\{\max\left[R_j\right]\right\} = N \cdot \lambda \cdot \frac{1}{24}\frac{1}{24}\sum_{i=1}^{24}\sum_{k=1}^{24} r_{i,j,k} \tag{A–3}$$

In which the average of the 24 peaks is taken. This is our interpretation of Posiva's submission although as stated above, it is difficult to understand their logic. This work still requires a clearer explanation.

A.3 Early human intrusion

Posiva's response to STUK's question as to why the human intrusion is considered to occur at 1,000 years rather than say at 200 years is that Posiva believes that written records of the repository will be available for 1,000 years or more and so the probability of human intrusion before 1,000 years would be lower than 10^{-7}/year assumed in the safety case. No evidence for this assertion is presented.

However, Posiva admits that were it to consider human intrusion at an earlier time, say at 200 years, shorter lived actinides such as Sr-90 and Cs-137 will contribute to the dose. Based on Smith, et al. (2013, Figure 13), Posiva argues that the dose to the drillers would primarily be from inhalation. From Figure 3-1, we see that Pu-239 and Am-241 produces the highest inhalation dose but Sr-90 and Cs-137 are not far behind. Sr-90 and Cs-137 do produce high ingestion doses. It is not stated in Posiva's response but we assume that these doses are probability weighted. We believe that, once a site is selected, not much can be done about human intrusion but continue to believe that a realistic analysis and demonstration of complying regulatory requirements should never-the-less be included in a safety case.

Reference

Smith, G.M., J. Molinero, A. Delos, A. Valls, K. Smith, A. Conesa, and T. Hjerpe. "Human Intruder Dose Assessment for Deep Geological Disposal." Working Report 2013-23. Eurajoki, Finland: Posiva Oy. 100 p. 2013.

A.4 Common cause failure

With respect to the canister, Posiva admits that "the welding technique and associated quality management, including the techniques for non-destructive testing (NDT), have not yet been worked out in detail." But then it asserts that," Manufacturing, welding and the different inspections are technically different processes that do not have any common root causes for failures, except possibly those arising from human behavior." Adequate explanation supporting this statement is not provided; it is certainly possible to have systematic errors introduced in any of the steps but certainly the human errors can cause problems with not only the canisters but other components also such the manufacturing, inspection, transport, and emplacement of the buffer. Posiva emphasizes staff training and cultivation of safety culture as reasons for avoiding human errors. We believe that such measures are appropriate and necessary but the assumption that such measures will avoid all human errors is unrealistic.

We continue to recommend a careful look at the staff training and also a demonstration that components can be manufactured, inspected, transported and emplaced as assumed in the safety case be planned before proceeding with commercial production.

A.5 Probabilistic sensitivity analysis of rock shear scenario

In the PSA only one canister is assumed to fail and the time of failure is sampled from Log-Uniform (20,000–200,000) distribution – time in years. The sampled times may be thought of as the time at which an earthquake occurs. The duration of high water flows during the glacial retreat is also sampled from a Long-Uniform (100–1,000) distribution – time in years. The TD and TDZ paths are ignored (only the F path is considered) even though the tunnel is considered which acts as a (permanent) sink which seems to be a non-pessimistic assumption. In its response, Posiva presents PSA results for several radionuclides. Looking at the mean ranks (Figures 5-1 to 5-10) of parameters for individual radionuclides, it appears that the time of canister failure is of the highest importance for radionuclides that have relatively shorter half-life (less than 5 × 10^3 years – see Table 2-1, page 5 of Posiva WR 2013-61). The fuel alteration rate and the IRF fractions are next in importance. The importance of buffer is also apparent as the time of establishment of advective conditions in the buffer as well as amount of clay colloids shows up as important parameters. Below, we reproduce one figure that shows the mean rank of parameters for the total release.

It stands to reason that for dynamic systems, parameter sensitivities will vary with time. The time for the above figure is the time at which the normalized release rate reaches its peak; this time is not mentioned in Posiva's RAI response but we assume that this time is much later than the time of the earthquake event and the peak release is made up of long-lived radionuclides. Therefore the time of canister failure shows up as of little importance. As can be inferred from Figure A.1, high values of fuel alteration rate, increase in flow during glacial retreat, solubility of radium, density of bentonite colloids, and flow rate in fractures lead to high values of peak normalized release. Similarly, low values of sorption of radium in intact rock, WL/Q for

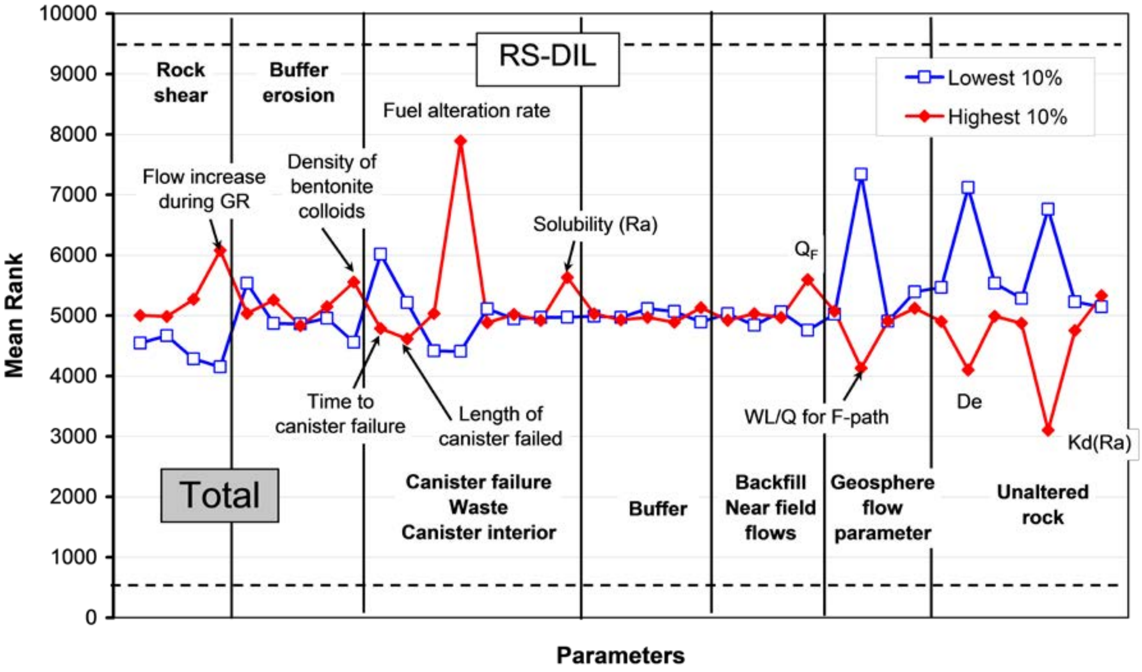

Figure A.1. Mean rank of parameters plot for the RS-DIL scenario considering total release at the geo-bio boundary. The plot shows the sensitivity to parameters of peak normalized release taking all radionuclides into account (taken from Figure 5-11 in Posiva's response to RAIS).

Table A.1. Parameter importance ranking in the RS-DIL scenario (Table 5-15 of Posiva's RAI response).

Parameters	RCC/SRRC		Modified M-W	
	Near Field	Far Field	Near Field	Far Field
Rock shear				
Duration of high flows during glacial retreats (GR)		9		
Flow increase factor during GRs	4	5	2	3
Buffer erosion				
Flow increase factor due to advective conditions	3		4	
Density of bentonite colloids (during glacial retreats)	9*	7	5	8
Canister failure				
Time to canister failure	5	6	7	
Length of canister failed			10	9
Waste				
Fuel alteration rate	1	2	1	1
Canister interior				
Solubility (Nb)	9*			
Solubility (Ra)	6	10	9	6
Hole Buffer				
Kd (Nb)	7		6	
Kd (Ra)	8		8	
Tunnel backfill				
Near field flow				
QF	2	8	3	7
Geosphere flow parameters				
WL/Q for F-path		3		5
Unaltered rock				
De		4		4
Kd (Ra)		1		2
Kd (U)				10

(*)Two parameters with the same value of the statistic

the F-path, and diffusion coefficient into intact rock also produce high values of the normalized release rate. Table 5-15 in Posiva's RAI response provides importance ranking of parameters based on various sensitivity measures and is reproduced below.

In Table 5-18 of its response, Posiva describes how the identified important parameters will drive its future work. Obviously, more detailed programs and plans will have to be drawn up to better define and bound the uncertainties considered in the PSA.

A.6 Probabilistic sensitivity analysis for a fixed position of a canister

STUK requested Posiva to present a PSA of a case where the location of the defective canister is not sampled. In response, Posiva presents three analyses; case where the defective canister is located at (1) a pessimistic location; (2) an average location, and (3) an optimistic location. The analysis is still based on a single realization of the DFN model. In its request for additional information, STUL did not request full sampling of the DFN model. This was because; we understood that the DFN model is time consuming to run. Based on comparing about 10 realizations, Posiva has concluded that the realizations don't vary much among themselves. However, Posiva's argument in this regard is not persuasive. If this is indeed true then why go to the trouble of representing fractures stochastically? We believe that Posiva should either make a stronger case for using a single DFN realization (e.g., examine the statistic of 500–1,000 realizations) or use full DFN sampling in its safety assessment. Figure 6-7 in the response summarizes the results.

Two points to be noted in Figure 2 are (1) the peak normalized release rate can vary three orders of magnitude depending on the location of the emplacement hole and (2) the contribution of the far field increases as one moves from the pessimistic to the optimistic hole. The figure showing the mean parameter ranks is also reproduced below.

From this figure, we note that most of the sensitive parameters are the same in the three cases except for the high importance of matrix diffusion in the case of optimistic location (green line). This can be easily explained as in cases with higher flow rates, matrix diffusion in the far field will play an important role in lowering the peak The other interesting result is that certain parameters (QF, QDZ, WL/Q for the F and the DZ paths) that were identified as important in PSA when defective canister location was also sampled; don't show up as important in either of the three cases. None of this show up as important when mean parameter ranks is plotted for individual radionuclides. This could be the result of reduction in variation of these parameters due to a fixed deposition hole location but a more complete explanation needs to be developed. Overall, Posiva has produced significant

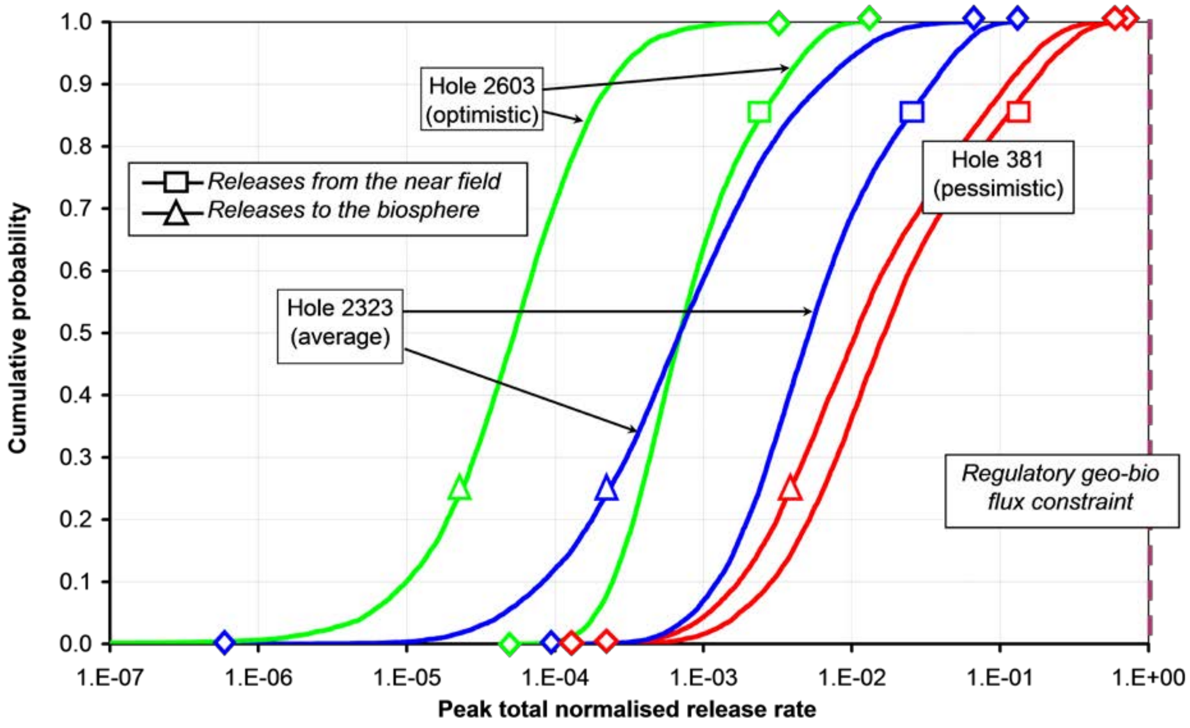

Figure A.2. Cumulative probability distributions of normalized release rates for the three emplacement holes with defective canisters.

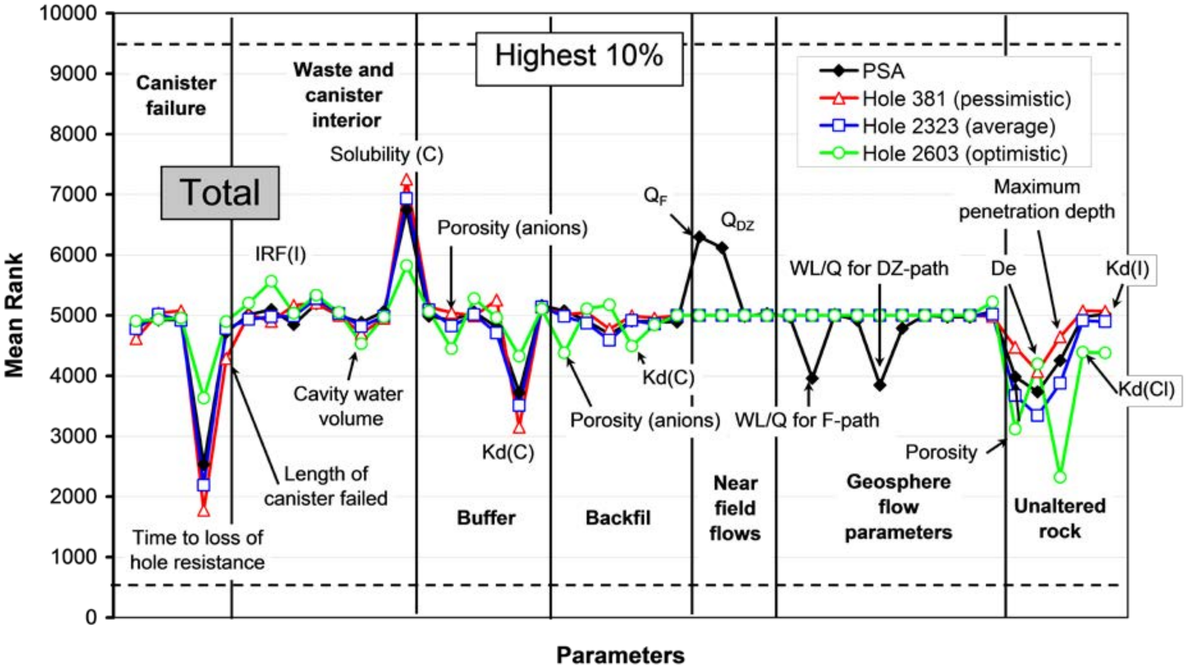

Figure A.3. Mean parameter ranks for the three locations of the effective canisters.

new sensitivity results which help to understand the system behaviour better.

A.7 Potential damage to the spent fuel during rock shear

Regarding potential damage to fuel during rock shear, Posiva states that the radionuclide release rate of 10^{-7}/year used in the reference case in Posiva 2012-09 is based on experimental data on small UO_2 fragments which took into account an increased surface area compared to a whole UO_2 pallet. Also, in the present safety case, it is the radionuclides that are released instantaneously (C-14, Cl-36, and I-129) that dominate the release and the release rate of these will not be affected by any potential increase in surface area during rock shear. Posiva then presents results of deterministic sensitivity analyses. These results show that (1) increasing the dissolution rate by an order of magnitude has negligible effect on peak normalized release rates, (2) increasing dissolution rates by two orders of magnitude in the first 1,000 years (the analyses assume shear failure of one canister at 200 years) does show increase in release rates especially for C-14, and (3) increasing the corrosion rate of zircloy and other metal parts increases the release rates of C-14 and Cl-36. Posiva also notes the PSA result of the RS-DIL scenario in which the fuel dissolution rate shows up as an important parameter and states that it will continue to conduct work to reduce the uncertainty in this parameter.

Summary

(1) Posiva analysis of an early earthquake is reasonable although it is apparent that further work is required to decrease the uncertainty in the magnitude-frequency relationship that is used to estimate the frequency of large earthquakes.

(2) Posiva's explanation of how releases are estimated from multiple canister failures remains confusing; a clearer explanation needs to be developed.

(3) Continued work is required on identification of potential defects in barrier components, including due to human errors, and the possibility of several components failing simultaneously.

(4) Posiva identifies important parameters for the RS-DIL scenario and discusses how such information will be used in defining future work; Posiva is encouraged to develop detailed plans for such work.

(5) More effort should be devoted to understanding the PSA results and find explanation for variability in results; for example reasons for certain parameters that were identified as important in the reference case yet were found to be unimportant once the location of the defective canister was not sampled.

(6) Posiva's conclusion that work would continue in reducing the uncertainty in spent fuel dissolution rate is endorsed.

APPENDIX B Review of Posiva response to request for additional information regarding slow saturation of buffer

Based on reviews conducted by STUK staff and by STUK consultants, requests for additional information (RAIs) were prepared and transmitted to Posiva for responses. One such request was related to buffer saturation. The review of the additional information provided by Posiva on this topic is provided in the following.

B.1 Process description

Posiva's description of buffer saturation process indicates that it is rather a complex process, especially during the thermal period when effects of rising temperatures must be considered. However, it is apparent that ultimately the rate of buffer saturation depends on the rate (1) at which the host rock can supply water to the buffer or deposition hole and (2) at which the buffer can absorb water. Posiva estimates that if the water supply rate is $< 4 \times 10^{-3}$ L/min, then the time to saturation is controlled by the rate at which the buffer can sorb water and vice a versa. By design, Posiva avoids placing deposition holes in rock volume that contains the major water carrying fractures/features. Deposition holes are not only located in the rock volume that is either more or less free of fractures or is sparsely fractured. Even in the sparsely fractured rock, deposition holes are rejected if the inflow, at the time of construction, exceeds a certain amount (0.1 L/min); similarly an entire deposition tunnel may be rejected if the inflow to the tunnel exceeds a designated inflow (1 L/year/meter) account (see RSC criteria in Posiva 2012-24). The saturated hydraulic conductivity of buffer rings at the design specific 60% initial saturation is estimated at 5.59×10^{-14} m/s (Posiva 2012-04, page 218). The hydraulic conductivity of pallets is estimated to be two orders of magnitude larger. At saturation, the density of buffer is estimated to be 2,000 kg/m^3. The water retention curve (saturation versus suction pressure) for the buffer can vary with temperature and the degree of swelling and the presence of water vapor and air initially may also complicate the saturation process.

Based on a test by SKB (TR10-38), in which a clay samples was not fully saturated in 4 years under conditions of plentiful supply of water, Posiva states that it considers the minimum time for saturation to be 15 to 20 years. Posiva plans to conduct a full scale test at Onkalo (see Kehitysohjelma, 2014). Our interest is not necessarily to look for a fully dynamic simulation of buffer saturation but a discussion of those processes that may affect the safety functions of the buffer (e.g., its swelling that provides support to the canister and erosion that may affect rate of flow of water to and from the canister). In its response, Posiva makes reference to several reports for detailed description of the saturation process. We did not review the referenced reports. Reported below are the two conclusion reached by Posiva.

1. Tests on MX-80 show that desiccation and shrinkage occurs at high temperatures (≈ 100 °C or lower) but that the properties (water retention capacity, low permeability, self-healing) of bentonite are not affected as it swells and saturates.
2. The saturation is heterogeneous along the length of the buffer; the degree of saturation at any location on the buffer depends on the distance of that location from the source of water (see Figure Q2-1 in Posiva response). This occurs especially if the water supply rate is low.

Reference

Kehitysohjelma (ed. T. Jalonen). Loppusijoituskonseptin kehitysohjelma, document POS-018285. Posiva Oy. 2014.

Table B.1. Estimated distribution of the saturation times (Based on Table Q1-4).

Source of water to deposition hole	Number of deposition holes expected to experience this condition (total deposition holes with canisters 4500)	Saturation time in the order of (years)	Comment
Host rock matrix	2025 (45%)[2]		Lack of data on K of host rock is a major reason for uncertainty in estimating saturation times
K[1] < 10^{-14} m/s	45 (1%)	T[3]$_{sat}$ > 500	
10^{-14} < K < 10^{-13} m/s	405 (9%)	50 < T_{sat} < 500	
10^{-13} < K < 10^{-12} m/s	900 (20%)	20 < T_{sat} < 50	
K > 10–12 m/s	675 (15%)	15 < T_{sat} < 20	
Additional supply of water through tunnel backfill	900 (20%)		Inflow rate to deposition holes < 10^{-3} l/min (0.5 m^3/y), but inflow rate to tunnel section above the deposition hole > 10^{-3} l/min
Small amount	600 (13%)	50 < T_{sat} < 500	
Larger amount	300(7%)	T_{sat} < 50	
Fractures intersecting deposition holes	1575(35%)	15–20	Inflow rate > 10^{-3} l/min (0.5 m^3/y)

[1] K = Hydraulic conductivity

[2] Percentages are with respect to the total number of deposition holes (i.e., 4,500).

[3] T_{sat} = Time to saturation

B.2 Histogram of buffer saturation

The following table based on Table Q1-4 in Posiva's response summarizes the estimated distribution of saturation times.

Posiva produced histogram is reproduced as Figure B-1.

Thus a relatively small number (< 45) of the deposition holes will see saturation times that may be in thousands of years (10,000–15,000 years). A much larger number, in hundreds, may see a saturation time of the order of 500 years.

Posiva admits to significant uncertainties in the above estimates, the major one being that the hydraulic conductivity of intact host rock is not well known and it is that source of water that is expected to cause long saturation times. Posiva should device a method to measure this parameter at the beginning of construction.

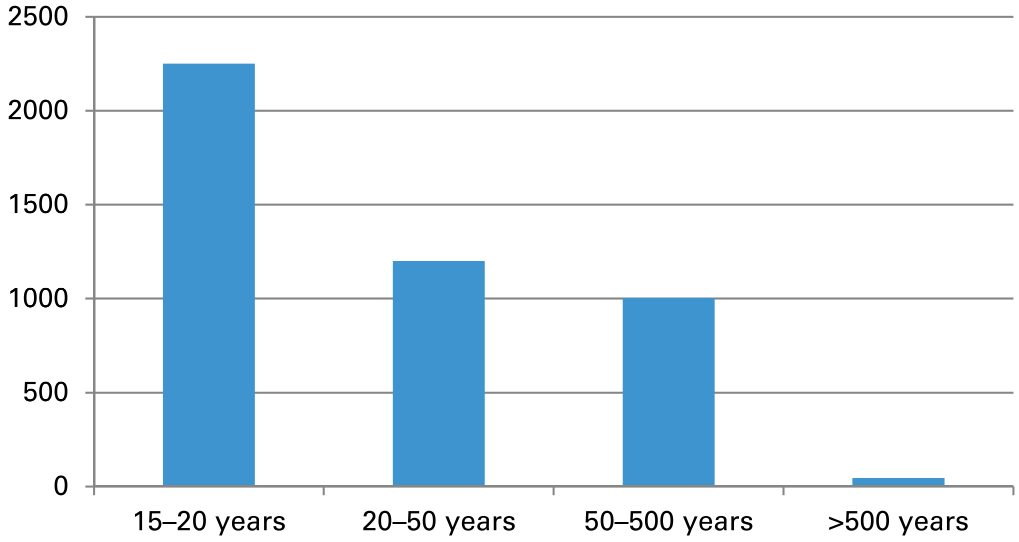

Figure B.1. Number of deposition holes (y-axis) and saturation time (x-axis).

B.3 Factors controlling time to buffer saturation

Posiva states that the principal factors that control buffer saturation time are the same that control the inflow of water to the deposition holes, that is, the hydrologic regime consisting of rock matrix, fractures, hydraulic conductivities and hydraulic boundary conditions. Longer saturation times will occur if the inflow rate is $< 4 \times 10^{-3}$ L/min; this rarely happens when water inflow is from a fracture. Posiva argues that changes in the physical or chemical properties of bentonite clay from steam or vapor or from chemicals in seeping water are minor; see further discussion in the following.

B.4 Effect of uneven saturation on buffer erosion/piping

No new information is presented in Posiva's response on this topic that is not already available in Posiva 2012-04. Potential for erosion is negligible if the local flow rates are $< 10^{-4}$ L/min. Based on laboratory tests, Posiva estimates the worst case mass loss to be 740 ± 370 kg which corresponds to 370 m^3 of water flowing through the deposition hole. Smaller inflow can lead to non-uniform saturation and creation of low cohesion clay pockets. These could potentially lead to erosion; this is the only effect identified by Posiva of non-uniform saturation. Posiva admits that the exact conditions of piping are still unclear and the differences between inflow rates in the laboratory versus those in the deposition holes makes difficult the interpretation of laboratory results.

Piping is faster and channels bigger where the inflow is high and localized, meaning where the water velocities are high. The potential localization of flow in fractures has been suggested by one of STUK's hydrology consultant who postulates that the flow in fractures occurs in channels with cross-sectional area much smaller than the cross-sectional flow area of the entire fracture. This brings forth the issue of possible higher localized water velocities even when the flow rate is the same as determined by the existing DFN model. In our opinion, channelization is very likely in fractures but the extent of channelization is hard to determine and even harder to verify in the field. However, to the extent possible, alternate conceptual models should be explored and we believe that Posiva should investigate this matter prior to the next phase of licensing.

B.5 Effect of uneven saturation on stresses in copper shell

Posiva cites Börgesson, et al. (2009) as the appropriate reference for information on this topic; several other reports are also referenced on specialized topics; we did not review any of these reports. Stress calculations in the copper shell due to loads caused by uneven saturation and hence uneven swelling are presented in Hernelind (2014). Posiva's response indicates that the stresses calculated are small and the strains are estimated to be less than 5–6 percent. The implication is that uneven swelling of buffer does not affect significantly the safety functions of the canister. We suggest more careful study of this topic as a longer-term subject primarily because it is a process that can affect several canisters simultaneously at an early time.

References

Börgesson, L., L.-E. Johannesson, and H. Raiko. "Uneven Swelling Pressure on the Canister–Simplified Load Cases Derived From Uneven Wetting, Rock Contours and Buffer Density Distribution." SKBDoc id nr 1206894, ver 1.0. Swedish Nuclear Fuel and Waste Management Co. 2009.

Hernelind, J. "Analysis of Canister With Unfavourable Pressure Load." SKBdoc 1419643, ver 1.0. Swedish Nuclear Fuel and Waste Management Co. 2014.

B.6 Effect of water vapor on swelling pressure

During the thermal period, due to decay heat, moisture in the buffer (at the time of emplacement, buffer is 60 percent saturated) evaporates, diffuses to cooler portions and condenses. In order to address whether this process affects buffer swelling, Posiva conducted a modeling exercise. The model results (See Figures Q6-1 to Q6-3 in Posiva Response) showed that close to the canister, the time versus swelling pressure curve is slightly below the curve that would be obtained if vapor formation was ignored. This is to be expected as close to the canister, vaporization decreases the liquid content in the buffer hence slight reduction in swelling pressure. But eventually (after about 40 years in Posiva model) the swelling pressure catches up. At points in the buffer close to the host rock (location of vapor condensation), the effect is the opposite. In either case, the effect is minor. Because the time to saturation in the plots provided by Posiva is about 50 years, we assume this is the case where the host rock is supplying water at a rate greater than the intake capacity of the buffer. The effect of the water vapor may be somewhat more pronounced in relatively dry deposition holes. Overall, we believe that Posiva has provided sufficient information to show that the effect of vapor on the rate of swelling of buffer is small.

B.7 Effect of vapor on mechanical properties of buffer

The question posed to Posiva was whether the formation and migration of water vapor from the region of buffer-canister contact can raise the peak temperature to greater than 100 °C and if so then can the mechanical properties of that portion of buffer be affected. Posiva did not respond to this question.

Instead, Posiva presented modeling results of vapor diffusion from buffer to backfill and migration of liquid water from backfill to buffer. The purpose of the presentation seems to be to show that the net water flux is from the backfill to the buffer implying (not stated by Posiva) that therefore, the temperature is not likely to exceed 100 °C.

However, in response to question 10, Posiva discusses the so called “Couture effect” (Couture, 1986) in which the free swelling of MX-80 decreased in contact with steam at 150–250 °C was observed. However, Posiva reports that more recent hydrothermal experiments do not show this effect. SKB has also reported similar results as reported by Karnland and Birgersson, 2006.

Reference

Karnland O. and M. Birgersson. “Montmorillonite Stability With Special Respect to KBS-3 Conditions.” SKB Technical Report TR-06-11. 2006.

B.8 Effect on thermal profile if pellets in the buffer-rock gap do not swell

Posiva presents analyses of several cases in which the evolution of the canister temperature with time is calculated. One case in which the buffer-rock gap is assumed to have air in it is analysed to answer the question posed by STUK. The analysis shows that the peak temperature in this case would be about 8 °C higher than the case in which the gap is full of water. However, the peak temperature at about t = 10 years is still shown to be below 100 °C. Posiva refers to Pintado and Rautioaho (2013) for greater detail.

Reference

Pintado, X. and E. Rautioaho, “Thermo-Hydraulic Modelling of Buffer and Backfill.” Posiva Oy. Eurajoki Finland. POSIVA 2012-48. ISBN 978-951-652-230-5. 2013.

B.9 Potential of microbial growth

Posiva argues that the design specifications for the buffer are such that they exclude the potential for much microbial activity. These design specifications require bentonite for the buffer to have small pore size, low (< 1 percent by weight) organic content, low sulphur content (< 1 percent by weight), and high (> 1,600 kg/m^3) dry density. Also, based on experimental evidence, it can be said that microbial activity is eliminated when the swelling pressure exceeds 2 MPa which is estimated to be achieved in less than 15 years even with low inflow of water (Pintado, 2014).

Posiva states that availability of free water is essential for microbial activity. Therefore, the likely locations for microbial activity in deposition holes with long saturation times will be the buffer-rock and buffer-backfill interfaces. Even at these locations, in the early period, no free water may be available but microbes may reappear once water does become available. Never-the- less, the activity will cease once the swelling pressure reaches the 2 MPa limit.

Posiva admits that the extent of sulphate reduction in the near field during long saturation times is not yet well known. This and other uncertainties (for example effects of organic carbon in the buffer and role of methane) will continue to be investigated.

B.10 Effect on chemical properties of buffer

Changes in chemical composition of buffer are much greater under saturated conditions than under unsaturated conditions. Two main concerns are (1) cementation effects due to precipitation of SiO_2 and other silicates and (2) illitisation of montmorillonite resulting in loss of swelling capacity. Posiva estimates that in deposition holes with saturation times of 50–100 years, there is only minor dissolution and reprecipitation of SiO_2 and $CaSO_4$ (< 2 vol percent). The maximum illitisation is estimated to be less than 10 vol percent but likely much less. None of these changes are expected to degrade the performance much. In "tight" deposition holes, these changes are expected to be even less because of lower solute transport and lower chemical reactivity. Posiva cites the in-situ tests at Äspö (Karland, et al., 2009 and Svensson, et al., 2011) in which compacted bentonite was kept in contact with simulated Äspö water. Except for minor SiO_2 dissolution, the chemical composition was found to be intact.

References

Karnland O., S. Olsson, A. Dueck, M. Birgersson, U. Nilsson, and T. Hernan-Hakansson. "Long Term Test of Buffer Material at the Äspö Hard Rock Laboratory, LOT project." Final Report on the A2 Test Parcel. SKB Technical Report TR-09-29. 2009.

Svensson D., A. Dueck, U. Nilsson., S. Olsson, T. Sandén, S. Lydmark, S. Jägerwall, K. Pedersen, and S. Hansen. "Alternative Buffer Material." Status of the Ongoing Laboratory Investigation of Reference Materials and Test Package 1. SKB Technical Report TR-11-06. 2011.

B.11 Confidence that performance targets will be fulfilled when needed

In response to this request for additional information, Posiva repeats the information they provided in answer to the previous questions. Posiva summarizes the uncertainties with respect to buffer performance due to variation in saturation time as (1) conditions leading to piping, (2) clay density limit for eliminating microbial activity, (3) effect of elevated temperature on cementation-type effects, (4) changes in pH/pCO_2 conditions due to biodegradation, (5) fluxes of H_2S in the partially saturated buffer, and (6) permeability of the intact host rock.

Posiva will continue work to reduce these uncertainties.

B.12 Reference list to support Posiva responses to STUK RAI

See the extensive list of references in Posiva's response.

B.13 Time-dependence of fulfillment of performance targets

Some buffer performance targets are functions of saturation and therefore their fulfilment may evolve as saturation evolves. Table B-2 based on Table Q13-1 in Posiva's response provides a summary of these performance targets.

Continued development and testing of buffer (including the full-scale tests being planned for Onkalo) would constrain the uncertainties in the buffer performance.

Summary

(1) The saturation time of buffer depends on the rate at which host rock can supply water and the rate at which buffer can absorb water; a small number (< 45 out of 4,500) deposition holes may see saturation times longer than 500 years.

(2) Buffer erosion depends on localized water velocity. It is therefore more likely in deposition holes with higher flow rates. We recommend Posiva to consider alternative conceptual models for implementation in the DFN structure. The alternative model will assume that water will travel in channels within fracture surfaces at local velocities higher than are determined by the current conceptual model.

(3) The effect of uneven swelling of buffer on stress state of the copper shell is small. This topic needs further study as several canisters can be simultaneously affected by this process.

(4) Calculations indicate that canister temperature will remain < 100 °C even in drier holes. We assume that the canister temperature will be monitored during the early period to assure that this design requirement is met.

(5) Effect of vapor and steam during the thermal period is also estimated to be small. Posiva recognizes several uncertainties; these topics should be prioritized for conducting RD&D in the future, including full-scale testing at Onkalo. The lack of knowledge about hydraulic conductivity of host rock is a major uncertainty; methods for estimating it during construction should be developed.

Table B.2. Saturation-dependent performance targets (Based on Table Q13-1 in Posiva's response).

Performance Target	Comment
Buffer	
L3-BUF-16: The buffer shall provide support to the deposition hole walls to mitigate potential effects of rock damage.	Based on various modeling results, this may take at most a few tens of years.
L3-BUF-14: The buffer shall limit the transport of radiocolloids to the rock.	Given the design of the buffer, this target is only a weak function of saturation.
L3-BUF-8: The buffer shall limit microbial activity	For relatively dry deposition holes, it will likely take 10 – 15 years to attain this performance target.
L3-BUF-12: The buffer shall be impermeable enough to limit the transport of radionuclides from the canisters into the bedrock, and L-3BUF-13: The buffer shall be impermeable enough to limit the transport of corroding substances from the rock onto the canister surface.	In Posiva's safety assessment, there is no scenario (except for early earthquake scenario requested as additional information by STUK) in which release occurs before 1,000 years. There are a very small number (< 45) of deposition holes in which saturation time will be > 1,000 years. Even in these cases, the buffer next to the canister will probably take the longest to saturate. Therefore, the likelihood of fulfilling these performance targets is high.
Backfill	
L3-BAC-17: The backfill shall contribute to the mechanical stability of the deposition tunnels.	See L3-BUF-16 above.
L3-BAC-8: The backfill shall limit advective flow along the deposition tunnels.	Some advective flow may develop and persist for a short period if erosion channels develop.
Closure	
L3-CLO-7: Closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes.	See L3-BAC-8 above.
L3-CLO-6: Closure shall restore the favourable, natural conditions of the bedrock as well as possible.	After closure the disturbances caused by the construction cease. The recovery of the flow field is relatively quick, but the recovery of the salinity field may take from several hundreds of years to around 1000 years (see Posiva 2013, Sections 6.1.1 and 6.1.2).