STUK-B 197 / NOVEMBER 2015

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STUK's review on the construction license stage post closure safety case of the spent nuclear fuel disposal in Olkiluoto

Säteilyturvakeskus
Strålsäkerhetscentralen
Radiation and Nuclear Safety Authority

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ISBN 978-952-309-292-1 (print) Erweko Oy, Helsinki 2015
ISBN 978-952-309-293-8 (pdf)
ISSN 0781-1713

STUK's review on the construction license stage post closure safety case of the spent nuclear fuel disposal in Olkiluoto. STUK-B 197. Helsinki 2015. 146 pp.

Keywords: nuclear waste, waste disposal, safety case, post-closure safety, construction licence, Olkiluoto, spent nuclear fuel, decision, review report

Summary

In December 2012, Posiva Oy (Posiva) submitted to the Government an application for the construction of a spent nuclear fuel encapsulation plant and disposal facility at Olkiluoto, Eurajoki. In connection with the construction licence application for the Olkiluoto spent nuclear fuel encapsulation plant and disposal facility, Posiva submitted to the Radiation and Nuclear Safety Authority (STUK) for approval the safety case concerning the post-closure safety of disposal in accordance with the Government Decree on the Safety of Disposal of Nuclear Waste (736/2008) The Government Decree stipulates that compliance with the requirements concerning post-closure radiation safety of the disposal facility and the suitability of the disposal method and disposal site shall be proven through a safety case.

Posiva has presented an extensive safety case and a vast number of research documentation and analyses that support the demonstration of post-closure safety. The safety case presents the safety concept, the data and analyses used in the safety case.

Based on STUK's review of the safety case documentation, the post-closure safety of the facility has been analysed in a sufficient manner for the purposes of the construction licence stage. The methods and analyses used in the safety case are, in general, representative of the current international level and the results demonstrate that, after the closure, the facility is safe to people and other living nature in the surroundings as required by the Government Decree. Furthermore, Posiva has indicated the suitability of the disposal method and disposal site in a sufficient manner for the purposes of the construction licence stage. The review shows, however, that there is a need to further improve the safety case by clarifying the safety arguments and the related methods and by reducing the uncertainties concerning the performance of barriers.

This report is based on a review of the safety case presented in Posiva's construction licence application and the related documents submitted to STUK. This report consist of the decision and the presentation memorandum of the safety case and appended review report of the safety case. which presents background information and details concerning the requirements in the decision as well as a great deal of inspection observations.

STUKin arvio turvallisuusperustelusta käytetyn ydinpolttoaineen loppusijoitukselle Olkiluodossa. STUK-B 197. Helsinki 2015. 146 s.

Avainsanat: ydinjäte, loppusijoitus, turvallisuusperustelu, pitkäaikaisturvallisuus, rakentamislupa, Olkiluoto, käytetty ydinpolttoaine, päätös, tarkastusraportti

Tiivistelmä

Posiva Oy (Posiva) toimitti joulukuussa 2012 valtioneuvostolle hakemuksen käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitoksen rakentamiseksi Eurajoen Olkiluotoon. Posiva on toimittanut rakentamislupahakemuksen yhteydessä valtioneuvoston asetuksen (736/2008) ydinjätteiden loppusijoituksen turvallisuudesta edellyttämän loppusijoituksen pitkäaikaisturvallisuutta käsittelevän turvallisuusperustelun Säteilyturvakeskukselle (STUK) hyväksyttäväksi. Valtioneuvoston asetus edellyttää, että loppusijoituslaitoksen pitkäaikaisturvallisuutta koskevien säteilyturvallisuusvaatimusten täyttyminen ja loppusijoitusmenetelmän ja -paikan soveltuvuus osoitetaan turvallisuusperustelulla.

Posivan STUKille toimittama turvallisuusperustelu on laaja ja sen tueksi on julkaistu suuri määrä pitkäaikaisturvallisuuden osoittamista tukevia tutkimusaineistoja. Turvallisuusperustelussa esitetään turvallisuuskonsepti sekä käytetyt lähtötiedot ja analyysimenetelmät.

STUKin tarkastuksen perusteella laitoksen pitkäaikaisturvallisuus on analysoitu rakentamislupavaiheeseen riittävällä tavalla. Turvallisuusperustelussa käytetyt menetelmät ja analyysit edustavat tämän hetkistä kansainvälistä tasoa ja niillä on osoitettu, että laitos on turvallinen ympäristön ihmisille ja muulle elolliselle luonnolle laitoksen sulkemisen jälkeen kuten valtioneuvoston asetus edellyttää. Lisäksi Posiva on osoittanut loppusijoitusmenetelmän ja -paikan soveltuvuuden rakentamislupavaiheeseen riittävällä tavalla. Tarkastus osoittaa kuitenkin, että turvallisuusperustelua on edelleen tarpeen kehittää selkeyttämällä turvallisuuden argumentointia ja siihen liittyviä menetelmiä, sekä pienentämällä vapautumisesteiden toimintakykyyn liittyviä epävarmuuksia.

Tämä raportti perustuu Posivan rakentamislupahakemuksen esittämän turvallisuusperustelun ja STUKille toimitettujen siihen liittyvien asiakirjojen tarkastukseen. Raportti koostuu STUKin Posivan turvallisuusperusteluaineistoa koskevasta päätöksestä ja esittelymuistiosta sekä niiden liitteenä olevasta turvallisuusperustelun tarkastusraportista, jossa esitetään tarkemmin päätöksenvaatimusten taustat ja yksityiskohdat sekä runsaasti tarkastushavaintoja.

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In connection with the construction licence application for the Olkiluoto spent nuclear fuel encapsulation plant and disposal facility, Posiva Oy (Posiva) submitted to the Radiation and Nuclear Safety Authority (STUK) for approval the safety case concerning the post-closure safety of disposal in accordance with Government Decree 736/2008.

The Government Decree on the Safety of Disposal of Nuclear Waste (736/2008) stipulates that compliance with the requirements concerning post-closure radiation safety of the disposal facility and the suitability of the disposal method and disposal site shall be proven through a safety case.

Based on STUK's review of the safety case documentation, the post-closure safety of the facility has been analysed in a sufficient manner for the purposes of the construction licence stage. The results demonstrate that, after the closure, the facility is safe to people and other living nature in the surroundings as required by the Government Decree. Furthermore, Posiva has indicated the suitability of the disposal method and disposal site in a sufficient manner for the purposes of the construction licence stage. STUK approves the safety case and presents the following requirements. The enclosed presentation memorandum and the document *Review report – post-closure safety case* contain the justifications for the requirements.

Characteristics and performance of the natural barrier

1. For improving the reliability of the safety case, STUK requires Posiva to progressively develop the combination of the results and model descriptions of different fields of research that are related to the characterisation and demonstration of performance of the natural barrier. This work must be completed before submitting an operating licence application.
2. Before submitting an operating licence application, Posiva must evaluate, in more detail, the alternative possibilities of climate evolution and their impact on the disposal system.

Suitability of the disposal site

3. Before starting the construction of the deposition tunnels and deposition holes, Posiva must present, based on the performance analysis of the bedrock, the relationships between the design requirements and the surrounding rock characteristics that should be maintained. The relationships must indicate how (mechanical, geochemical and hydrogeological) disturbances to the host rock from construction are controlled and maintained within the set design requirements and how the rock can be expected, when the design requirements are met, to maintain its favourable characteristics in the long term.
4. Posiva must expand its current measurement data on rock stresses and prepare more specific interpretations of the baseline stresses of the rock before starting the construction of the disposal facilities. Furthermore, the research on rock stresses and stability and the related development measures must be continued during construction.
5. Posiva must expand its seismic studies and include the results of further examinations in its operating licence application for the disposal facility, at the latest. The coverage of the material must also be expanded during operation. The effects of earthquakes must also be examined under varying isostatic load conditions (such as ice ages).
6. Posiva must present a plan for verifying the reliability of fracture network modelling before starting the construction of the disposal facilities. The assessment of the hydrogeological disturbances from excavation, assessment of

measurement methods and preparation of modelling data reporting must be started after a construction licence is issued. Further justifications for the selected modelling method and an assessment of its reliability must be presented by the operating licence application stage, at the latest.

7. Posiva must demonstrate sufficient consistency between the hydrogeochemical and hydrogeological interpretations by the operating licence application stage, at the latest.
8. Posiva must further specify its justifications regarding the conclusions on natural resources in Olkiluoto in connection with its operating licence application for the facility, at the latest.

Positioning of disposal facilities

9. Before starting the construction of the disposal facilities, Posiva must supplement the rock classification guidelines as necessary for taking into account Requirement 3. Furthermore, before starting the construction of the disposal facilities, Posiva must present a plan on the procedures for evaluating the reliability of the classification and plans on the further development of the classification.
10. Before starting the construction of the disposal facilities, Posiva must further specify the approval procedures related to the rock classification to cover the different stages of construction, including pilot hole studies.
11. During the construction of the first deposition tunnels, Posiva must evaluate the extent of the rock classification criteria and the performance of the procedure and append a report on the evaluation to the operating licence application.

Disposal canister

12. Posiva must continue its work on the disposal canister manufacturing methods in order to enable the manufacture of components that meet the requirements for both BWR and VVER type canisters before submitting an operating licence application.
13. Before submitting an operating licence application, Posiva must assess in more detail the safety significance of the factors that reduce canister performance and the related development needs (copper corrosion in pure, oxygen-free water; development of the Copper Sulphide Model (CSM), copper corrosion at high chloride concentrations, the effect of nitrogen compounds from explosive residues on copper stress corrosion and microbial effects on canister performance) by examining the effects of these factors and development needs and their related uncertainties on the performance targets more clearly than what was presented in the construction licence application.
14. Posiva must continue the examination of the creep properties of copper and especially determine the effects of the creep mechanism, alloy materials and impurities (phosphorus, sulphur), temperature and stress levels.

Buffer, backfill and closure

15. Before submitting an operating licence application, Posiva must clarify the effects of the uncertainties related to the time needed to reach the intended buffer and backfill performance on the performance of the disposal system.
16. Posiva must present the expected performance of the closure structures of the disposal facility more clearly by the operating licence application stage.
17. Before submitting an operating licence application, Posiva must further specify the safety significance of the factors that impair the performance of the buffer, backfill and closure by examining the effects of these factors and their related uncertainties on the performance targets more clearly than what was presented in the construction licence application.

Spent nuclear fuel

18. Posiva has to continue the work on improving the reliability of the safety case by reducing the uncertainties related to the radionuclide release rate from the fuel matrix, the IRF and C-14 inventory and the release of IRF and C-14.
19. Posiva must continue the examination of the long-term development of the disposal canister geometry and examine the consequences of criticality before submitting an operating licence application.

Repository for low and intermediate level waste

20. Posiva must present more detailed plans on the future repository for low and intermediate

level waste of the disposal facility and a more specific assessment of the combined effects of the different types of nuclear waste intended to be disposed of in the facility before starting the construction of the repository for low and intermediate level waste.

21. Posiva must combine the effects from the disposal of low and intermediate waste into a scenario and safety analysis that covers the entire disposal facility and present in its safety case a more detailed assessment of the combined effects of the different types of nuclear fuel intended to be disposed in the facility. Posiva must also update the safety case in this regard and present it in connection with its operating licence application.

Safety functions and performance targets

Before submitting an operating licence application, Posiva must:

22. re-assess its approach to determining the safety functions and performance targets in order to clarify the safety case and to eliminate inconsistencies in the definitions of performance targets;
23. define each performance target based on a measurable or assessable characteristic of a barrier and include in each target a criterion that describes this characteristic in order to enable clear and unambiguous assessment of compliance with and reduction of the performance target;
24. present a clear and unambiguous connection between the barrier safety functions, performance targets and design requirements;
25. develop conceptual models that describe the safety functions and factors affecting them in order to enable more unambiguous assessment of compliance with the performance targets;
26. support compliance with the performance targets more unambiguously with the performance analysis for the barriers, especially taking into account the uncertainties related to the early development stage of the disposal system.

Scenario analysis

In connection with submitting an operating licence application, Posiva must:

27. present the scenarios as evolution schemes describing the potential future behaviour of the disposal system;
28. clarify the method of constructing scenarios so that it is easier to ensure that the scenarios are comprehensive in terms of the potential future developments of the disposal system;
29. present clearer justifications on selecting the specific scenarios for the safety case;
30. in the scenario analysis, demonstrate more systematic and comprehensive preparedness for the declined performance of the barrier safety functions, including those caused by barrier quality non-conformances (such as manufacturing and installation errors).

Development and reliability of the safety case

Posiva must:

31. conduct further sensitivity assessments comprehensively for calculations related to different scenarios and for the migration of radionuclides in the biosphere;
32. submit, in connection with its operating licence application, a clearer review of the effects of a failure of several disposal canisters, weighted by the probability of an earthquake, and a report on how the calculations are linked to the future development of the related disposal system. The report must more thoroughly present how the changing conditions due to ice sheet melting are conservatively taken into account in the calculations;
33. improve the structure and presentation of the safety case (clarity, transparency, traceability, consistency of the data) and present the conclusions in the safety case and their grounds more clearly, so that compliance with the safety requirements can be verified more easily in connection with the operating licence application;
34. submit to STUK all the reports for the safety case in connection with the operating licence application.

Director	Risto Paltemaa
Section Head	Jaakko Leino

Safety case for the disposal of spent nuclear fuel in Olkiluoto, presentation memorandum

General

On 28 December 2012, Posiva Oy (Posiva) submitted to the Government an application for the construction of a spent nuclear fuel encapsulation plant and disposal facility at Olkiluoto, Eurajoki.

In connection with the construction licence application for the Olkiluoto spent nuclear fuel encapsulation plant and disposal facility, Posiva submitted to the Radiation and Nuclear Safety Authority (STUK) for approval the safety case concerning the post-closure safety of disposal in accordance with the Government Decree on the Safety of Disposal of Nuclear Waste (736/2008) The Government Decree stipulates that compliance with the requirements concerning post-closure radiation safety of the disposal facility and the suitability of the disposal method and disposal site shall be proven through a safety case. The safety case compiles evidence, analyses and justifications on disposal in accordance with the safety requirements.

When reviewing the safety case, STUK has consulted several external experts on science and technology.

Posiva is a pioneer in the preparation and presentation of the safety case and the justifications of the post-closure safety of the disposal of spent nuclear fuel. Posiva has presented an extensive safety case and a vast number of research documentation and analyses that support the demonstration of post-closure safety. Posiva's safety case follows the best practices specified by IAEA and NEA. There are no general guidelines in terms of the documentation or structure of the safety case, but there is an international agreement on the key points of the safety case. The safety case must include a clearly presented safety concept and a comprehensive summary of the data and analyses. Posiva's presentation of the safety concept is clear, and the data and analyses are, in general, representative of the current international level.

Review of the safety case concerning post-closure safety

Based on STUK's review of the safety case documentation, the post-closure safety of the facility has been analysed in a sufficient manner for the purposes of the construction licence stage. The results demonstrate that, after the closure, the facility is safe to people and other living nature in the surroundings as required by the Government Decree. Furthermore, Posiva has indicated the suitability of the disposal method and disposal site in a sufficient manner for the purposes of the construction licence stage. The review shows, however, that there is a need to further improve the safety case by clarifying the safety arguments and the related methods and by reducing the uncertainties concerning the performance of barriers.

This presentation memorandum is based on a review of the safety case presented in Posiva's construction licence application and the related documents submitted to STUK. In addition to the presentation memorandum, the English-language document *Review report – post-closure safety case* shall be appended to the decision on the safety case. The review report of the safety case presents background information and details concerning the requirements in the presentation memorandum as well as a great deal of inspection observations. This presentation memorandum presents requirements for the most important safety aspects.

Legal justifications

Nuclear Energy Decree, Sections 35, 108 and 109; Government Decree 736/2008 and Guide YVL D.5

Decision proposal

I propose that STUK approve the safety case concerning the post-closure safety of the Olkiluoto encapsulation plant and disposal facility with the following requirements:

Characteristics and performance of the natural barrier

The Olkiluoto bedrock has been researched in diverse ways over the course of 25 years. The characterisation is sufficient for starting the construction of the disposal site. Characterisation must be continued as the construction project progresses to less researched parts of the disposal site. Posiva's description of the disposal site is based on the results of several different fields and methods of research, and combining the data to form an overall understanding requires further development efforts. The work on combining the results and model descriptions of different fields must be continued and deepened in order to improve the reliability of the safety case.

1. For improving the reliability of the safety case, STUK requires Posiva to progressively develop the combination of the results and model descriptions of different fields of research that are related to the characterisation and demonstration of performance of the natural barrier. This work must be completed before submitting an operating licence application.

One essential aspect of the performance analysis for the disposal site is assessing the impact of the future climate on the disposal system. The important and justified basis for the safety case is formed by the information on Weichselian glaciation and interpretations of the previous glacial stages. The description of future climate evolution based on different observations and model calculations is sufficient for the purposes of the construction licence stage. The coverage of the future climate evolution model can be extended by varying the timing, durations and conditions of the warm and cold climate periods that are used as the initial data for the evolution model. Similarly, the performance analyses must consider how the disposal system as a whole performs under different mechanical, hydrostatic, thermal and chemical load conditions and under the varying conditions of alternative evolutionary possibilities.

2. Before submitting an operating licence application, Posiva must evaluate, in more detail, the alternative possibilities of climate evolution and their impact on the disposal system.

Suitability of the disposal site

An essential part of the description of the disposal site, in the safety case, is based on the interpretations of the performance analyses with regard to suitability and performance of the site. The analyses are based on observations and interpretations of the characteristics and paleohydrogeology of the disposal site as well as assessments of the long-term future development of the site.

Already at an early development stage of the KBS-3 concept, Posiva presented targets for the long-term performance of the bedrock, which are based on ensuring the performance of the engineered barriers. Posiva's performance analysis of the bedrock demonstrates, in a manner sufficient for the purposes of the construction licence stage, that the expected long-term future development of the characteristics deemed favourable in the rock surrounding the disposal repositories is stable and foreseeable and that the engineered barrier based performance targets that Posiva has established for the bedrock will be met with a high degree of certainty.

The disposal facilities must be constructed and closed in a way that maintains the rock characteristics favourable to long-term safety. The purpose is that any disturbance to the host rock caused by construction remains controlled and in accordance with the set design requirements so that the anticipated mechanical, geochemical and hydrogeological conditions are maintained favourable to the engineered barriers during construction and that they start, within reasonable time after the closure, developing towards the baseline characteristics which occurred before construction work in the bedrock. Posiva presents this purpose on a general level in the safety concept of the KBS-3 method but does not unambiguously discuss the role of the rock surrounding the disposal facilities or how it maintains its characteristics in terms of the safety functions or performance targets. There must be dependencies for the surrounding rock characteristics that should be maintained and the design requirements, and they must be used for justifying the limits for acceptable disturbances during construction and operation. Posiva must also demonstrate that the anticipated mechanical, geochemical and hydrogeological characteristics that are favourable to the engineered barriers are maintained within their set limits during construction and that they start, after the closure, developing towards the baseline conditions which occurred before construction work.

3. Before starting the construction of the deposition tunnels and deposition holes, Posiva must present, based on the performance analysis of the bedrock, the relationships between the design requirements and the surrounding rock characteristics that should be maintained. The relationships must indicate how (mechanical, geochemical and hydrogeological) disturbances to the host rock from construction are controlled and maintained within the set design requirements and how the rock can be expected, when the design requirements are met, to maintain its favourable characteristics in the long term.

During the excavation of the underground research facilities, Posiva has gathered information on the stability of the Olkiluoto bedrock. Based on this information, Posiva expects the stability of the rock surrounding the deposition tunnels and deposition holes to be sufficient. However, there are still uncertainties in understanding the rock stresses of the baseline bedrock and the stress measurement results. Posiva must reduce these uncertainties before starting the construction of the disposal facilities (central tunnels, deposition tunnels), as rock stresses and stability are essential factors that guide design and construction work. Furthermore, additional clarifications will be needed on the effects that the heterogeneity of the rock has on stability as well as a better understanding of the rock mechanical properties of the brittle deformation zones in different scales.

4. Posiva must expand its current measurement data on rock stresses and prepare more specific interpretations of the baseline stresses of the rock before starting the construction of the disposal facilities. Furthermore, the research on rock stresses and stability and the related development measures must be continued during construction.

Posiva argues for the low seismic activity of the bedrock in the Fennoscandian Shield with historical and measurement data. The materials support the assumptions that the Olkiluoto bedrock is seismically stable and that the likelihood of an earthquake that would damage a disposal canister is very low. Posiva's seismic surveys are sufficient for the purposes of the construction licence stage, but they must be expanded in order to improve the reliability of the safety case. The seismic risk must be examined more thoroughly by taking into account the structures of the Olkiluoto bedrock and their properties in more diverse ways and by more extensively evaluating the earthquake magnitudes and frequencies under different geological conditions. The assessment of the seismic risk regarding the disposal system must be expanded by conducting probabilistic consequence analyses that more comprehensively take into account the mechanisms of earthquake initiation and propagation as well as the spreading of displacements into the surrounding deformation structures.

Posiva generalises large and small brittle deformation zones as individual surfaces. Posiva must also examine modelling methods that describe rock fragmentation in a more non-uniform and empirical manner. Changing the examination method may affect, for instance, interpretations of earthquake magnitudes, respect distances from brittle deformation zones and assumptions made on the individual critical sizes of fractures. Posiva must also analyse in more detail the effects of temperature increases on the stability of the bedrock during the operation and after the closure of the disposal facility. The thermal load generated by disposed spent nuclear fuel may affect the stability and water conductivity of the rock.

5. Posiva must expand its seismic studies and include the results of further examinations in its operating licence application for the disposal facility, at the latest. The coverage of the survey material must also be expanded during operation. The effects of earthquakes must also be examined under varying isostatic load conditions (such as ice ages).

Posiva presents the tightness of the Olkiluoto bedrock and rock classification system to demonstrate the low flow of bedrock groundwater around the disposal facilities. Posiva states that, with this system, it is able to identify the tight sections of the rock that are suitable for disposal. While the current presentations of the rock tightness and the low groundwater flow are sufficient, Posiva will need to compile a clear overview of the flow model for bedrock groundwater, its compatibility with the geological models and the data used for the models. Due to the hydraulic characteristics of the disposal site bedrock and the hydrogeological disturbances caused by excavation, there are uncertainties in the characterisation methods. Therefore, the reliability of the measurement methods must be verified. In connection with the different research and implementation stages of the disposal facilities, Posiva must systematically ensure that the intended and completed deposition tunnels meet the applicable requirements.

The reliability of fracture network modelling must be verified during construction by comparing the hydrogeological modelling results of the disposal facilities with the information obtained from completed tunnels. There are alternative modelling methods available that take into account water-conducting rock heterogeneity in brittle deformation zones. Such alternative methods should be examined for verifying the reliability of the selected modelling method, at the minimum. Different modelling methods may lead to, for example, disposal facilities that are drier than currently expected or individual water flow channels that have a smaller fracture surface but that enable high flows.

6. Posiva must present a plan for verifying the reliability of fracture network modelling before starting the construction of the disposal facilities. The assessment of the hydrogeological disturbances from excavation, assessment of measurement methods and preparation of modelling data reporting must be started after a construction licence is issued. Further justifications for the selected modelling method and an assessment of its reliability must be presented by the operating licence application stage, at the latest.

Posiva has presented plausible justifications on the favourable chemical properties of groundwater at the disposal depth. The hydrogeochemical characterisation of the Olkiluoto bedrock in its baseline conditions and the interpretation of the development of palaeohydrogeochemistry are Posiva's strongest arguments for the stability of the rock surrounding the disposal repositories. Posiva's safety case also includes estimates of the development of salinity in the next 50,000 years. In terms of the dilution of groundwater in the rock surrounding the disposal facilities, these developments seem overly pessimistic as they ignore the interaction between water and rock during surface water infiltration. Posiva must further specify and improve the description of hydrogeochemical development. Additionally, Posiva must improve its understanding of how the disturbances from construction are restored to normal after sections of the facility are closed. One important area of groundwater chemical stability that requires further examination is connected with the reasons that cause discrepancies between chemical composition of bedrock porewater and bedrock groundwater in the brittle deformation zones.

7. Posiva must demonstrate sufficient consistency between the hydrogeochemical and hydrogeological interpretations by the operating licence application stage, at the latest.

It is the considered opinion of Posiva that Olkiluoto is not a future area of interest in terms of natural resources. Posiva's justification is sufficient for the construction licence stage. In the documentation for the operating licence application, the reporting concerning natural resources must be clarified and updated as more data become available on the geological properties of the area.

8. Posiva must further specify its justifications regarding the conclusions on natural resources in Olkiluoto in connection with its operating licence application for the facility, at the latest.

Positioning of disposal facilities

When selecting suitable blocks of bedrock and verifying the adequate quality of the rock surrounding the disposal facilities, Posiva uses a rock classification system with specific criteria and verification methods defined for the scales of the repository, panel area, deposition tunnels and deposition holes. Verification of compliance and approval take place gradually. Posiva has prepared guidelines for the classification system, which are followed in the suitability assessment of the first deposition tunnels and deposition holes. It is essential to evaluate the reliability of the rock classification system during and after the construction of the first stage of the disposal facility and to consider the experiences gained in the further development of the system. For example, further development is needed in the classification criteria for different scales and construction stages and in the prediction-outcome procedure. Posiva must finish the procedures for the assessment process and present more specific plans on the further development of the rock classification system before starting the construction. The entire rock classification system will be re-evaluated in connection with reviewing the operating licence application.

The current classification particularly emphasises the mechanical stability and low groundwater flow despite construction of the bedrock blocks selected for disposal. Posiva must assess during the first construction stage of the disposal facility whether the classification system addresses the observable parameters of the deposition tunnel that have significance to post-closure safety. Posiva must also clarify the relationship between the rock classification criteria and the characteristics that should be maintained in the rock surrounding the repository. Furthermore, Posiva must present more specific justifications on determining the respect distances from structures that limit the positioning of the disposal facility and from the extensive individual fractures.

9. Before starting the construction of the disposal facilities, Posiva must supplement the rock classification guidelines as necessary for taking into account Requirement 3. Furthermore, before starting the construction of the disposal facilities, Posiva must present a plan on the procedures for evaluating the reliability of the classification and plans on the further development of the classification.
10. Before starting the construction of the disposal facilities, Posiva must further specify the approval procedures related to the rock classification to cover the different stages of construction, including pilot hole studies.
11. During the construction of the first deposition tunnels, Posiva must evaluate the extent of the rock classification criteria and the performance of the procedure and append a report on the evaluation to the operating licence application.

Disposal canister

Posiva has been developing manufacturing technologies for disposal canisters since the 1990s. Posiva has mainly focused on developing manufacturing technologies for the reference canister type (BWR). By the construction licence stage, Posiva has manufactured canister components that meet the initial mechanical and quality requirements (copper overpack and cast iron insert for BWR bundles).

12. Posiva must continue its work on the disposal canister manufacturing methods in order to enable the manufacture of components that meet the requirements for both BWR and VVER type canisters before submitting an operating licence application.

The safety function of the disposal canister presented in the safety case is based on the mechanical durability of the insert and the chemical durability of the copper overpack. Posiva has presented conditions and events that impact the performance of the canister and related reports as development needs in terms of the integrity of the disposal canister. Such development needs presented by Posiva include:

- copper corrosion in pure, oxygen-free water;
- development of the Copper Sulphide Model (CSM);
- copper corrosion at high chloride concentrations;
- the effect of nitrogen compounds from explosive residues in Onkalo on copper stress corrosion; and
- microbial effects on canister performance.

Of the factors that Posiva has identified, the development of the CSM and the adverse effects of microbial activity and nitrogen compounds from explosive residues on the canister safety function are especially significant in terms of canister performance and thereby post-closure safety. These factors can affect and thereby compromise the integrity of each canister.

Other threats to disposal canister integrity include damaging of the copper overpack due to plastic deformation and/or creep. Posiva has studied the creep properties of copper with tests and modelling. The creep mechanism of the canister copper under the varying temperatures and stress conditions in the disposal facility or the effect of phosphorus alloy on copper creep are not known well enough.

The safety significance of the factors that affect the performance of barriers must be further specified by examining the effects of these factors and their related uncertainties on the performance targets more clearly than what was presented in the construction licence application.

13. Before submitting an operating licence application, Posiva must assess in more detail the safety significance of the factors that impair canister performance and the related development needs (copper corrosion in pure, oxygen-free water; development of the Copper Sulphide Model (CSM), copper corrosion at high chloride concentrations, the effect of nitrogen compounds from explosive residues on copper stress corrosion and microbial effects on canister performance) by examining the effects of these factors and development needs and their related uncertainties on the performance targets more clearly than what was presented in the construction licence application.
14. Posiva must continue the examination of the creep properties of copper and especially determine the effects of the creep mechanism, alloy materials and impurities (phosphorus, sulphur), temperature and stress levels.

Buffer, backfill and closure

Posiva has identified conditions and events (incidental deviations) that impair the performance of the buffer and backfill and that may affect post-closure safety. Such incidental deviations include reduction of sulphate to sulphide, which causes corrosion of the canister overpack, in low-density areas due to insufficient homogenisation of backfill, and chemical erosion of the buffer due to infiltrated meteoric or glacial water, which may reduce the buffer density in some deposition holes.

In addition to the incidental deviations identified by Posiva, the possible factors that impair the performance of the buffer and backfill may include the following, for example:

- mineralogical transformation of montmorillonite clay in the disposal groundwater conditions;
- microbial activity that may contribute to formation of sulphide, which causes canister corrosion, and dissolution of montmorillonite;
- piping erosion due to groundwater flow from the disposal hole to the disposal tunnel; and
- cementation of the buffer, which may, for example, reduce its plasticity and swelling properties.

Of these factors, microbial activity and the mineralogical transformation of montmorillonite are especially significant in terms of buffer and backfill performance because their effects that impair the performance of the barrier safety functions may affect each deposition tunnel and deposition hole. These factors can affect each canister, thereby accelerating their loss of integrity. If piping erosion occurs, even if it affects just a part of the deposition holes, it may be a significant factor that impairs the buffer and canister performance because it takes place at the early stage of disposal, which enables it to have a significant effect on the later development of the surroundings of the deposition holes. Cementation of the buffer is a key factor when evaluating the possible effects of rock displacement from seismic activity on the mechanical durability of canisters. There are significant uncertainties related to the time needed to reach the intended buffer and backfill performance, and their effects on the performance targets must be examined more clearly and in more detail.

Although the implementation of closure is not relevant for several decades, Posiva must establish a better understanding of the expected behaviour of closure as part of the disposal system.

The safety significance of the factors that affect the performance of barriers must be further specified by examining the effects of these factors and their related uncertainties on the performance targets more clearly than what was presented in the construction licence application.

15. Before submitting an operating licence application, Posiva must clarify the effects of the uncertainties related to the time needed to reach the intended buffer and backfill performance on the performance of the disposal system.
16. Posiva must present the expected performance of the closure structures of the disposal facility more clearly by the operating licence application stage.

17. Before submitting an operating licence application, Posiva must further specify the safety significance of the factors that impair the performance of the buffer, backfill and closure by examining the effects of these factors and their related uncertainties on the performance targets more clearly than what was presented in the construction licence application.

Spent nuclear fuel

The release of radionuclides from a fuel element is a parameter significant to the assessment of safety. There are still uncertainties concerning this parameter and the instant release fraction (IRF) inventory, C-14 inventory and radionuclide release, which have a significance in terms of assessing safety reliably.

18. Posiva has to continue the work on improving the reliability of the safety case by reducing the uncertainties related to the radionuclide release rate from the fuel matrix, the IRF and C-14 inventory and the release of IRF and C-14.

The design of the disposal canister takes into account the requirements for the criticality safety of spent nuclear fuel. The post-closure criticality safety of the disposed fuel has been demonstrated through conservative criticality analyses in a manner sufficient for the purposes of the construction licence. Posiva's criticality safety analyses cannot entirely rule out the criticality of a disposal canister on a long time span. In this respect, the analyses use highly conservative assumptions on the development of the disposal canister geometry in the long term. Therefore, recriticality of disposed fuel seems to be very unlikely.

19. Posiva must continue the examination of the long-term development of the disposal canister geometry and examine the consequences of criticality before submitting an operating licence application.

Disposal of low and intermediate level waste

In addition to spent nuclear fuel, the disposal facility includes repositories for low and intermediate level waste generated during the operation and decommissioning of the encapsulation plant. The documentation that Posiva has submitted to STUK discusses the processing, disposal and post-closure safety of disposal of low and intermediate level waste in three different reports. The aspects presented in the report are not connected to the actual safety case of the disposal of spent nuclear fuel.

Posiva's construction licence application documents do not indicate the calculated combined annual post-closure radiation doses and activity releases for the entire disposal facility. Posiva's performance analysis for the disposal site does not include the disposal facility for low and intermediate waste, which will be constructed along the access tunnel. The dose and release limits presented in Government Decree 736/2008 apply to all nuclear waste disposed of in one disposal facility. The repositories for spent nuclear fuel and low and intermediate level waste must be discussed as a whole because of their potential interaction due to the chemical changes in groundwater or thermal change from spent nuclear fuel, for example. Therefore, the different types of repositories that are located in one facility do not have individual dose and release limits. Instead, compliance with the requirements by the authorities must be demonstrated for the entire disposal facility, and the potential interaction between the repositories and the related uncertainties must be evaluated in a scenario and safety analysis that covers the entire disposal facility. Posiva has supplemented its construction licence application with the report POSIVA-STUK-10290, 27 August 2014 by presenting initial examinations of the disposal and post-closure safety of low and intermediate level waste.

20. Posiva must present more detailed plans on the future repository for low and intermediate waste of the disposal facility and a more specific assessment of the combined effects of the different types of nuclear waste intended to be disposed of in the facility before starting the construction of the disposal repository for low and intermediate level waste.
21. Posiva must combine the effects from the disposal of low and intermediate waste into a scenario and safety analysis that covers the entire disposal facility and present in its safety case a more detailed assessment of the combined effects of the different types of nuclear waste intended to be disposed of in the facility. Posiva must also update the safety case in this regard and present it in connection with its operating licence application.

Safety functions and performance targets

According to Government Decree 736/2008, the post-closure safety of disposal must be based on safety functions of mutually complementary barriers, and the safety functions shall effectively prevent releases of disposed radioactive materials into the bedrock. Safety functions refer to factors preventing and limiting the releases and migration of disposed radioactive materials.

In its construction application licence documents, Posiva has presented the purposes of the barriers and specified their safety functions. The safety functions presented by Posiva describe, on a general level, the purpose of each barrier as well as the functions for isolation and for preventing and limiting radionuclide releases.

Each safety function must have performance targets based on high-quality scientific knowledge and expert judgement. The targets refer to a characteristic that can be measured or assessed, and a safety function is considered fulfilled if the criterion of the target is met. Posiva has set the performance targets for the safety functions but does not clearly present the method of deriving the performance targets. Not all Posiva's performance targets have been defined based on a characteristic of a barrier that can be measured or assessed. Most of the performance targets are missing a criterion that describes the characteristic.

Posiva's performance analysis for the barriers must support the set performance targets more specifically based on clear justifications and especially criteria. More unambiguous performance targets also enable the justification and assessment of the uncertainties related to the development of the disposal system.

A systematic and comprehensive preparedness for developments that deviate from the expected evolution requires forming a clear view of the possible declined performance of the safety functions and the extent of such declined performance. Posiva's documentation does not clearly demonstrate preparedness for the declined performance of different safety functions.

In order to assess compliance with the performance targets more specifically, further work is needed on the definitions of the safety functions and the conceptual models that describe the safety functions and the factors affecting them. The conceptual models are essential also when establishing a clearer understanding of the extent to which the safety functions are impaired outside the operating range indicated by the performance target criteria.

There are design requirements set for engineered barriers, which, according to Posiva, are derived from the performance targets for the safety functions. However, the connection between the design requirements and the performance of the barriers is not presented unambiguously.

Before submitting an operating licence application, Posiva must:

22. re-assess its approach to determining the safety functions and performance targets in order to clarify the safety case and to eliminate inconsistencies in the definitions of performance targets;
23. define each performance target based on a measurable or assessable characteristic of a barrier and include in each target a criterion that describes this characteristic in order to enable clear and unambiguous assessment of compliance with and impairment of the performance target;
24. present a clear and unambiguous connection between the barrier safety functions, performance targets and design requirements;
25. develop conceptual models that describe the safety functions and factors affecting them in order to enable more unambiguous assessment of compliance with the performance targets;
26. support compliance with the performance targets more unambiguously with the performance analysis for the barriers, especially taking into account the uncertainties related to the early development stage of the disposal system.

Scenario analysis

Posiva has defined the scenarios as developments that may lead to the failure of disposal canisters and release of radionuclides.

Posiva has established the base scenario for the repository system with the assumption that one or a few disposal canisters suffer initial damage while other barriers perform as expected and in compliance with the performance targets set for their safety functions. The variant scenarios are established based on incidental deviations identified by Posiva that lead to a release of radionuclides, and the disturbance scenarios are established by taking into account the unlikely disruptive events impairing post-closure safety as per the requirements of Guide YVL D.5. Posiva has established the surface environment scenarios for the first 10,000 years independently of the repository system scenarios.

Based on the scenarios, STUK finds that Posiva is not unambiguously prepared for quality non-conformances that impair the performance of the barrier safety functions except for the disposal canister (initial hole penetrating the overpack).

Posiva's variant and disturbance scenarios do not explore systematically and comprehensively enough the possibility that one or more performance targets are not met. Furthermore, based on Posiva's method of constructing scenarios, it cannot be ensured that Posiva is sufficiently prepared for all possible developments of the disposal system that are significant in terms of assessing safety.

In connection with submitting an operating licence application, Posiva must:

27. present the scenarios as evolution schemes describing the potential future behaviour of the disposal system;
28. clarify the method of constructing scenarios so that it is easier to ensure that the scenarios are comprehensive in terms of the potential future developments of the disposal system;
29. present clearer justifications on selecting the specific scenarios for the safety case;
30. in the scenario analysis, demonstrate more systematic and comprehensive preparedness for the declined performance of the barrier safety functions, including those caused by barrier quality non-conformances (such as manufacturing and installation errors).

Development and reliability of the safety case

Posiva's safety analysis is based on deterministic calculations but supplemented with a probabilistic sensitivity assessment. The sensitivity assessment has been conducted for a select group of calculations that discuss the release of radionuclides and their migration in the bedrock. The sensitivity assessment identifies the most significant parameters of the safety analysis, and the assessment is sufficient for the construction licence stage. Further sensitivity assessments must be conducted more comprehensively for calculations related to different scenarios and for the migration of radionuclides in the biosphere.

According to STUK's request, Posiva has supplemented its construction licence application with the report POSIVA-STUK-10270, 3 July 2014. STUK requested more information on a consideration of the effects of a failure of several disposal canisters, weighted by the probability of an earthquake. Posiva has linked its consideration to a probabilistic earthquake assessment, but the probabilities presented are not sufficiently justified. In this respect, Posiva's report cannot be considered sufficient. Posiva must present a clearer examination of the failure of several canisters, taking into account the rapidly changing geological conditions due to ice sheet melting.

Posiva's data and quality management procedures have improved the reliability of the safety case. However, there are inconsistencies in the initial data for the materials that have been compiled at different stages. Therefore, the consistency of the initial data in the analyses must be improved, for example by "freezing" the initial data at a sufficiently early stage, so that they are consistent in the safety case that is submitted in connection with the operating licence application. In general, the reliability of the initial data and models is sufficient for the construction licence stage.

While Posiva's safety case can be deemed reliable, it requires further development. The summary of the safety case must present a more understandable and unambiguous description of the evolution of the barriers, identification of the parameters with the highest safety significance and the barriers that have the most significance on the calculated safety assessment, and a summary of the uncertainty analysis. Furthermore, comparing these with the concept development programme will facilitate assessing the reliability of the safety case.

The structure and presentation of the safety case require further development in order to better demonstrate compliance with the safety requirements.

In the safety case, Posiva does not always state its own position explicitly on safety-related matters or provide grounds for its choices. Posiva must present its conclusions and their grounds more clearly. The references in the safety case must be clear, and the material referred to must be available for access by the time Posiva submits an operating licence application.

Based on the review, the reliability of the safety case is sufficient for the construction licence stage. However, the performance and safety analysis require further development in order to further improve the reliability of the safety case. Posiva must:

31. conduct further sensitivity assessments more comprehensively for calculations related to different scenarios and for the migration of radionuclides in the biosphere;
32. submit, in connection with its operating licence application, a clearer review of the effects of a failure of several disposal canisters, weighted by the probability of an earthquake, and a report on how the calculations are linked to the future development of the related disposal system. The report must more thoroughly present how the changing conditions due to ice sheet melting are conservatively taken into account in the calculations;
33. improve the structure and presentation of the safety case (clarity, transparency, traceability, consistency of the initial data) and present the conclusions in the safety case and their grounds more clearly, so that compliance with the safety requirements can be verified more easily in connection with the operating licence application;
34. submit to STUK all the reports for the safety case in connection with the operating licence application.

Hearing

A hearing on the content of the decision and the set deadline took place by an e-mail to Posiva's Samu Myllymaa, Vesa Ruuska and Tiina Jalonen on 30 January 2015. Based on the response to the hearing, Posiva wishes to discuss the requirements with STUK and together agree on the criteria for compliance with each requirement, as some requirements of the decision on the safety case are very general in nature. Furthermore, Posiva has proposed changes to the following requirements (marked with strikethrough and bold formatting):

Suitability of the disposal site

3. Before starting the construction of ~~the disposal facilities~~ **deposition tunnels and deposition holes**, Posiva must present, based on the performance analysis of the bedrock, the relationships between the design requirements and the surrounding rock characteristics that must be maintained. The relationships must indicate how (mechanical, geochemical and hydrogeological) disturbance to the host rock from construction is controlled and maintained within the set design requirements and how the rock can be expected to maintain its favourable characteristics in the long term when the requirements are met.

Posiva proposes that, based on a telephone conference on 5 February 2015, Posiva must present the reports as per the requirement after the construction of the central tunnels. In Posiva's understanding, the requirement refers to constructing the disposal facilities with minimal disturbance so that the conditions can develop towards their normal state after the construction.

The proposed change has been approved.

4. Posiva must expand its current measurement data on rock stresses and prepare more specific interpretations of the stresses of the rock in its normal state before starting the construction of the ~~disposal facilities~~ **deposition tunnels and deposition holes**. Furthermore, the research on rock stresses and stability must be the subject of continuous research and development during construction.

Posiva proposes a limitation similar to that in Requirement 3. "Before starting the construction of the deposition tunnels and deposition holes, in order to obtain more research data on the central tunnels."

Furthermore, Posiva must conduct additional rock stress measurements even before starting the construction of the central tunnels. As the excavation of the central tunnels limits the location of the panel, it is important to establish a sufficient understanding of the rock stresses in the area already before starting the excavation of the central tunnels.

6. Posiva must present a plan for verifying the reliability of fracture network modelling, **which is potentially used for demonstrating the suitability of the facilities,** before starting the construction of the disposal facilities. The assessment of the effects of excavation, assessment of the hydrogeological measurement methods and prepa-

ration of initial data reporting must be started immediately after a construction licence is issued. Further justifications for the selected modelling method and an assessment of its reliability must be prepared by the operating licence application stage, at the latest.

Posiva proposes that, for clarity, the underlined sentence is made into a separate requirement, which explicitly concerns the Excavation Damage Zone (EDZ). Furthermore, the remaining two sentences should be combined and the bolded sections added because Posiva has not decided whether it will use fracture network modelling for demonstrating the suitability of the facilities.

The requirement has been revised for clarity.

8. STUK expects an update regarding the reports on natural resources in Olkiluoto **and their justifications** in connection with Posiva's operating licence application for the facility, at the latest.

Posiva proposes the above wording for clarifying that the requirement concerns the justifications in particular.

The requirement has been revised for clarity in this respect.

Positioning of disposal facilities

9. Before starting the construction **of the disposal facilities**, Posiva must supplement the rock classification guidelines as necessary for taking into account Requirement 3. Furthermore, before starting the construction **of the disposal facilities**, Posiva must present a plan on the procedures for evaluating the reliability of the classification and plans on the further development of the classification.

Posiva proposes the above additional wordings for further specifying the requirement. The stages of the Rock Suitability Classification procedure also cover the initial construction stages, including the pilot hole studies for central tunnels (= 1st stage of panel construction), as described in the RSC guidelines submitted to STUK.

10. The approval procedures related to the rock classification must also be staged to cover the initial construction stages, including the pilot hole studies, and the classification criteria must be further specified, demonstrating their connection with rock characteristics favourable to long-term safety that must be maintained. The revised rock classification system will be re-evaluated by the operating licence application stage.

This requirement should reference Requirement 9.

Requirements 9 and 10 have been revised. They are replaced by Requirements 9, 10 and 11.

Canister

11. Posiva must continue its work on the disposal canister manufacturing methods in order to enable the manufacture of components that meet the requirements for both BWR and VVER type canisters before submitting an operating licence application.

Posiva proposes no changes to this requirement. The sentence structure may be clarified as above.

The requirement has been revised in this respect.

13. Posiva must continue the examination of the creep properties of copper, and the effects of the creep mechanism, alloy materials, temperature and stress levels on creep.

Posiva proposes specifically listing phosphorus as an alloy material and sulphur as impurity.

The requirement has been revised in this respect.

Buffer, backfill and closure

Before submitting an operating licence application, Posiva must:

14. clarify the effects of the uncertainties related to the time needed to reach the intended buffer and backfill performance on the performance targets;

In Posiva's understanding, this refers to the saturation of the buffer and backfill, and Posiva requests a clarification in this respect.

The requirement has been revised for clarity in this respect.

Disposal facility for low and intermediate level waste

Posiva must:

19. present more detailed plans on the future repository for low and intermediate waste of the disposal facility and a more specific assessment of the combined effects of the different types of nuclear waste intended to be disposed of in the Posiva facility before starting the construction **of the**

disposal repository for low and intermediate level waste;

Posiva proposes adding the above wording.

The requirement has been revised for clarity in this respect.

Safety functions and performance targets

21. re-assess its approach to determining the safety functions and performance targets in order to clarify the safety case and to eliminate inconsistencies in the definitions of performance targets;

Posiva has no comments on this requirement. However, Posiva wants an active dialogue regarding Requirements 21–25. The requirements of the relevant YVL Guides could be clarified in this respect in connection with a possible revision of the YVL Guides.

A dialogue will be initiated with Posiva regarding these requirements.

Scenario analysis

26. present the scenarios as evolution schemes describing the potential future behaviour of the disposal system;

Posiva proposes no changes to this requirement. However, Posiva wants an active dialogue regarding Requirements 26–29 especially during the planning of the TURVA-2020 project.

A dialogue will be initiated with Posiva regarding these requirements.

29. in the scenario analysis, demonstrate more systematic and comprehensive preparedness for the declined performance of the barrier safety functions, including those caused by barrier quality non-conformances.

Posiva proposes no changes to this requirement. Here, Posiva wants an active dialogue on the meaning of "more systematic and comprehensive preparedness". In Posiva's understanding, it must provide a better description of which cases are included in which scenario, i.e. which types of quality non-conformances must be considered in the scenario analyses.

Development and reliability of the safety case

30. conduct further sensitivity assessments comprehensively for calculations related to different scenarios and for the migration of radionuclides in the biosphere;

Posiva proposes no changes to this requirement. However, Posiva wants an active dialogue regarding Requirements 30–36 especially during the planning of the TURVA-2020 project.

A dialogue will be initiated with Posiva regarding these requirements.

32. improve the structure and presentation of the safety case, so that compliance with the safety requirements can be verified more easily by the operating licence application stage;

Posiva requests a clarification of "safety requirements" in this context.

The request has been revised for clarity, and Requests 32, 33, 34 and 36 have been combined.

35. ~~complete~~ submit all the reports for the safety case for approval ~~before submitting~~ in connection with submitting an operating licence application, at the latest; and

Posiva proposes the above changes in wording for clarity.

The requirement has been revised in this respect.

The draft decision and presentation memorandum have been submitted for a hearing on 9 February 2015 regarding the changes (to Requirements 6, 9, 10 and 11). In the second hearing, Posiva had no comments on the content of the decision.

Jaakko Leino

1 Introduction

In December 2012, Posiva Oy (Posiva) submitted the spent nuclear fuel encapsulation and disposal facility construction licence application (CLA) to the Finnish Government and the related technical documentation to Radiation and Nuclear Safety Authority of Finland (STUK). Posiva has spent many years carrying out RD&D on the so-called KBS-3 concept for spent fuel disposal and proposes to use this method and the engineered barriers that it comprises at the Olkiluoto site. Part of Posiva's RD&D has been the detailed investigation and characterisation of the Olkiluoto site, including the construction of a major underground research and characterisation facility (ONKALO), which now gives access to rock volumes at depth that are proposed to be used for disposal. Posiva is thus now preparing to move to the next stage of its project, which is to begin construction of the actual disposal facilities underground. An important part of the CLA technical documentation is a post-closure safety case that includes a demonstration of post-closure safety for up to 1 000 000 years after repository closure. A safety case is a formal compilation of evidence, analyses and arguments that quantify and substantiate a judgement that the repository will be safe.

Government Decree 736/2008 sets the safety target for geological repositories in Finland. STUK's Guide YVL D.5 sets the regulatory requirements for implementing the government decree.

STUK has reviewed the safety case documentation and argumentation presented by Posiva and reached conclusions on the adequacy and fitness of Posiva's submission, considering the stage at which the spent fuel disposal programme has currently reached. A specific focus of our review has been to ensure that the safety case for the repository follows the structure and intent of the regulatory requirements and is sufficiently developed and convincing to allow construction of disposal facilities at Olkiluoto. At this stage, we need to be confident that it will be feasible to construct the facility and that it will meet our safety requirements. It is expected that Posiva will continue to develop its safety case, with an update to be presented to STUK in several year time.

To assist in our review of the CLA safety case STUK has engaged several consultants with expertise in various disciplines and formed three review areas: (1) Disposal site and natural barrier, (2) Engineered barriers system (EBS) and (3) Safety assessment. A key consultant from each area compiled a consolidated review report from each review area. The current report presents STUK's view on the above matters, based on review findings from STUK's personnel and supported by the consolidated review reports.

Posiva's safety case consists of 14 TURVA-2012 portfolio main reports and 7 supporting reports, together with and a much larger set of supporting references. STUK held workshops with consultants during the review and some workshops also involved meeting with Posiva staff aimed at obtaining clarifications on certain selected topics. Based on our findings during the review STUK sent several request for additional information to Posiva.

Along with SKB in Sweden, Posiva is a forerunner in arguing that a repository for spent nuclear fuel in crystalline basement rocks will be safe. Both organisations have adopted the same, KBS-3 disposal concept (with much common development work), and both have compiled and presented a post-closure safety case to their national regulatory authorities within a year of each other. The two safety cases have many common features, but are by no means identical, as significantly different approaches have been taken to several important topics. Both organisations have been centrally involved in international efforts to develop the underlying principles of safety cases for geological disposal, as well as common understanding of appropriate terminology and methodologies.

Based on our review, STUK concludes that Posiva provides, overall, a clear and credible case that the proposed repository will be safe and will meet our regulatory requirements. The safety case is also in accordance with international best practices. Posiva makes clear presentation of the safety concept and the technical data and the analyses are, in general, state-of-the-art. However, in STUK's opinion there remains a need to develop safety argumentation and methodologies further, and there is also a need to reduce some uncertainties regarding performance of the barriers.

Posiva's safety case should be forward-looking and further developed in each licensing phase. As discussed in our overall recommendations, we expect the broad matters identified above to be addressed, along with numerous matters of detail, in the safety case that Posiva will present as part of its operating licence application, in several years time. This will have to be fully compliant with all our requirements before a license can be granted to dispose of any spent fuel.

2 Disposal concept and general principles

2.1 General principles

2.1.1 Safety strategy/concept

Government Decree 736/2008 and Guide YVL D.5 require that nuclear waste disposal shall follow the principle of the multibarrier system which is an application of the defence-in-depth principle in post closure safety field. YVL D.5 sets regulatory requirements for a disposal method that would meet the safety expectation. According to YVL D.5 when planning the disposal of radioactive waste and spent fuel, the waste matrix, waste package, buffer, emplacement room backfill and disposal facility closure structures at least shall be considered as engineered technical barriers. The bedrock surrounding emplacement rooms shall serve as the natural barrier.

Posiva has described the safety principles and safety concept of spent fuel disposal in the safety case synthesis (Posiva 2012-12). The principles involve the multibarrier system that is composed of engineered barriers (canister, buffer, tunnel backfill and plugs and closure) and host rock. Posiva has not included the spent nuclear fuel (SNF) as part of the barrier system although the slow release rate from the spent fuel matrix is one part of the safety concept and the dissolution rate of UO_2 is one important feature in the safety assessment. Posiva has however described the characteristics that SNF is expected to have. The role of SNF is discussed in more detail in Section 3.1. The safety functions of the barriers are discussed in Section 2.2 and the different barriers in Sections 3 and 4.

Posiva's safety concept aims primarily for long-term isolation and containment of SNF and secondarily for retention and retardation of radionuclides in case canisters leak. Containment by the canister is anticipated to be the principal safety objective of the KBS-3 concept. The long-term integrity of the canister, however, relies on the ability of the buffer to provide protection for the canister, whose performance can in turn depend on the backfill and tunnel plugs. The host rock has an important role in creating and maintaining favourable and foreseeable bedrock and groundwater conditions. The host rock is also expected to retard radionuclide transport to the surface environment. The depth of the disposal facility is chosen to mitigate impacts from natural phenomena on the ground surface and human actions.

Posiva's post colure safety case portfolio that contains the design basis, description of the disposal system, description of features, events and processes (FEPs), performance assessment, formulation of radionuclide release scenarios, models and data for the repository system, biosphere data basis and assessment of radionuclide release scenarios, biosphere assessment, complementary considerations and synthesis of the safety case. In addition to this Posiva has submitted to STUK a preliminary safety analysis report (PSAR) which describes design, construction, operation, closure and operational safety of the encapsulation plant and disposal facility.

Posiva's safety case portfolio does not describe the safety of the low- and intermediate-level (LILW) disposal vaults that are also planned to be part of SNF disposal facility. This is analysed in a separate assessment of LILW disposal safety which Posiva has also submitted to STUK.

Conclusions

Posiva has followed a stepwise approach to implementation of nuclear waste disposal. Posiva has also taken advantage of spent nuclear fuel activity decrease through interim storage. Posiva has developed a safety concept that is in line with regulatory requirements. Posiva has not defined spent nuclear fuel as a disposal barrier, but has otherwise considered the role of spent fuel matrix in post closure safety.

Posiva has submitted a safety case portfolio that in general fulfils the regulatory requirements. An integrated safety case, that takes into account both SNF and LILW disposal, should be presented in the operating licence application documentation.

2.1.2 Phased implementation

Government Decree (736/2008) requires that the disposal of the nuclear waste shall be implemented in stages, with particular attention given to post-closure safety. This means, for example, reduction of spent nuclear fuel activity with interim storage and building up knowledge for the step-wise development and progress of the disposal concept. The regulatory Guide YVL D.5 describes the stages involved in the development and implementation of nuclear waste disposal: selection of the disposal concept; selection and characterisation of the disposal site, which may include the construction of an underground research facility at the site; design of the disposal facility with related research and development work; construction of the disposal facility; waste emplacement activities and other operations of the disposal facility; backfilling and closure of emplacement rooms and other underground rooms and post-closure monitoring measures where required.

Posiva has followed the government decision from 1983 in the development of spent fuel disposal. The decision sets the policy of spent fuel management and gives the timeline for the main steps in nuclear waste disposal, which were updated later with decisions by Ministry of Employment and Economy (TEM, formerly KTM, Ministry of Trade and Industry). The first main step was the Decision-in-Principle (DiP) which concluded that the proposed KBS-3 disposal concept and Olkiluoto as the disposal site would be suitable. After the DiP, Posiva entered into more detailed site investigations. As required by safety requirements and authorized by the DiP, construction of the underground rock characterisation facility (Onkalo) was started in 2004. Posiva has taken cooling of SNF into account in facility design and has set waste acceptance criteria for the SNF so that the minimum cooling time is 20 years and on average the cooling time is 30-40 years.

Posiva has described in its construction licence application and in its safety case documentation the principles for stepwise construction and operation of a disposal facility. Posiva has plans to excavate emplacement rooms in sequences to minimize the potential disturbance of the host rock. Also the disposal, backfilling and closure of emplacement rooms are planned to be implemented so that the favourable rock characteristics to post-closure safety are maintained.

The procedures for disposal facility construction and SNF emplacement are given in PSAR, which has been accepted by STUK (1/H42241/2012, 10.2.2015).

Conclusions

Posiva has followed a stepwise approach to implementation of nuclear waste disposal. The stepwise implementation is followed in the main licensing steps, according to the Government decision, and in disposal facility construction, emplacement activities and closure.

2.2 Multibarrier system

Safety functions and performance targets of the barriers

According to para 11 of Government Decree (GD) 736/2008, post-closure safety shall be based on safety functions achieved by mutually complementary barriers. Guide YVL D.5 defines safety functions as factors preventing and limiting the release and migration of disposed radioactive materials: that is, as factors contributing to the safety objectives of containment and isolation. Safety functions shall effectively prevent release of disposed radioactive materials into the bedrock for a certain period, the length of which depends on the duration of the radioactivity hazard of the waste. For short-lived waste, this period shall be at least several hundred years and, for long-lived waste, at least several thousand years. The safety functions that should at least be considered are listed in paras. 406 and 408 of Guide YVL D.5.

STUK has reviewed Posiva's documentation concerning safety functions and performance targets. Posiva has defined the safety functions as the main roles that the barriers have in establishing the required long-term safety of the disposal system (e.g., Posiva 2012-03). STUK-POSIVA-10115

(POS-016958, 11.11.2013) suggests that the way Posiva has defined the safety functions is compliant with the requirements in Guide YVL D.5.

The safety functions defined by Posiva for the KBS-3 multibarrier system of canister, buffer, backfill, closure and host rock are to:

Canister
- Ensure a prolonged period of containment of the spent fuel. This safety function rests first and foremost on the mechanical strength of the canister's cast iron insert and the corrosion resistance of the copper surrounding it.

Buffer
- Contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favourable to the canister,
- Protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides and
- Limit and retard radionuclide releases in the event of canister failure.

Backfill
- Contribute to favourable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters,
- Limit and retard radionuclide releases in the possible event of canister failure and
- Contribute to the mechanical stability of the rock adjacent to the deposition tunnels.

Host rock
- Isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface,
- Provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers and
- Limit the transport and retard the migration of harmful substances that could be released from the repository.

Closure
- Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals,
- Contribute to favourable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings and
- Limit and retard inflow to and release of harmful substances from the repository.

Posiva states that no safety function can be assigned to the spent nuclear fuel. According to Posiva 2012-03 the reason for this is that the spent fuel is not "designed" in any way (e.g. conditioned or reprocessed) before packing in canisters.

Posiva argues that safety functions are to be maintained at the times and to the extent they are needed to ensure a required level of post-closure safety. This means that all the safety functions of a barrier may not be fulfilled simultaneously. However, it is not clearly stated by Posiva when each safety function is assumed to be fulfilled.

STUK considers Posiva's safety functions as broad safety objectives similar to containment and isolation. Containment for hundreds of thousands of years is considered by Posiva to be a requirement.

Posiva's safety functions and performance targets are discussed in more detail in Section 5.1.1 of this review report.

Conclusions

It is concluded that Posiva's and STUK's interpretations of a safety function differ from one another. In future Posiva should redefine safety functions so that it is easier for STUK to evaluate the performance of the barriers in relation to the fulfilment of the safety functions. Despite the different interpretations of a safety function, the current formulation of the safety case can be used satisfactorily to demonstrate an adequate level of post-closure safety. Therefore, it can be concluded that Posiva has adequately described and defined the safety functions at this licensing phase.

2.3 Monitoring

GD 736/2008 requires that planning of the construction, operation and closure of a disposal facility shall take account of the need to ensure long-term safety via investigations and monitoring. According to GD 736/2008 long-term performance of barriers shall be confirmed by establishing an investigation and monitoring programme, to be implemented during the operational period of the final disposal facility. YVL D.5 describes in more detail regulatory requirements for investigations and the monitoring programme. During the construction and operation of the disposal facility, a research, testing and monitoring programme shall be executed to ensure that the site and the rock to be excavated are suitable for disposal, and to collect supplementary information of the safety-relevant characteristics of the host rock and the performance of the barriers.

According to YVL D.5 this programme shall include at least: characterisation of the rock volumes intended to be excavated; monitoring of rock stresses, movements and deformations in rock surrounding the emplacement rooms; hydrogeological monitoring of the host rock surrounding the emplacement rooms; monitoring of groundwater chemistry; monitoring of the performance of engineered barriers.

2.3.1 Investigation and monitoring programme

Posiva has considered the topic of monitoring in Posiva report 2012-01, which describes Posiva's plans for monitoring of rock mechanics, hydrology, hydrogeochemistry, surface environment, foreign materials and the engineered barrier system (EBS) until 2018. Posiva will update the monitoring programme in 2017 to cover the operational period. The report also gives a generic description of each field of monitoring during the operation period. In addition to being a description of the monitoring and investigation programme, Posiva presents an extensive list of how monitoring data will be utilised in the planning and construction of the disposal facility.

Posiva states that the results of geoscientific monitoring will be used mainly for validation of existing models, with the exception of biosphere modelling, which uses the monitoring data in the actual modelling work.

Posiva also states that, in the extreme case that site properties deviate from acceptable conditions in a large rock volume, or over the entire planned disposal area, Posiva would evaluate the possibility of changing its plans for final disposal or would revise the requirements for the disposal site. As Posiva states, this kind of decision would have to be justified by a new version of the safety analysis and would require fresh STUK regulatory assessment and acceptance.

2.3.2 Monitoring of the disposal site

The geoscientific monitoring plans presented cover rock mechanics, hydrogeology and hydrogeochemistry and are almost as extensive as those in Posiva's prior monitoring programme during 2004–2011, used for monitoring the effects of construction of Onkalo.

In the field of rock mechanics, Posiva has presented the effects of the monitoring results on planning and construction, and the performance of the EBS. The re-activation of fractures, tectonic movements, and seismicity are considered to have negligible effect on the initial data for planning and construction. The performance of the EBS is determined to be unaffected by the re-activation of fractures, spalling, tectonic movements and seismicity. Posiva has planned to use two fractures penetrated by the Onkalo ramp for convergence measurements that would be made twice a year. Some single fractures, representing normal and shear displacements, will be monitored, if such fractures are found in the disposal rock volume. Posiva has not clearly explained the reasoning for the sufficiency of the proposed measuring activities. The current monitoring programme does not include monitoring of redistribution of rock stress, which Posiva considers to be part of the site investigations, rather than part of the monitoring programme.

In the field of hydrogeology, the monitoring programme is considered to to cover conditions in the deeper part of the bedrock in an adequate way. A large programme of monitoring of surface hydrogeology and infiltration conditions is included in the monitoring plans for the surface environment. Posiva plans to increase the number of measurements of waters infiltratinginto the disposal facility, as an automatic measuring system will be installed in all measuring weirs.

Monitoring of fractures with low transmissivities situated deep in the bedrock will be increased, in order to gain data on groundwater salinities. On the other hand, Posiva may cease Gefinex SAMPO measurements, because there are many disturbances due to construction activities on the ground surface. Monitoring of the effects of the fresh surficial waters of the Korvensuo reservoir on the deep groundwaters will be continued. The Korvensuo reservoir waters originate from the River Eurajoki, representing very different hydrogeochemical characteristics compared to the deep groundwaters of the Olkiluoto bedrock.

The 2012-2018 programme for monitoring of foreign materials is concise. According to Posiva, the chemical composition of groundwaters flowing along in fractures around Onkalo does not reflect any effects from foreign materials. However, the monitoring of Onkalo has only taken place for about 10 years. This time may be too short for example for the small amounts of organic additives of shotcrete to be seen in the hydrogeochemical monitoring. Shotcrete has been used in large quantities in Onkalo. In its plan for the analysis programme Posiva indicates that geomicrobes would only be studied with cultivation-based methods, not supported by additional modern gene technology methods. Posiva acknowledges that foreign materials have effects on the hydrogeochemical conditions but does not describe how the hydrogeochemical monitoring programme can tell the difference between a change caused by foreign materials and one caused by other factors.

Together with the hydrogeological monitoring programme, Posiva will pay special attention to the hydrogeochemical properties of the fresh waters in the Korvensuo reservoir in the hydrogeochemical monitoring, and the potential effects of the Korvensuo waters on hydrogeochemical conditions in the Olkiluoto bedrock, especially at the planned repository depth.

The monitoring programme for the surface environment is comprehensive. Posiva also uses data from the environmental monitoring programme of TVO's nuclear power plants. Posiva has identified some development needs in the monitoring programme for the surface environment. Posiva should put more emphasis on monitoring activities that could give indications of the future evolution of Olkiluoto's surface environment, which and would help to improve models and confirm performance.

In the field of hydrogeology and hydrogeochemistry the monitoring programme is adequate as well as the surface environment the monitoring programme. For rock mechanics, monitoring the planned extensometer measurements, and convergence measurements seem to be limited and Posiva has terminated the monitoring of redistribution of rock stress. Posiva needs to provide arguments that the measurements remaining in the rock mechanics monitoring programme will give a comprehensive view of changes in rock mechanics at the planned repository depth and volume.

Regarding the disposal site the monitoring programme for 2012–2018 is practically an updated version of the previous version, targeted at the monitoring of Onkalo's construction and its possible effects on the bedrock at Olkiluoto. Monitoring of the EBS has been added and the other programmes have been updated according to observations, new approaches and priorities. Generally the number of annual observations has been decreased compared to the previous monitoring programme. Should there be rapid changes; the current monitoring programme may not be able to detect them.

2.3.3 Monitoring of the EBS

According to Posiva, the necessary equipment and methods for EBS monitoring will be planned, studied, developed and tested during the monitoring programme for 2012–2018. Posiva gives a short generic description of engineered barriers monitoring during the operational phase. The main principles of monitoring have been identified, and some priorities are mentioned, although still at a general level.

Posiva has described plans for EBS monitoring development in the disposal concept development programme (POS-018285, v.1). However the plan to use EBS and disposal system tests and demonstrations in monitoring development is vague. STUK considers that Posiva's FISST test (Full scale In Situ System Test) would be a possible place to test monitoring equipment.

Posiva is carrying out collaboration with SKB on EBS monitoring aiming to identify and screen out measurable parameters and suitable monitoring methods.

Conclusions on monitoring

The monitoring programme presented in Posiva report 2012-01, is adequate at this licencing phase and gives the monitoring plans and programmes for 2012–2018. For the operational phase, the report gives a short generic description of each monitoring field.

Posiva needs to re-consider the measuring intervals in the different monitoring programmes. In STUK's opinion there is a risk that the longer measuring intervals compared to those used in the previous monitoring programme in 2004–2011, might not capture possible rapid changes. At the time when Posiva Report 2012-01 was published in 2012, the effects of the construction of Onkalo were not so clear, compared to the observations Posiva reported in 2014.

The monitoring plan for the EBS is at a very early stage, and needs further work starting from an overall strategy for EBS monitoring. The technical problems related to detection equipment need to be solved.

Posiva has not included rock stresses as part of monitoring programme and this matter is discussed in Section 4.2 of this report. In the other geoscientific fields, hydrogeology and hydrogeochemistry monitoring plans are considered to put emphasis on the most critical matters, considering post-closure safety.

3 Disposal site and barrier system

3.1 Spent nuclear fuel

3.1.1 Characterization of the spent nuclear fuel

Based on Guide YVL D.3 acceptance criteria shall be defined for any properties of spent nuclear fuel (SNF) that have a bearing on the operational and the long-term safety of final disposal. Records shall be prepared of each final disposal canister. Initial enrichment level, burn-up, heat generation, activities of dominant nuclides, structural and material properties that have a bearing on the post-closure safety and potential leakage or damage to a nuclear fuel assembly must be determined for individual assemblies and canisters from the records.

Posiva 2013-01 provides an overview of SNF characterization, which relies heavily on the description provided in WR 2005-71. Posiva presents averaged fuel parameter values for enrichment of the fresh fuel, burn-up, and decay heat. Such parameters provide some details of the operational histories of the fuel. This information is sufficient to carry out the required source term calculations based on defining a representative reference inventory that takes account of the full range of SNF.

Posiva does not go into great detail about the structural properties of the SNF, other than a short description in the context of radionuclide partitioning between the UO_2 matrix and the radial outer edge, or rim zone, of the fuel pellet, for the instant release fraction (IRF) model assumptions. However, the description of different radionuclides in the different physical components of the spent fuel is handled adequately. Posiva groups the gap and grain boundary together, as a single phase to be considered as the IRF. This is adequate and reasonable, assuming that Posiva equates the maximum percentage of noble gases (e.g., Xe, Kr isotopes) found in the matrix-cladding gap to the percentage of other volatile radionuclides (e.g., Cs, I isotopes) that are expected to be found in both the gap and grain boundaries. It is noteworthy that Posiva identifies possible 'exotic' inventories of *"… activation and fission products initially adhering to the surfaces of spent nuclear fuel rods (crud)."* These inventories (probably largely C-14 from neutron activation of O-17 in H_2O during reactor operations) are 'exotic' because they do not show up in conventional 'ORIGEN-type' calculations of radionuclide inventories for reactor fuel. The method for deriving the reference inventory from the activity calculations is presented in appendix F of Posiva 2013-01. Posiva's screening approach to select the key safety-relevant radionuclides for analyses is described and is carried out in four steps. In the fourth step Posiva uses ad hoc calculations and its experience from earlier safety analyses to reduce the number of significant radionuclides further. This fourth step is not described in sufficient detail.

Posiva appropriately sets up the source term according to different radionuclide inventories in the SNF components, and different release (i.e., dissolution rate for UO_2 matrix, corrosion rate for cladding and structural steels) rates of these radionuclides into groundwater once the containment is breached. Posiva's approach is to combine the least favorable fuel nuclide specific activities for each fuel type for the reference inventory, which provides confidence that cautious data have been selected. It would further enhance confidence if more detailed data on the similarity of the fuel types were available to support this approach, other than just noting the burn-up and enrichment histories, and major difference between the other metal components.

Posiva provides no detailed information or implied impacts on the source term relating to possible leakage or damage in the fuel rod or bundle. However, Posiva has supplemented its application regarding damaged fuel rods and bundles. Posiva considers that the release rates and source term are conservative enough to include possible damaged fuel.

STUK requested additional information regarding the approach to selection of fuel bundles to be encapsulated into each canister. Posiva provided more information in its response (POS-0193860, 2.9.2014). Posiva states that criticality safety and residual heat production will be taken into account when loading canisters. Loading curves for criticality safety will be calculated and sufficient cooling times applied. Posiva is also planning SNF database to manage fuel handling during the operational period.

Conclusions

Posiva has adequately characterized SNF and the source term and the requirements are fulfilled at this phase of the licensing process.

3.1.2 Performance

According to YVL Guide D.5, the immobilization of radioactive substances in the waste matrix shall be considered as a safety function provided by means of engineered barrier.

According to YVL Guide D.5 targets based on high quality scientific knowledge and expert judgement shall be specified for the performance of each safety function. The potential changes and events affecting the disposal conditions during each assessment period shall be taken into account. Performance targets for the safety functions of engineered barriers shall be specified taking account of the activity level of waste and the half-lives of dominant radionuclides.

According to YVL Guide D.5 conceptual models shall be constructed to describe the underlying events and processes, and conceptual models shall also be constructed to describe the safety functions and the factors affecting them.

Posiva has not assigned any safety functions or set any performance targets for spent nuclear fuel. Posiva states that, the properties of spent fuel have been considered when designing the disposal concept and in the safety case. Furthermore, Posiva states that, in the KBS-3 safety concept, radionuclides are not bound in the waste matrix by design: therefore, no performance target can be set to the SNF.

Although Posiva has not set performance targets, the SNF needs to be characterized so that the relevant waste acceptance criteria (WAC) can be defined. Posiva has characterized SNF but has not defined unambiguous WAC. Posiva has supplemented PSAR Y7 and included WAC. Posiva considers the selection of fuel assemblies for each canister as an optimization process, which takes into account heat production (cooling time, enrichment, burn-up) and criticality safety (enrichment, burn-up).

Posiva uses one conceptual model to describe the source term and applies it to all fuel types in the inventory, irrespective of irradiation history. The radionuclide inventory used is described as representative or bounding of the range of fuel types.

Posiva states that *"Fuel dissolution is assumed to take place at a constant fractional rate, with congruent release of radionuclides."* Posiva 2013-01 describes the conceptual model and key controlling parameters that influence release from each component of the source term (UO_2 matrix, cladding and other metal components). For the UO_2 matrix, the range in release rates is described with a deterministic justification for selection of the 10^{-7}/year rate, which is sufficient and includes a clear statement of the cautious nature of this rate, followed by a clear justification of the assumptions (i.e. congruent release) and an indication of ongoing work in the REDUPP project to reduce uncertanties. The same release rate is considered to apply release from damaged spent fuel (e.g. rock shear scenario) or from leaking fuel bundles.

The amount and behaviour of the instant release fraction (IRF) is well justified. Posiva refers to recent research data and presents a number of arguments for the definition of IRF behaviour and parameters. These are based on experimental observations, known correlations with fission gas release (FGR) data (e.g. FGR-IRF leaching test results are provided to enhance confidence for the selection of the input data) and feedback from assessments. This is used to make informed decisions about the treatment of IRFs and other activities contributions from crud in the reference and complementary calculation cases. The selection of the IRF data and comparison with earlier Posiva values and SKB-10-52 data are well presented with an appropriate amount of justification and references. The ongoing work to reduce uncertainties regarding the IRF is mentioned. Posiva is participating in the FIRST Nuclides project to improve understanding in this area further.

For zircaloy and metal component release, Posiva provides a summary of source reference data for metal corrosion rates to support a number of simplifications for the treatment of the metal release fraction, which can be considered a cautious approach. However, Posiva assumes zircaloy and steel parts, containing C-14 activation product, to dissolve in 1000 years, which is most likely highly conservative and would over-emphasize the significance of C-14 in the base scenario.

Conclusions

Posiva has not defined post-closure safety related criteria for SNF other than for heat production and criticality safety. Posiva should consider the WAC regarding inventory of the most significant nuclides and fuel alteration rate which are consistent with the analysis made in the safety case.

According to Posiva's probabilistic sensitivity analysis of the safety case, the fuel alteration process is one of the most safety significant parameters. In its ongoing RD&D work, Posiva should provide a stronger basis for the assumed 10^{-7}/year dissolution rate value and reduce uncertainties related to the IRF inventory, especially in Cl-36, I-129 and C-14.

Although Posiva has not set a performance target for SNF its description of the performance of the spent nuclear fuel its handling in the safety case are considered to be adequate at this phase of the licensing process.

3.1.3 Post-closure criticality safety

YVL Guide D.5 states that the SNF contained in a disposal canister shall remain subcritical, including the long term. The design shall accommodate conditions where the leaktightness of the container has been lost and the container has sustained mechanical or corrosion-induced deformations. According to YVL Guide D.3, the disposal canisters shall be designed so as to ensure criticality safety (the exclusion of a chain reaction sustained by neutrons) in planned operational conditions and in the event of an anticipated operational occurrence or postulated accident. The requirements pertaining to criticality safety are set out in Guide YVL B.4.

Posiva submitted a memorandum (TVO 144244) regarding the criticality safety of the disposal canister. According to the memorandum, assuring subcriticality requires the application of burn-up credit (BUC) for all canister types. With 5 % enrichment, the required minimum burn-ups are approximately 36 MWd/kgU for OL1/2, 36 MWd/kgU for LO1/2 and 51 MWd/kgU for OL3 fuel assemblies.

100 % of OL1/2 fuel assemblies fulfill the criterion established in the loading curve with the actinide-only BUC level.

Over 94 % of the LO1/2 fuel assemblies fulfill the criterion established in theloading curve with the actinide-only BUC level and 99 % with the actinides+rare earth elements BUC level.

100 % of the OL3 fuel assemblies will fulfill the loading criterion if a 12 month equilibrium cycle is used with the actinide-only BUC level. For 18 or 24 month cycles the application of the actinides+rare earth elements BUC level is required. 100 % of the 18 month cycle will fulfill the criterion established in the loadingcurve. With higher enrichment levels, the application of the actinides+rare earth elements BUC levels are not enough.

Certain fuel assemblies not fulfilling the loading criterion will require a new analysis and a canister-specific loading design. Posiva states that these fuel assemblies can be loaded with assemblies with high burn-up.

Considering long-term evolution of the canister, in the scenario where the fuel assembly and the canister are destroyed, Posiva states that when fuel pellets are mixed with cladding and sufficient amount of corrosion producst from the cast iron insert, subcriticality is maintained. The sufficient amount of corrosion products from the cast iron insert is at least 50-60 % of the particle volume. If the geometry is significantly different, (e.g. cast iron corrosion products migrate away and mixing conditions do not hold so that 50-60 % comprises magnetite particles), subcriticality might not be maintained. The porosity of the corrosion products introduces some uncertainty to the long-term criticality calculations. The long-term canister evolution thus needs further evaluation with respect to post-closure criticality.

Conclusions

Posiva applied burn-up credit to reach the conclusion of post-closure subcriticality. In STUK's opinion, this approach is adequately justified and STUK's requirements are fulfilled at this stage, although long-term canister evolution, especially possible changes in geometry, needs further analysis. Future analysis before an operating licence application should consist of considerations of possible changes in geometry causing criticality and evaluation of the consequences of canister criticality as a bounding analysis.

3.2 Canister

3.2.1 Characterization

Based on the requirements in Guide YVL D.5, the properties of the canister materials shall be characterized. Emphasis should be put on the properties that affect the long-term performance, durability and mutual suitability of each material. Canister materials must not jeopardize the performance of other barriers.

Posiva 2012-13 states that copper has been chosen for the shell material because it has well-known properties, good thermal and mechanical properties, and resistance to corrosion in reducing environments. Cast iron has been chosen for the insert to provide mechanical strength, radiation shielding and to maintain the fuel assemblies in the required configuration.

According to Posiva 2012-13, the material for the copper components is phosphorus-alloyed, oxygen-free copper with the following requirements: O < 5 ppm, P 30-100 ppm, H < 0.6 ppm, S < 8 ppm. The purpose of phosphorus is to improve the creep strength and ductility of the copper. The insert is made of nodular graphite cast iron. The material shall fulfil the standard requirements in EN 1563:2010 grade EN-GJS-400-15U regarding mechanical properties. The lid of the insert is made of a structural steel plate according to EN 10025 grade S355J2 or similar grade with at least the same tensile strength and ductility, in the as hot-rolled or normalized condition. Material for square tube cassettes shall fulfil the standard requirements in EN 10219-1 grade S355J2H or EN 10210-1 grade S355J2H.

Posiva has set a safety function for the canister which is to *"ensure a prolonged period of containment of the spent nuclear fuel"*. According to Posiva, this safety function rests on the mechanical strength of the canister's cast iron insert and the corrosion resistance of the copper overpack. Posiva has stated that copper has resistance to corrosion in reducing environments. Posiva 2012-11 presents evidence for the suitability of the canister materials. For copper, several archaeological and geological analogues are described. For iron archaeological analogues are described. As a conclusion, Posiva states that both archaeological and natural analogue studies suggest that the corrosion rates for copper and steel assumed in the safety assessment are generally conservative.

Posiva has also stated that the cast iron insert provides good mechanical properties. Therefore there is a relationship between canister material properties and safety functions. However, Posiva does not consider the mechanical properties of the copper overpack within the safety functions or performance targets, although it is clear that the copper overpack will be subject to mechanical loads such as plastic strain and creep.

Posiva has chosen copper as the shell material for its well-known properties and resistance to corrosion in reducing environment, which STUK considers to be appropriate. However, there is an emerging issue regarding corrosion resistance of copper in oxygen-free pure water. Hydrogen production has been detected during some laboratory experiments, but the processes involved are not well understood at present. Posiva 2013-01 states that work on clarifying the nature of the hydrogen generating process in such experiments will continue. STUK will follow up these developments.

There is also an issue regarding the mechanical properties of copper. Posiva has stated that adding phosphorous to copper improves creep strength and ductility. However, according to STUK's understanding, the longevity of the effects of incorporating phosphorous into copper remains uncertain. The effect of phosphorus to enhance copper creep resistance is not fully understood at the moment. The current scientific quality and amount of data, modelling and assessment of possible slow-strain rate, creep ductility and failure of copper need further confirmation. The concern is that creep ductility rupture could be a common-mode failure process, by which many copper canisters might fail earlier than expected.

Conclusions

Posiva has characterized properties of canister materials and the majority of the critical properties are well-undestood at the present. However, there are some topics (especially copper creep and corrosion) that need further clarification.

3.2.2 Manufacturing and inspection of the canister components

GD 736/2008 and YVL guides set requirements for canister properties, quality, manufacturing and inspection. The properties of the waste packages and a description of the packaging methods shall be presented. Quality specifications necessary in terms of the operational safety of the nuclear waste facility and the post-closure safety of disposal shall be defined. The quality level of the classified object and the inspections and testing for verifying the quality shall be adequate as regards the significance of the object in terms of safety.

Canister manufacturing and inspection methods are described in Posiva 2012-16, Posiva 2012-35, Posiva 2010-04 and Posiva 2009-03. Copper components are manufactured from copper billet by hot forming techniques; the pierce and draw method (Posiva's reference method), and extrusion. The insert is manufactured by casting. Some components for the insert are manufactured from steel; the lid, the lid fixing screw and the tube cassette for the fuel assemblies.

Canister manufacturing methods are described in the above reports, which state that copper canister components that fulfil Posiva's requirements (e.g., mechanical properties, grain size) can be fabricated. Manufacturing demonstrations of the insert have confirmed its acceptable fracture resistance only for the BWR type of insert. Posiva should thus carry outfurther development of the casting process. Posiva should improve the manufacturing process for VVER-440 and EPR inserts in order to achieve similar mechanical material properties to those of the BWR insert. In accordance with YVL Guide D.5 manufacturing methods shall be qualified before components are fabricated. Posiva has presented a qualification plan and schedule.

The earlier the reference sealing method for the canister was EBW (Electron Beam Welding) and Posiva's documentation regarding the canister sealing is mainly related to EBW. In March 2014 Posiva made a decision to change the reference sealing method from EBW to Friction Stir Welding (FSW). SKB has also chosen FSW for its canister sealing method. As part of the additional information POSIVA-STUK-10226, Posiva delivered to STUK two state of the art reports for EBW (WR 2014-22) and FSW (WR 2014-21).

Posiva 2012-13 presents preliminary allowable weld defects both for EBW and FSW including defect types that are not allowed in high quality (class b or c) weldments. According to theadditional information provided to STUK, Posiva will continue its development work for FSW with SKB. Based on this work defect types and sizes will be considered in more detail in the future.

Posiva has also delivered to STUK a document (Posiva-STUK-10215) *"Disposal concept development programme / Loppusijoituskonseptin kehitysohjelma"*, which contains detailed information regarding the development work for FSW.

Posiva aims to carry out quality and integrity control of the canister components using several non-destructive methods: visual testing, penetrant testing, eddy current testing, ultrasonic testing and x-ray testing. According to Posiva 2012-16, the final inspections are based on the qualified inspections, which follow ENIQ requirements.

Posiva has set preliminary acceptance criteria for the canister components, which are presented in Posiva 2010-04, Posiva 2012-13 and Posiva 2012-35. Posiva states that the master requirement for the acceptance criteria of canister components and weld is an intact wall thickness of 35 mm in 100 % of the canisters and 40 mm in 99 % of the canisters. This master requirement is based on the corrosion allowance of the copper overpack.

Acceptance criteria for the insert are related to its load carrying safety function and are presented in Posiva 2012-35.

As mentioned, Posiva is developing several methods for the NDT of the canister components and weld. According to the YVL Guide NDT-methods shall be qualified. Posiva has presented a qualification plan and schedule.

Conclusions

Posiva's general description of the manufacturing methods for the canister components fulfils the STUK's requirement at this stage as does its general description of the inspections methods for the canister components.

Posiva has presented manufacturing methods for the canister components and qualification plans for the methods and STUK's requirements are fulfilled at this stage. However, Posiva should perform further development of the casting process for the cast iron insert.

Posiva has presented non-destructive testing methods for the canister components and qualification plans for the NDT-methods that fulfil STUK's requirements at this stage.

STUK will follow-up Posiva's manufacturing and welding development work as part of the STUK's inspection programme for the construction phase.

3.2.3 Performance

According to YVL Guide D.5, performance targets based on high-quality scientific knowledge and expert judgement shall be specified for each safety function. The potential changes and events affecting the disposal conditions during each assessment period shall be taken into account. Performance targets for the safety functions of engineered barriers shall be specified taking account of the activity level of the waste and the half-lives of dominating radionuclides.

According to YVL Guide D.5 conceptual models shall be constructed to describe the underlying events and processes, and conceptual models shall also be constructed to describe the safety functions and the factors affecting them.

Performance targets for the canister are presented in Posiva 2012-03. According to Posiva the performance targets have been set so that individual deviations or deficiencies will not endanger long-term safety. In the case of the canister Posiva states that incidental deviations refer to manufacturing defects and operating errors that may reduce the lifetime for a few canisters. Posiva considers any defect will most likely be in the weld (Posiva 2012-12). Posiva's base scenario addresses the most likely lines of evolution, but takes into consideration the possibility of one or a few canisters with one initial undetected penetrating defect.

Posiva 2012-04 states that the design and manufacturing of the canister must satisfy the performance target: *"the canister shall initially be intact when leaving the encapsulation plant for disposal except for incidental deviations"*, (L3-CAN-4), and also that, in the expected repository conditions, the canister shall remain intact for hundreds of thousands of years, except for incidental deviations (L3-CAN-5).

Posiva 2012-04 states that the canister shall have sufficient mechanical strength to ensure minimal probability of collapse for isostatic pressures up to 45 MPa, it shall withstand expected dynamic mechanical loads and it shall have sufficient mechanical strength to ensure its rupture limit exceeds the maximum shear stress on the canister, corresponding to a 5 cm displacement in any direction across the deposition hole. Posiva has performed shear load analysis only for the reference canister (BWR) at this stage.

Posiva has determined acceptance criteria for the insert of the reference canister (BWR), which are presented in Posiva 2012-13 and Posiva 2012-35 and state that the reference canister can withstand the specified loads with a sufficient safety margin even if the material has allowable defects.

Posiva 2013-01 presents the copper creep model, which consists of three components; a) base material strain model; b) base material creep rupture model; c) electron beam weld strength factor and strain model.

WR 2014-22 states that the creep properties of friction stir welds are almost the same as for the base material. The main reasons for these results are that variation in the microstructure between the weld and the base material is small and matches previous studies as in grain size.

Creep ductility of copper is a function of creep/strain rate, which is controlled by the evolution of the external pressure on the canister. Posiva's copper creep model does not take into account possible large variation in strain rate caused by possible large variation in buffer re-saturation time. A possible implication arising from delayed saturation is creep-ductility failure of the copper canister. More studies to confirm current interpretations of this issue should be conducted by Posiva.

Posiva's base scenario takes into consideration the possibility of one or a few canisters with an initial undetected penetrating defect. An initial, undetected 1 mm diameter pinhole on the weld of the copper canister is assumed. Posiva states that the potential for this defect type is due to the use of electron beam welding. In March 2014, Posiva made a decision to change its reference sealing method to FSW, although Posiva's additional information (POSIVA-STUK-10226) states this change does not affect its base scenario. WR 2014-22 presents typical weld defects for FS-weld and preliminary acceptance criteria for a FS-weld. This weld defect type list does not contain a pinhole, such as the defect assumed in the base scenario. STUK thus considers that Posiva's decision to change the reference sealing method to FSW requires a reassessment of the type and properties of a potential undetected defect in the weld.

Posiva has reported that the demo canister has withstood an isostatic pressure of up to 138 MPa. Based on this it seems that the safety factor is around three (138/44) in the case of isostatic loading.

Posiva 2013-01 states that one objective of the Models and Data report is to describe the conceptual models used and their main assumptions. However, Sections 6.12–6.27.3 in Posiva 2013-01 do not describe a conceptual model for the safety function of the canister. On the other hand, Posiva presents models describing relevant processes.

WR 2014-22 states that FSW provides better corrosion resistance than EBW, because of the lower residual stresses, the minimal grain growth and the absence of any resultant concentration of impurities at the grain boundaries: FSW is closer to the base material properties.

Posiva 2012-04 states that "The canister shall withstand corrosion in the expected repository conditions" which corresponds to performance target L3-CAN-7. According to Posiva, this performance target is met when the minimum initial intact wall thickness is more than 35 mm and remains more than zero for hundreds of thousands of years. Posiva takes into account different corrosion processes and chemical loads, but the corrosion depth due to different corrosion processes remains unclear. However, Posiva has considered and documented corrosion depths during different phases of final disposal, such as the operational phase, and corrosion during and after buffer re-saturation. Posiva 2011-01 presents realistic and conservative values for corrosion depths during different phases but does not provide a quantitative value of corrosion rate that will ensure a minimum overpack thickness of >0 mm over the assessment period of 1 Ma. The chemical integrity of the copper overpack is highly dependent on the performance of the buffer and on sulphide concentration in the groundwater, although there are numerous aggressive species or processes that can affect the corrosion rate of the copper overpack, such as oxygen, chloride, nitrogen compounds, acetates, ammonia, radiation, microbes, etc. The bentonite buffer is expected to limit the transport of aggressive species towards the canister, which is the most important assumption regarding chemical integrity of the copper overpack.

Features, Events and Processes (FEPs) regarding corrosion of copper overpack are presented in Posiva 2012-07. The report does not describe all relevant FEPs in sufficient detail. In Posiva 2013-01, corrosion processes are described comprehensively. Posiva 2012-04 justifies the evolution described in the base scenario and describes some variant scenarios, such as corrosion as a consequence of buffer erosion. Posiva 2011-01 and Posiva 2013-01 present the relevant corrosion models that are used to evaluate relevant parameters. The key models are Copper Corrosion Model (CCM), Copper Sulphide Model (CSM) and Microbially Induced Copper Corrosion Model (CCM-MIC). The performance of the CCM-MIC model has not been confirmed with experimental data.

Posiva's approach for evaluating general corrosion is based on thermodynamic and mass-transport-limited approaches and kinetic models. The longest phase or period of time is the anoxic phase, after oxygen has been consumed, and buffer resaturation, when corrosion is expected to be caused only by sulphide and chloride. Posiva conducts conservative scoping calculations with high sulphide concentrations, which indicate that general corrosion is not the determining factor when designing canister wall thickness.

Regarding localized corrosion processes, Posiva rules out pitting, crevice corrosion and stress corrosion cracking (SCC). In Posiva 2011-01 Posiva makes a clear position statement that the canister is not subject to pitting in the classical sense of the term. Instead, the canister is expected to be subject to surface roughening. Posiva considers different forms of pitting in Posiva 2011-01 and uses a pitting factor (PF) to evaluate possible depth of pits. PF can be chosen in a conservative manner and Posiva has also considered conservative values for PF. Crevice corrosion is expected to stop by itself; the reasoning for this is restricted mass-transfer to the tip of the crevice.

Posiva applies a decision-tree approach in evaluating SCC, in which there are three pre-requisites that must occur simultaneously, adequate tensile stress, high enough corrosion potential and relevant aggressive species concentration. Using this model, Posiva concludes that the threat of pitting corrosion is relevant only during the oxic phase and, even then, it is unlikely owing to the low amounts of aggressive species in the ground water and the high temperature. There is an additional possibility of residues from explosives during construction forming nitrogen compounds and which can cause SCC.

The key uncertainties regarding corrosion of copper are thus in processes such as corrosion in oxygen-free water, microbially induced corrosion and SCC caused by explosive residues. There has also been discussion about hydrogen embrittlement of copper, radiation induced corrosion of copper and SCC caused by sulphides. Together with SKB, Posiva has examined adsorption of hydrogen in metallic copper and radiation induced corrosion, as well as corrosion in oxygen-free water. Posiva has also recognized the following processes subject to further research in its RD&D programme:

1. copper corrosion in oxygen-free water
2. enhancement of CSM
3. copper corrosion in high chloride concentrations
4. effect of explosive residues to SCC, and
5. microbially induced corrosion of copper.

STUK will follow Posiva's progress in its RD&D work regarding these issues.

Posiva states that the general corrosion rate of the cast iron insert will be similar to that of carbon steel, which is around 0.1–1 µm/a. Posiva uses a mass-balance model to assess the depth of the internal corrosion due to water initially present in the canister. Posiva calculates that the depth of corrosion is approximately 40 µm with an assumption that there is initially 600 g of water inside the canister. Posiva recognizes that subsequent anaerobic corrosion of the cast-iron insert will lead to hydrogen generation. Such corrosion products will have much larger molar volumes than the uncorroded cast iron, so their formation might lead to widening of the initial defect in the case of an initially defective canister.

One uncertainty that Posiva mentions is microbial activity inside an initially penetrated canister. Microbial activity, however, is assumed to be unlikely by Posiva, because the ingress of water to the canister is slow and the radiation inside the canister should suppress the microbial activity. On the other hand, the number of initially defective canisters is assumed to be small.

Posiva excludes SCC of cast iron because the corrosion environment is different, compared to environments where SCC of cast iron has been observed.

Conclusions

Posiva has described and justified the performance of the canister adequately at this phase. However, there will remain uncertainties regarding performance of the canister that shall need further RD&D work before an operating licence application. The most safety significant uncertainties are related to copper corrosion and creep ductility. Posiva has submitted a development plan of the disposal concept where it has recognized the following subjects for further research: copper corrosion in oxygen-free water; enhancement of CSM; copper corrosion in high chloride concentrations; effect of explosive residues on SCC; microbially induced corrosion of copper and creep ductility. STUK will follow the progress of Posiva's RD&D work on these issues.

3.3 Buffer

3.3.1 Characterization and suitability

Based on Guide YVL D.5 Posiva should identify the relevant properties of each buffer material to be characterized. Emphasis in the characterization should be on properties affecting the long-term performance, longevity and mutual compatibility of each (buffer/barrier) material.

A buffer material must be sufficiently stable in repository conditions to ensure the performance (i.e. to fulfil the performance targets) of the buffer.

A buffer material must not jeopardize the performance of other barriers, e.g. the canister and backfill. This means that it should not contain concentrations of materials that could directly or indirectly affect other barriers such as iron, organic material, nitrogen compounds, oxidizing compounds and whose hydroxide ions and their maximum concentrations need to be established.

Posiva should describe how a buffer material can be changed without compromising the performance of the buffer. In addition, Posiva should identify a list of favourable conditions for other barriers that can be adversely affected by harmful chemical materials contained in the buffer components.

Posiva has considered the topic of buffer material characterization in various safety case reports, e.g., Posiva 2012-05 and 2012-17.

Posiva 2012-17 (table 3-1) presents the reference, MX-80 type, material design specifications, lower-upper limits or maximum values, as follows: montmorillonite content 75-90 wt%; total sulphur content <1 wt%; sulphide content <0.5 wt%; organic carbon content <1 wt%. Methods to be used in the testing are also suggested by Posiva for each parameter.

Posiva has a material characterization scheme for the buffer, which STUK considers to be currently lacking in depth. Posiva's current approach concentrates on a few chemical properties (sulphur content <1 wt%, organics content <1 wt%, sulphide content <0.5 wt% and montmorillonite content 30-38 wt% for Friedland clay and 75-90 wt% for bentonites). If these requirements are satisfied, Posiva considers a bentonite material suitable for the buffer and directly exchangeable with the reference material. STUK considers that this approach might not give sufficient consideration to all material properties affecting performance.

The reasoning of how Posiva has arrived at the limits presented for total sulphur, sulphide, iron and organic content is not transparently presented in the safety case.

Posiva's approach does not explain the material properties from which performance (swelling pressure, low permeability) of the buffer originates from. For example the layer charge of the montmorillonite may dominate the swelling properties of the bentonite clay, but is not currently included in the characterized properties. According to additional information submitted to STUK (POSIVA-STUK-10351), Posiva has not yet found a relationship between layer charge and performance (swelling pressure, permeability), but will continue to study the topic.

The range of acceptable montmorillonite contents in a buffer material has been defined by Posiva using an empirical approach. The relation between the empirical expression and theoretical concepts governing the swelling behaviour of clay-based materials has not been evaluated. Uncertainties in the parameter range obtained from the empirical approach have not been evaluated.

Posiva has not presented a description of how the characteristic properties of the buffer (chemical, mineralogical, hydraulic, mechanical and microbiological) will evolve with time. Repository conditions have the potential to significantly change material properties of the buffer and backfill. Changes in material properties could result from differences in temperature and groundwater chemistry between the repository near-field environment and the environment from which the raw buffer and backfill materials were originally extracted. Reactions involving accessory minerals in the bentonite could play an important role in controlling the chemistry of pore waters in the buffer and backfill.

In its disposal concept development programme, Posiva has acknowledged the shortcomings in its characterization procedures and has explicit plans to deal with the topic (project acronyms ECCA, DEMPA). STUK intends to monitor this work closely. Posiva also describes in the development programme a procedure, on general level, by which Posiva is going to test and compare various bentonite clays and Friedland clay in order to find a suitable material for backfill blocks for the full-scale test in ONKALO.

Posiva has indicated that the substitution of the current reference bentonite with different montmorillonitic bentonites is possible if future circumstances so require. It is sensible to make such contingency plans, but any new buffer or backfill material may require substantial testing and associated modelling of behaviour to confirm the suitability of such a substitution.

The relationships between bentonite density, swelling pressure and swelling capacity have not been presented nor discussed thoroughly by Posiva although swelling capacity has been utilized by Posiva in the design. Swelling capacity is the factor that contributes to the design requirement stating that "the buffer shall be designed to be self-sealing after installation and self-healing after any hydraulic or mechanical disturbances" (L4-BUF-16) so a good understanding of swelling capacity and the factors that affect it, such as density, temperature and porewater chemistry is required. Swelling capacity contributes to the attainment of some of the performance targets but can also be a limiting factor as bentonite does not swell beyond its capacity in repository conditions, which may be beneficial in some circumstances.

Posiva 2012-11 argues for the long-term stability of bentonite and backfill materials under repository conditions and deals with several open safety-relevant issues. However, Posiva states that only a few of these issues are truly amenable to natural analogue studies and so few data exist.

Conclusions

For this licensing phase, Posiva's characterization approach does not need to be fully developed as long as Posiva is aware of the shortcomings involved and is carrying out dedicated research work to improve the understanding of the properties affecting on the behaviour of the bentonite materials. STUK considers it sufficient to identify a programme of work to ensure that a scheme is in place at the appropriate time. Clearly, this programme will need to take account of the issues identified above and Posiva will need to carry out more work to ensure that the scheme is comprehensive. The currently documented understanding of material properties affecting the performance of the clay/bentonite barrier is mainly empirical and fairly limited. Posiva has acknowledged this situation and has plans (Development programme, project ECCA) to improve understanding and to study the relationships between the material properties and the performance further. While STUK considers that the understanding is sufficient at this licensing phase it requires more work to be completed before an operating licence application.

It is likely that any future decision to replace MX-80 by another type of bentonite may require significant additional, material-specific data and associated modelling of behaviour to confirm the suitability of such a substitution.

3.3.2 QC

According to the YVL Guide B.2 requirements Posiva should classify the barriers as systems and structures contributing to safety and further to inspection classes, where applicable. Posiva should also determine the relationship between the system, structure or device and the inspection class and testing procedure, and in addition, develope the necessary guides, instructions and system-specific quality manuals in order to carry out the QA/QC procedures properly. The QC procedure covers the fabrication (material, conditions, devices, personnel, documentation) and emplacement phases (compliance with the requirements, documentation).

Posiva has considered the quality control procedures in Posiva 2012-17 and 2012-18. In these reports QC is embedded in all phases from material selection/approval and manufacturing of components to emplacement of buffer and backfill, ending up with the verification of compliance with the requirements. The QC chain is continuous for the whole process described. This is also essential to shorten the time needed for a process.

System level safety and testing classification is documented in Posiva's suggestion for classification document (POSIVA-STUK-10315, POS-014690, version 2 and POS-014313, version 5). Although the QC is described in a comprehensive way in various parts of the production line reports, a combined description of all QC activities is missing. A description of all the activities will eventually be needed. Posiva has not yet described the methods of quality verification for the structures of the barrier system. For example, the way to verify compliance with the requirements of the lower and upper part of a buffer or a backfilling sequence has not been presented and the need for instant availability of the results to enable the necessary decision making process is not discussed. Posiva has plans to produce the necessary QC documentation, but has not described clearly how and when the instructions, manuals, method and process descriptions, needed to handle the QC process, are to be developed.

Posiva will inevitably need to produce a set of testing procedures to enable the testing of various materials and structures to be carried out in a correct manner. Posiva has planned such a project (Development programme, DEMPA) partly in cooperation with SKB.

Conclusions

STUK considers that the route to a sound QC system is understood by Posiva and the eventual QC programme is likely to utilize well-developed quality system methodologies. Because QC activities for the buffer will not come into play for some time (allowing adequate time to prepare them), Posiva's description of QC activities in connection with producing systems like the buffer and backfill are considered sufficient at this phase of licensing. There is clearly work to be done in producing both the technology and the necessary documentation for various parts of the process.

3.3.3 Performance

Guide YVL D.5 requires that performance targets be specified for each safety function based on high-quality scientific knowledge and expert judgement. In doing so, account shall be taken of the factors affecting the disposal conditions during each assessment period as well as their combined effects. In defining performance targets for the safety functions provided the buffer, account shall also be taken of the quantities and half-lives of radioactive materials. Conceptual models shall be constructed to describe the safety functions of the buffer and the factors affecting them.

Posiva 2012-07 presents the description of each factor (FEP) considered by Posiva to be reasonable likely to affect the development of the disposal system. Such descriptions are intended to address relevant interactions between a specific factor and all the other factors influencing it. As such they serve the purpose of providing the basis for conceptual models constructed to describe the safety functions and the factors affecting them. The objective of Posiva 2013-01 is to describe the conceptual models used and their main assumptions. A conceptual model constructed on the basis of a FEP description has a central role in credibly setting a performance-target criterion, arguing for the assumed extent of declined performance of a safety function, and decreasing the uncertainty in a safety function beyond the criterion. Mathematical and computational models derived from conceptual models can be used to support the specification of the performance-target criteria and to gain an improved understanding of the extent to which safety functions can be impaired beyond these criteria. Presentation of the reasoning and rationale for the derivation of the performance targets is a key aspect of Posiva 2012-03. Posiva's assessment of the fulfilment of the performance targets is presented in Posiva 2012-04. The reasoning behind the specification of the performance targets is elucidated further in Posiva's response to STUK's request for additional information, POSIVA-STUK-10115 (POS-016958, 11.11.2013).

Most of the performance targets for the buffer lack an associated criterion which makes assessment of their fulfilment in relation to the performance assessment reported in Posiva 2012-04 difficult. Many of them also lack apparent correspondence with Posiva 2012-07, do not meet the requirements of Guide YVL D.5 as they are not a measurable or assessable characteristic of the buffer, or do not have a conceptual model to support their unambiguous definition.

According to performance target L3-BUF-21, the amount of substances in the buffer that could adversely affect the canister, backfill or rock shall be limited. It is stated in POSIVA-STUK-10115 that the corresponding performance-target criteria are found in the design specifications L5-BUF-10 and L5-BUF-11. These specifications are derived from design requirements which further clarify and provide more details about the performance targets. They are used in design, construction and manufacturing to ensure a desired initial state for the barrier and therefore are not considered as performance-target criteria. In L5-BUF-10, Posiva states that the sulphur content shall be less than 1 wt%, with sulphides making, at most, half of this in the initial state of the barrier. The sulphur content measured in the buffer should be below the design requirement. Posiva 2012-04 makes assumptions of the sulphide fluxes to the buffer and to the canister from the buffer. Posiva also states that the sulphide concentration in the bentonite porewater is foreseen to remain in the same range as prevailing in the surrounding groundwater. In L5-BUF-11, Posiva states that the organics content in the buffer shall be lower than 1 wt% initially. In addition to the substances mentioned in L5-BUF-10 and L5-BUF-11, Posiva 2012-03 states that ironhas the potential to affect bentonite detrimentally. In POSIVA-STUK-10248/10.6.2014, Posiva does not present a criterion for the iron concentration in the bufferand states, in POSIVA-STUK-10248, that there is no need to set such a criterion. Although it appears that the concentrations of substances mentioned in the performance target will remain such that they do not affect the canister, backfill or rock adversely, uncertainties remain in the development of sulphur (incl. sulphide), organics and iron in the buffer over the assessment period of 1 Ma, especially given the significant uncertainties involved during the early evolution phase of the repository.

Performance target L3-BUF-6 states that the buffer shall transfer heat from the canister efficiently enough to keep the buffer temperature below 100 °C. It is stated in POSIVA-STUK-10115 that this design limit for the buffer temperature is not a threshold value specifically for chemical changes in bentonite, but a round design number that is clearly safe. Posiva 2012-04 presents the target temperature as being based on a suitable thermal conductivity of the buffer.

In Posiva 2012-04, the temperature criterion is shown to be met with a reasonable margin based on model calculations which assume that the gap between the canister and buffer remains open and that the effective thermal conductivity of the buffer is 1.0 W/m/K. However, Posiva has not considered the possibility that the buffer would desiccate to the extent that its effective thermal conductivity would drop markedly below this value in its analyses. Consequently, uncertainties remain with respect to showing that the buffer temperature will stay below 100 °C and, according to independent model calculations by STUK's external experts this temperature criterion could be exceeded. Posiva needs to present further arguments on why this temperature limit is not a threshold value specifically for chemical changes in bentonite, as this is contrary to a statement in Posiva 2013-01.

According to the performance target L3-BUF-19, the buffer shall allow gases to pass through it without causing damage to the repository system. The only damage to the repository system by gas pressure build-up is suggested (POSIVA-STUK-10248), to be formation of cracks in the buffer, in case that gases dissolved in the pore water cannot penetrate through the buffer effectively. In such circumstances, the gases will discharge along these cracks. The fulfilment of this target is not supported by Posiva's performance analysis.

However, it is stated in POSIVA-STUK-10115 that, although no specific criterion is given, the fulfilment of the performance target will be checked for candidate buffer materials with specific densities. It is unclear if such checking will be done for a buffer comprising montmorillonite in calcium-exchanged form and at the elevated temperatures foreseen to prevail during the early evolution phase of the repository. Posiva needs to present further arguments for the fulfilment of this performance target as it is stated in Posiva 2012-07 that significant uncertainties remain about the gas transport in the buffer, related to mechanistic understanding, system modelling and data.

According to performance target L3-BUF-8, the buffer shall limit microbial activity. POSIVA-STUK-10115 states that the corresponding performance-target criterion is found in design specification L5-BUF-9, which requires the minimum saturated density of the buffer to be 1950 kg/m^3. However, as this specification is used to ensure a desired initial state for the buffer, it is not considered as a performance-target criterion.

Posiva's conception of limited microbial activity within the buffer is supported by experimental evidence referred to in Posiva 2012-04. It is stated in POSIVA-STUK-10248 that microbial activity will be limited in the buffer, the pore space of which is assumed to be well homogenized and be constituted by inter-laminar openings of 1–2 nm. Posiva has not referred to any studies of microbial activity in compacted calcium bentonite, (a cation form into which the buffer is expected to evolve), which may sustain microbial activity owing to its more inhomogeneous pore structure compared to the predominantly sodium form. SKB reports R-11-22 and P-13-16 consider the possibility of microbially mediated sulphate reduction on the canister surface under conditions similar to those in a KBS-3 disposal facility, and the SKB document 1292468 (06.09.2011) states that there might not be a clear cut-off value for microbial activity with respect to swelling pressure/density. Despite the conclusions made in SKB R-11-22, P-13-16 and SKB document 1292468 regarding the possibility of microbial activity in the buffer, Posiva does not present plans for further studies in POSIVA-STUK-10248. Posiva needs to improve its argumentation regarding microbial activity within the buffer and its effects on post-closure safety.

According to performance target L3-BUF-10, the buffer shall mitigate the impact of rock shear on the canister. A conservative premise for the performance target is the assumption that the buffer will turn predominantly into calcium form in the repository. Such material is known to exhibit greater stiffness and strength than the sodium form and, as a result, to be inferior in its performance against rock shear. A saturated density of ≤2050 kg/m^3 for the buffer is stated to ensure protection of a canister against a shear displacement of less than 5 cm.

According to SKB report TR-10-34, which Posiva refers to in the response to STUK's request for additional information POSIVA-STUK-10262, there are uncertainties regarding the material models of the unaffected buffer, the prime ones being in the model of calcium bentonite. Such material models are used to assess the impact of rock shear on the canister numerically. The current material model is based on the knowledge of sodium bentonite and a limited amount of tests on calcium bentonite. Consequently, Posiva needs to improve its understanding of the relationshipo between the properties of the buffer and the characteristics of a shear displacement, including a revision of the material model of bentonite, to reinforce the argument for the performance target.

Performance target L3-BUF-12 states, that the buffer shall be impermeable enough to limit the transport of radionuclides from the canisters into the bedrock. According to design requirement L4-BUF-9, a hydraulic conductivity of less than 10^{-12} m/s for the buffer is sufficient to meet this target and to make diffusion the dominant transport mechanism for solutes. POSIVA-STUK-10115 states that the hydraulic properties of the buffer are maintained for dry densities that exceed 1400 kg/m^3 and, even for dry densities of 1000–1400 kg/m3, the conditions remain largely non-advective. The risk of advective conditions is stated to increase if the dry density approaches 1000 kg/m^3.

The criterion for the hydraulic conductivity to ensure diffusion-dominated transport in the buffer is certainly credible. Also, the design density of the buffer (L5-BUF-9) is specified with a good margin in relation to the criterion, which is shown in e.g. POSIVA-STUK-10332. However, it remains unclear which analyses the actual selection of this specific value is based on. In Posiva's TKS-2009 programme, a hydraulic conductivity of less than 10^{-10} m/s for the backfill (see L4-BAC-5) was considered to make transport diffusion dominated while in the construction licence application this value was justified on the basis of limiting advective flow. As the basis for L3-BUF-12 and L3-BAC-8 (L4-BAC-5) appears to be more or less the same, Posiva is should present arguments for how the difference of two orders of magnitude in hydraulic conductivity for the buffer and the backfill derives from the expected performance of these barriers. It is also unclear why this performance target has been specified given it is stated in POSIVA-STUK-10332 to be redundant in relation to the swelling pressure, for which no performance target has been specified.

According to 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. According to POSIVA-STUK-10115, this performance target is largely redundant, owing to its similarity to L3-BUF-12. It remains unclear why this performance target has been specified, because one and the same design requirement L4-BUF-9 applies to both L3-BUF-12 and L3-BUF-13.

Performance target L3-BUF-14 states that the buffer shall limit the transport of radiocolloids to the rock. It is stated in Posiva 2012-17 that above the saturated density of 1650 kg/m^3 for the buffer, transport of colloids will be limited in the buffer to such an extent that it can be neglected.

This target is considered unnecessary until such time as radiocolloids might be released from a breached canister into the buffer. POSIVA-STUK-10115 states that, above a dry density of about 600 kg/m^3, diffusion of colloids through bentonite is effectively hindered by physical filtration due to the compact microstructure of the material. It is also stated that the effects of the formation of relatively stronger complexes of radionuclides with organic colloids in bentonite remain an open question. POSIVA-STUK-10248 states that the pore structure in fully saturated buffer is constituted only of interlaminar openings of 1–2 nm size. If this is the case, colloids larger than 2 nm in size should be filtered from the buffer. However, lignosulfonate and humic colloids up to five times larger than 2 nm have been found to diffuse through compacted bentonite regardless of the dry density (up to 1800 kg/m3) and ionic strength of the equilibrating aqueous solution (Wold, S. & Eriksen, T. Appl. Clay Sci. 23 (2003) 43–50; Phys. Chem. Earth 32 (2007) 477–484). Neither of the studies was carried out with calcium bentonite which is anticipated to exhibit larger pores than the sodium form and, consequently, is more likely to sustain radiocolloid transport.

Posiva should provide clearer arguments for the minimum density required for the buffer to limit radiocolloid transport to the extent that it can be neglected with due consideration of the factors that have the potential to affect colloid transport (Posiva 2012-07).

Performance target L3-BUF-17 states that the buffer shall be able to keep the canister in the correct position, i.e., to prevent sinking and tilting. According to POSIVA-STUK-10115, this target is assumed to be met if the buffer is manufactured to comply with design requirements L5-BUF-3 and L5-BUF-5. Based on model calculations by SKB, POSIVA-STUK-10115 states that canister sinking is assumed to be less than 2 cm for a swelling pressure of ≥0.2 MPa. Analyses with reduced swelling pressure, corresponding to reduced density or reduced friction angle, are stated to show that long-term canister sinking is insensitive to consolidation and creep.

STUK notes that this is the result from a single modelling exercise, rather than experimental data. It remains unclear, from the performance point of view, why specifically 2 cm is considered as the maximum displacement to fulfil the performance target. The minimum swelling pressure of 0.2 MPa is redundant in relation to the target swelling pressure of 2–15 MPa for the buffer after the attainment of a swelling pressure of at least 2 MPa. The fulfilment of L3-BUF-17 is not supported by Posiva's performance analysis. STUK considers the rationale for the performance target to require further development. Posiva needs to provide futher arguments for the fulfilment of the performance target especially as regards the buffer's ability to prevent canister tilting. In doing so, Posiva needs to quantify the extent of canister tilting that would result in the performance target not being met.

It is stated in performance target L3-ROC-14 that groundwater at the repository level shall initially have sufficiently high ionic strength to reduce the likelihood of chemical erosion of the buffer or backfill. To meet this target, Posiva suggests that the total charge equivalent of cations in the groundwater shall initially be higher than 4 mM. Based on the current knowledge of the site and numerical modelling, POSIVA-STUK-10115 states that the criterion will be fulfilled both initially and in the long term.

Posiva argues for the low likelihood of chemical erosion of the buffer and backfill based mainly on SKB report TR-09-34. In POSIVA-STUK-10337, the performance target is defined to be valid over the whole assessment period of 1 Ma and not just initially as indicated by L3-ROC-14. Posiva provides arguments in POSIVA-STUK-10115 why the groundwater salinity at Olkiluoto is expected to exceed the 4 mM limit.

Despite the uncertainties in colloid formation from montmorillonite and their subsequent erosion, and the fact that chemical erosion of the tunnel backfill materials has not been investigated experimentally, the criterion is considered by STUK to have been robustly specified, especially if the value of 4 mM (rather 4 meq/l) is attributed to divalent cations alone. If the value does include both mono- and divalent cations, as indicated by the performance target, the criterion may no longer be as credible, as the minimum total charge equivalent of cations of 4 meq/l to ensure sufficient stability of montmorillonite, may not be valid subject to the assumptions made related to Figure 7-25 in Posiva 2012-04.

While arguing further for the criterion, Posiva should also address specifically the pH range 9–11 and provide complementary information that could give indications of the susceptibility of montmorillonite to colloid formation, such as observations from X-ray diffraction studies of the interplanar spacing of montmorillonite unit layers. Posiva is currently participating in the EU project BELBaR to improve the understanding of the factors influencing montmorillonite colloid formation and chemical erosion.

According to performance target L3-ROC-15, the groundwater at the repository level shall have limited salinity so that the buffer and backfill will maintain a high enough swelling pressure. To meet this target, the groundwater salinity at the repository depth should be less than 35 g/l (TDS), except during an early phase when salinities up to 70 g/l (TDS) might prevail due to construction activities. According to POSIVA-STUK-10115, this groundwater salinity will be met, both initially and in the long term based on current knowledge of the site and numerical modelling.

Posiva argues for the target swelling pressure of 2–15 MPa for the buffer in Posiva 2012-14. Posiva does not specify a minimum target swelling pressure for the backfill. Posiva 2012-18 estimates the swelling pressure of the backfill to be up to 7 MPa, which is not, however, considered as the maximum target swelling pressure.

In Posiva 2012-14, an empirical parameter, (where is the montmorillonite content and the water content at full saturation) was adopted, to aid specification of the acceptable ranges for the density and montmorillonite content of the buffer. Overall, the target swelling pressure for the buffer is found to be fairly robust for the buffer in relation to the effective montmorillonite dry density (EMDD). However, the empirical parameter appears less robust than the EMDD especially towards the lower end of the density range for the buffer.

While improving the argument for the performance target, Posiva also needs to consider in more depth some of the factors related to the swelling pressure of the buffer and backfill, including the effects from elevated temperature and incomplete homogenization. Also, there is some uncertainty regarding the applicability of the swelling pressure data presented by Posiva to adequately represent conditions on a larger scale in the buffer and backfill, which are composites of blocks and pellet fill and of blocks, foundation layer and pellet fill, respectively.

Posiva has specified performance targets L3-ROC-16, according to which the pH of the groundwater at the repository level shall be within a range where the buffer and backfill remain stable (no montmorillonite dissolution) and L3-ROC-17, according to which the concentration of solutes that can have a detrimental effect on the stability of buffer and backfill (K^+, Fe_{tot}) shall be limited in the groundwater at the repository level. It is stated in POSIVA-STUK-10115 that no quantitative criteria for these performance targets can reasonably be given and that the values observed at the site or estimated by numerical modelling are taken into account in the analysis. However, the (as yet unspecified) criteria are stated in POSIVA-STUK-10115 to be met initially and in the long term based on current knowledge of the site and numerical modelling.

Posiva 2012-04 states that chemical stability of montmorillonite is uncertain because of the significant uncertainties in the thermodynamic and kinetic data. For this reason, Posiva is not able to draw clear conclusions regarding montmorillonite stability. Posiva should manage this uncertainty as comprehensively as possible to show adequate stability of montmorillonite, to ensure robust performance of the buffer and backfill.

Posiva 2012-04 states that the dissolution rate of montmorillonite is low based on Figure 7-23 in the report. If the low dissolution rate shown is not subjected to quantitative analysis (e.g. by reactive transport modelling), a claim that a certain pH range (5–11 in L3-ROC-16) would be more acceptable than any other with respect to buffer and backfill performance is not well justified. It is unclear why Posiva has not considered the slow dissolution of montmorillonite using reactive transport modelling to support the stability argument. Instead, Posiva assumes that montmorillonite is an insoluble cation exchanger, the concentration of which remains invariant with time. Among the primary minerals in the buffer and backfill, montmorillonite is assumed to play a special role in relation to other primary minerals without for a justification for such an assumption. However low the dissolution rate may be, montmorillonite will always hydrolyse to a certain extent if undersaturated with respect to its surrounding aqueous environment. Hence, performance target L3-ROC-16 is not considered credible in its aim for *no* dissolution of montmorillonite in the buffer and backfill. It follows that at the lower limit of acceptable montmorillonite content of 75 % (design specification, L5-BUF-7), no dissolution of montmorillonite would be possible without L3-ROC-16 being violated, which is not credible.

Posiva 2012-14 states that the strongest argument for long-term stability of montmorillonite is provided by natural analogues. However, their use as a primary stability argument is not properly justified by discussion of examples that are directly relevant to repository conditions.

The scarcity of montmorillonite in the Olkiluoto host rock does not support its stability in the repository conditions. STUK notes that the reference groundwater compositions presented by Posiva do not unambiguously fall into the stability area of montmorillonite in thermodynamic stability diagrams. In this respect, it is unclear on what basis Figures 7-21 to 7-23 in Posiva 2012-04 are considered reliable enough to be used to argue for the stability, or instability, of minerals given that the underlying data for montmorillonite are considered highly uncertain by Posiva.

Apart from the effects from groundwater pH, the greatest effort by Posiva to argue for the stability of the buffer and backfill materials has been devoted to long-term alteration by illitization (Posiva 2012-04, Section 6.5.3). Posiva considers illitization unlikely, based mainly on empirical modelling. Reactive transport modelling has not been used to constrain illitization, which would combine thermodynamics and kinetics with the transport of chemical species. Also, Posiva has not provided sufficient arguments for neglecting the possibility of formation of minerals other than illite, depending on the chemical environment to which the buffer and backfill will be subjected in the repository. Thermal-chemical effects on bentonite include cementation, whereby the buffer may crack and become brittle, and devoid of swelling capacity, which could have far reaching implications for, e.g., the buffer's ability to absorb the impacts of rock shear of less than 5 cm, without canister breach. Little is currently known about the properties of the cemented buffer (SKB TR-10-34), the extent of cementation needed to affect the performance of the buffer adversely and the reversibility of the process.

Due to the crucial role montmorillonite plays in ensuring the performance of the buffer and backfill, and indirectly that of the canisters, Posiva needs to improve its arguments for montmorillonite long-term stability and consider the uncertainties involved more comprehensively. Such considerations would lend more credence to the ability of the buffer and backfill to perform in a robust fashion, even despite significant uncertainties involved.

Performance target L3-ROC-10 for the host rock states that groundwater at the repository level shall be anoxic, except during the initial period. This performance target is assumed to be met for several hundred thousand years under the expected repository conditions, whereby the buffer is assumed to perform as expected. Posiva 2012-04 notes the effect of dissolved oxygen concentration in the buffer. In order to avoid canister corrosion, a decisive role is played by the oxygen concentration in the buffer at the canister interface, rather than by dissolved oxygen in the groundwater. The role of the buffer in influencing dissolved oxygen concentration at the canister surface remains implied, as no explicit credit is taken in the performance target for its ability to influence the oxygen concentration.

According to performance target L3-ROC-11 for the host rock, the groundwater at the repository level shall have a high enough pH and low enough chloride concentration to avoid corrosion of the canisters by chloride. The performance target is assumed to be met for several hundred thousand years under expected repository conditions, whereby the buffer is assumed to perform as expected. Posiva 2012-04 notes the effect of pH and chloride concentration in the buffer. In order to avoid canister corrosion, a decisive role is played by the pH and dissolved chloride concentration in the buffer at the canister interface rather than by the pH and dissolved chloride concentration in the groundwater. The role of the buffer in influencing the pH and dissolved chloride concentration at the canister surface remains implied, as no explicit credit is taken in the performance target for its ability to influence the pH and dissolved chloride concentration.

Posiva's reasoning on canister corrosion in terms of the groundwater characteristics assumes that the buffer has no capability to influence the pore fluid oxygen concentration, the pore fluid pH and chloride concentration under expected repository conditions. Under such circumstances, a number of performance targets for the buffer are likely not to be met. Hence, performance targets L3-ROC-10 and L3-ROC-11 assume, counter to Posiva's assumption, declined performance of the buffer.

The specification of the criterion for a dissolved chloride concentration of less than 2 M is considered by STUK to have aimed for robustness. However, in doing so, the criterion does not match performance target L3-ROC-15, which considers attainment of a high enough swelling pressure for the buffer (≥2 MPa) and backfill (as yet unspecified). Depending on the chemical composition of the groundwater, the limits for the total dissolved solids (TDS) specified in L3-ROC-15 may be exceeded at the 2-M limit for the chloride concentration. Although the criterion for the groundwater pH also appears to have sought robustness, its relation to the pH criterion in performance target L3-ROC-16 remains unclear, as regards montmorillonite dissolution. With a decrease in pH from the near-neutral region, the dissolution rate of montmorillonite is known to increase. Hence, the pH criterion in L3-ROC-11 may be less credible than that in L3-ROC-16 to ensure montmorillonite stability in the buffer and backfill.

Posiva does not expect permafrost to reach the repository depth during the assessment period of 1 Ma (Posiva 2012-04). However, should permafrost reach the repository depth, the buffer and backfill are stated to be able to withstand it without any permanent damage to their safety functions. Any effects on swelling pressure or hydraulic conductivity due to freezing are considered by Posiva to be completely reversible upon thawing. Even if such reversal of effects from permafrost were to occur, the safety significance of the issue stems also from the effects on the material properties and safety functions *during* the time between freezing and thawing. A safety significant issue may arise from, for example, desiccation of the buffer and backfill due to cryosuction whereby water migrates from these barriers to a freezing zone. Should this occur, the swelling pressure of the buffer and backfill could decrease, due to shrinkage of these barriers, to the extent that their safety functions are adversely affected. In ice environments, metal ion transport can be faster than that in free solution and chemical reactions might be accelerated; both being examples of factors not considered in detail by Posiva. Posiva needs to show improved preparedness in the variant and disturbance scenarios for the possibility that one or several performance targets of the barriers are not met due to permafrost formation. Lack of fulfilment of a performance target beyond the associated criterion can be rationalized credibly using a conceptual model constructed to describe a relevant safety function and the factors affecting it.

Conclusions

Although there are several areas identified above where Posiva will need to provide further argumentation in future work, STUK considers that Posiva has described and justified the performance of the buffer adequately at this licensing phase. In particular, in moving towards an operating licence application, there are requirements for further developments with respect to the performance of the buffer, especially as many of the performance targets lack a criterion. Before submission of an operating licence application, Posiva should reconsider the safety functions and performance targets critically in order to improve and clarify their argumentation and to remove internal inconsistencies in the target specifications. Examples of performance issues that call for further argumentation include long-term chemical stability of montmorillonite and microbial activity in the buffer and backfill, owing to their potentially significant influence on the performance of these and other barriers. At present, it is difficult to assess if some of the performance targets are based on sufficient, high-quality scientific knowledge and expert judgement.

There is also a need to develop FEP descriptions further, to address all the relevant interactions within and between barriers more clearly and comprehensively, and to construct a conceptual model for each safety function of the buffer and the factors affecting them. This would contribute to a more robust specification of the performance-target criteria. Posiva's progress in its RD&D work regarding these issues will be followed by STUK.

3.4 Backfill

3.4.1 Characterization and suitability

Based on YVL D.5, Posiva should identify the relevant properties of each backfill material to be characterized. Emphasis in the characterization should be on properties affecting the long-term performance and compatibility with other barriers.

Backfill materials to be used need to be sufficiently stable in repository conditions with respect to, for example, temperature, groundwater chemistry and pressure, and need to maintain their performance (i.e., to meet the performance targets) in space and time. Materials should not jeopardize the performance of other barriers, e.g. the canister and buffer (e.g. not contain excessive amounts of materials that directly or indirectly exert adverse effects on other barriers, such as iron, organic material, nitrogen compounds, oxidizing compounds, hydroxide ions).

Posiva should describe how one backfill material can be substituted by another material, without compromising the performance of the backfill, or any other barrier. In addition, Posiva should identify a list of favourable properties of other barriers that can be adversely affected by harmful chemical substances contained in the backfill components.

Posiva has considered the topic of backfill material characterization in various documents, for example in Posiva 2012-18, 2012-05 and 2012-04.

Posiva 2012-18 presents the design specifications for the backfill and plug, including the properties for chemical characterization. For Friedland clay the montmorillonite content is defined to be 30-38 wt% and for the bentonite material the montmorillonite content is 75-90 wt%. For all materials, Posiva defines total sulphur content <1 wt%, sulphide content <0.5 wt% and organic carbon content <1 wt%. Typical material properties are given in Posiva 2012-18 (Tables 3-1, 3-2 and 3-3). This approach does not explain the material properties from which the performance (swelling pressure, low permeability) of the buffer originates.

Posiva has a characterization scheme for the clay/bentonite materials used in the backfill, which is simple and straightforward. However, as with the buffer materials scheme, STUK considers that it might not consider all material properties affecting performance. Posiva's approach concentrates on a few (the above-mentioned) chemical properties and the montmorillonite content. Posiva's safety case does not present a description of how the characteristic (chemical, mineralogical, hydraulic, mechanical and microbiological) properties of the backfill are foreseen to evolve with time.

If the required properties are satisfied, clay/bentonite materials are considered inter-changeable. Posiva has indicated that the substitution of the current reference backfill material with different montmorillonite-bearing bentonites is possible if future circumstances so require. It is sensible to make such contingency plans, but any new backfill material may require substantial testing and associated modelling of behaviour to confirm the suitability of such a substitution.

In the disposal concept development programme, Posiva has acknowledged that understanding of characterization procedures needs to be improved and intends to perform further work on the topic (project acronyms ECCA, DEMPA). Posiva's development programme also describes a general procedure by which various bentonite clays and Friedland clay will be tested and compared in order to find a suitable material for blocks for a full-scale test in Onkalo.

Conclusions

As with the buffer, for this licensing phase, Posiva's characterization approach for the backfill does not need to be fully developed as long as Posiva is aware of the shortcomings involved and is carrying out dedicated research work to improve the understanding of the properties affecting on the behaviour of the clay/bentonite materials. STUK considers it sufficient to identify a programme of work to ensure that a scheme is in place at the appropriate time. Clearly, this programme will need to take account of the issues identified above and Posiva will need to carry out more work to ensure that the scheme is comprehensive. The currently documented understanding of material properties affecting the performance of the clay/bentonite barrier is limited.

Any future decision to replace, for example, Friedland clay by another type of bentonite might require significantly more data and associated modelling of behaviour to confirm the suitability of such a substitution. However, Posiva has acknowledged the situation and intends to improve understanding and study the relationships between the material properties and the performance further. While STUK considers that the understanding is sufficient at this licensing phase it requires more work to be completed before an operating licence application.

3.4.2 QC

Based on YVL B.2, YVL D.5, Posiva should classify the barriers as systems and structures contributing to safety and further inspection classes, where applicable. Posiva should determine the relationship between the system, structure or device and the inspection class and testing procedure and, in addition develop the necessary guides, instructions and system specific quality manuals in order to carry out the QA/QC procedures properly.

The QC procedure covers the fabrication (material, conditions, devices, personnel, documentation) and emplacement phases (compliance with the requirements, documentation).

Posiva has considered the quality control procedures in Posiva 2012-17 and 2012-18. In these reports, QC is part of all phases from material selection/approval and manufacturing of components, to emplacement of buffer and backfill and verification of compliance with the requirements. The QC chain is continuous for the whole process. Although QC is described in a comprehensive way in various parts of the production line reports, a Chapter containing a summary description of all QC activities is missing.

Posiva has not described the methods of quality verification of the structures of the barrier system. For example, the way to verify compliance with the requirements of the lower and upper part of a buffer or a backfilling sequence has not been presented. The need for instant availability of the results for the necessary decision making process is not discussed. Posiva has plans to produce the necessary QC documentation, but has not described clearly how and when the instructions, manuals, method and process descriptions needed to manage the QC process are to be developed.

Posiva will inevitably need to develop a set of procedures to enable the testing of various materials and structures to be carried out in an acceptable manner. Posiva has planned such a project (Development programme, DEMPA), partly in cooperation with SKB.

Conclusions

STUK considers that the route to a sound QC system is understood by Posiva and the eventual QC programme is likely to utilize well-developed quality system methodologies. Because QC activities for the backfill will not come into play for some time (allowing adequate time to prepare them), Posiva's description of QC activities in connection with producing systems like the buffer and backfill are considered sufficient at this phase of licensing. There is clearly work to be done in producing both the technology and the necessary documentation for various parts of the process.

3.4.3 Performance

Guide YVL D.5 requires that performance targets be specified for each safety function, based on high-quality scientific knowledge and expert judgement. In doing so, account shall be taken of the factors affecting the disposal conditions during each assessment period, as well as their combined effects. In defining performance targets for the safety functions provided by means of the backfill, account shall also be taken of the quantities and half-lives of radioactive materials. Conceptual models shall be constructed to describe the safety functions of the backfill and the factors affecting them.

Posiva 2012-07 presents the description of each factor (FEP) considered by Posiva to be reasonably likely to affect the development of the disposal system. Such descriptions are intended to address relevant interactions between a specific factor and all the other factors that influence it. As such, they serve the purpose of providing the basis for conceptual models constructed to describe the safety functions and the factors affecting them. The objective of Posiva 2013-01 is to describe the conceptual models used and their main assumptions. Presentation of the reasoning and rationale for the derivation of the performance targets is a key aspect of Posiva 2012-03. Posiva's assessment of the fulfilment of the performance targets is presented in Posiva 2012-04.

Similarly to the buffer, most of the performance targets for the backfill are found to lack an associated criterion, which makes assessment of their fulfilment in relation to the performance assessment in Posiva 2012-04 difficult. Many of them also lack apparent correspondence with Posiva 2012-07, do not meet the requirements of Guide YVL D.5, in not being a measurable or assessable characteristic of the backfill, or do not have a conceptual model to support their unambiguous definition.

According to performance target L3-BAC-8, the backfill shall limit advective flow along the deposition tunnels. A hydraulic conductivity of $\leq 10^{-10}$ m/s over the whole cross-section of the disposal tunnel after full saturation of the backfill material is stated (design specification L5-BAC-5) to ensure fulfilment of this target. POSIVA-STUK-10115 states that the hydraulic conductivity of Posiva's reference backfill material (Friedland clay), measured in conditions expected in the backfilled tunnels, meets the target with a good margin.

The performance target is assumed to be met upon full saturation of the backfill. The references provided in POSIVA-STUK-10115 do not present information on how long full saturation of the backfill is foreseen to take, to support the performance target. Posiva 2012-03 states that the likelihood of advective conditions along the deposition tunnels is considered high, before backfill saturation. If the plug cannot maintain its hydraulic isolation capacity after 100 years and full saturation of the backfill takes longer than this, it is possible that advective conditions are established between a deposition tunnel and the central tunnel, until full saturation of the backfill. This would depend on how, and at what rate, the backfill in the central tunnel saturates. Posiva 2012-03 states that a limit of maximum local inflow into a deposition tunnel is 0.25 l/min at the time of backfill installation. It is unclear how this value, associated with the management of water inflow during the construction and the verification of the deposition tunnels for disposal, relates to the criterion for the hydraulic conductivity of the backfill.

In the calculations presented in Posiva 2013-01, three values of saturated hydraulic conductivity of the backfill, spanning two orders of magnitude, were considered as input to THM model calculations. No conclusion is presented as to whether the backfill hydraulic conductivity should specifically be less than any of the values considered in the calculations, as it is stated that the backfill *"hydraulic conductivity was that* ***required*** *(< 10^{10} m/s)."* (our emphasis). Similarly to performance target L3-BUF-12 for the buffer, it is unclear whether the criterion for L3-BAC-8 arises from an analysis carried out in the safety case.

According to performance target L3-BAC-9, the plugs shall isolate the deposition tunnels hydraulically during the operational phase of the repository. A hydraulic conductivity of less than 10^{-11} m/s for the concrete mass and a montmorillonite content of 75–90% for the bentonite seal (dry density >1400 kg/m^3) of the plug are stated in design specifications L5-BAC-18 and L5-BAC-19 to ensure fulfilment of the target.

Posiva asserts in POSIVA-STUK-10115 that the low-pH concrete to be used in the plugs can be made to provide a very low hydraulic conductivity. However, it remains unclear on which performance analysis the target hydraulic conductivity (≤10^{-11} m/s) for the plug, which is an order of magnitude lower than for the tunnel backfill material (cf. L4-BAC-5), is based on. Posiva is currently testing the performance of the backfill plugs within the EU project, DOPAS.

Performance target L3-BAC-13 states that the chemical composition of the backfill and plugs shall not jeopardise the performance of the buffer, canister or bedrock. According to design specifications L5-BAC-24 and L5-BAC-25, the organics and sulphur content in the backfill shall be less than 1 wt% to ensure the fulfilment of this target. The sulphide content shall be less than 0.5 wt%. Both of these design specifications pertain to mitigating microbial activity within the backfill, most notably reduction of sulphate to sulphide, which is a canister corroding agent.

POSIVA-STUK-10115 acknowledges the limited knowledge about microbial activity in the backfill material. It also considers microbial activity to be more likely in the backfill, especially at the host rock interface or in rock fractures containing eroded backfill material, than in the buffer. Posiva assumes that performance target L3-BUF-8 for the buffer is met at a saturated density of ≥1950 kg/m^3, whereby the effective montmorillonite dry density (EMDD) would exceed about 1300 kg/m3. In the absence of any relevant studies with the backfill materials, microbial activity can be expected to occur as the backfill EMDD is 960–1380 kg/m^3 (after homogenization 1000–1300 kg/m^3; Posiva 2012-18), being consistently lower than the threshold EMDD of 1300 kg/m^3 to limit microbial activity in the buffer. Consequently, not only microbial sulphate reduction but also microbial alteration of the primary backfill minerals, including montmorillonite, can be expected.

In Posiva 2012-03, it is stated that the substances in the backfill that are able to jeopardise the performance of the EBS and host rock are the same as those analysed for the buffer, e.g., sulphur, iron and organic compounds. According to design requirement L4-BAC-18, the amounts of oxidizing and nitric compounds in the backfill should also be limited. However, Posiva has not defined design specifications for the amounts of oxidizing and nitric compounds, and iron in the backfill.

According to performance target L3-BAC-16, the backfill shall keep the buffer in place if the dry density of the reference material lies in the range between 1600–1950 kg/m^3 (POSIVA-STUK-10115). POSIVA-STUK-10115 states that it has been shown by modelling that the backfill, designed and emplaced as required, keeps the buffer in place. The model calculations in Posiva 2012-25 to support this assertion assume the backfill to be dry and the buffer fully saturated. It is unclear how the swelling capacity of the buffer has been taken into account in these model calculations. For example, it is unclear if a possibility has been considered in which the buffer blocks beneath a canister would saturate first, resulting in heave of the canister and the overlying blocks, subject to the constraints of the swelling capacity of the buffer. The rationale behind this performance target is based in part on unpublished model results (POSIVA-STUK-10115).

It can be seen from POSIVA-STUK-10332 that the experimental swelling pressure data do not cover the full density range for the backfill that is considered acceptable by Posiva. Also, few data points exist for the swelling pressure of calcium-exchanged backfill materials. These findings, along with there being no specified target swelling pressure, do not unambiguously support the density range considered acceptable by Posiva.

In Posiva 2012-25, the maximum admissible heave is calculated to be 141 mm based on the assumption that the critical saturated density for the buffer to ensure proper sealing of a deposition hole is 1990 kg/m^3. In Posiva 2012-47, the calculated maximum vertical displacement is reported to be 16 cm. However, Posiva does not make an unambiguous conclusion about the maximum vertical displacement of the buffer, subject to fulfilment of the performance target.

POSIVA-STUK-10239 is not clear in presenting Posiva's understanding of the couplings between the density, swelling pressure and swelling capacity of the backfill, or how this understanding is utilized in specifying the performance targets.

Posiva has specified a performance target L3-BAC-17, according to which the backfill shall contribute to the mechanical stability of the deposition tunnels. A good contact of the backfill, the dry density of which is 1600–1950 kg/m^3, with the host rock is stated in design requirement L4-BAC-29 to ensure fulfilment of this target.

According to POSIVA-STUK-10239, *"a good contact with the host rock"* in design requirement L4-BAC-29 means that the installation of the pellet filling is carried out in a way that no visible gaps remain between the pellets and the rock. Posiva has not assumed a minimum swelling pressure necessary for the performance target to be met. It is unclear how a lack of visible gaps in the pellet filling contributes to the mechanical stability of the deposition tunnels, without any pressure being exerted by the backfill. Also, POSIVA-STUK-10332 (POS-019672, 3.10.2014) maintains that a sufficient (as yet unspecified) swelling pressure be created by the backfill to meet design requirement L4-BAC-28. Assuming that the backfill is able to homogenize and self-heal (Posiva 2012-18), and to have such a low hydraulic conductivity, it is unclear how these processes would occur without the backfill exerting a force on a tunnel wall.

The vague wording of design requirement L4-BAC-29 has been acknowledged in POSIVA-STUK-10239. Posiva has not currently specified a target for the swelling pressure of the backfill, because the target for the hydraulic conductivity is stated indirectly to include a target for the swelling pressure as well. However, there exists no implied relationship between the swelling pressure of the backfill and the mechanical stability of the deposition tunnels, due to the fact that Posiva does not present a relation between the hydraulic conductivity of the backfill and the mechanical stability of the deposition tunnels. Posiva states in POSIVA-STUK-10239 that it is possible that a criterion for the swelling pressure of the backfill will be specified from the viewpoint of self-healing.

Performance target L3-BAC-17, the underlying basis of which remains somewhat unclear to STUK, lacks a clear connection to the functionality expected of the barrier.

According to performance target L3-BAC-18, the plugs shall keep the backfill in place during the operational phase. Design specification L5-BAC-31A states that a mechanical strength of the plug of more than 7.5 MPa ensures fulfilment of this target.

As the hydraulic pressure at the repository depth of 420 m is about 4.1 MPa, the upper limit for the swelling pressure of the backfill material is about 3.4 MPa, to keep the plug in place (L5-BAC-31). In Posiva 2012-18, the swelling pressure of the backfill is stated to range from a few hundred kPa up to 7 MPa. On the other hand, Posiva 2012-18 expects the swelling pressure to be 1–3 MPa after homogenization of the backfill. Posiva does not present an estimate of the time it takes for the backfill to homogenize to the extent that the swelling pressure would be 1–3 MPa. This expected range of swelling pressures also remains unsupported by the experimental results from homogenization tests for Friedland clay reported in Posiva WR 2012-74. As to the time needed for the buffer to homogenize to the extent that its performance targets are met, Posiva 2012-14 states it to be "long" without elaborating it in further detail.

Testing of the plugs is underway within the EU project, DOPAS, and the final specifications will be decided on the basis of these tests (POSIVA-STUK-10115).

According to performance target L3-BAC-19, the backfill shall contribute to preventing uplift of the canister in a deposition hole. Compliance with this performance target is stated in POSIVA-STUK-10115 to depend on several characteristics of the backfill and buffer. It is also stated in POSIVA-STUK-10115 that it has been shown by modelling that the backfill, designed and emplaced as required, will keep the buffer (cf. L3-BAC-16) and the canister in place.

According to POSIVA-STUK-10239, performance target L3-BAC-19 is largely redundant in relation to L3-BUF-16 and, therefore, it is unclear why it has been specified.

Conclusions

Although there are several areas identified above where Posiva will need to provide further argumentation in future work, STUK considers that Posiva has described and justified the performance of the backfill adequately at this licensing phase. In particular, in moving towards an operating licence application, there are requirements for further developments with respect to the performance of the backfill, especially as many of the performance targets lack a criterion. Before submission of the operating licence application, Posiva should reconsider the safety functions and performance targets critically, in order to improve and clarify their argumentation and to remove internal inconsistencies in the target specifications. Due to the ambiguities in argumentation and lack of criteria, it is difficult to assess at present if some of the performance targets are based on sufficient, high-quality scientific knowledge and expert judgement. A clearer connection of the performance targets to the functionality expected of the backfill is called for in the operating licence phase.

There is also a need to develop FEP descriptions further to address all the relevant interactions within and between barriers more clearly and comprehensively and to construct a conceptual model for each safety function of the backfill and the factors affecting them. This would contribute to a more robust specification of the performance-target criteria. Posiva's progress in its RD&D work regarding these issues will be followed by STUK.

3.5 Disposal site and the natural barrier

3.5.1 Site characterisation

GD 736/2008 requires that the natural geological characteristics of the disposal site shall be favourable to the isolation of radioactive waste from the environment. As stated in YVL D.5 102, preparations for the disposal of SNF start with selecting and characterising the disposal site, which means collecting the data necessary for assessing the operational and long-term safety of the facilities.

According to YVL D.5 408, at least 1) the stability and water tightness of the rock, 2) low groundwater flow, 3) favourable groundwater chemistry, and 4) retardation properties of the planned disposal depth bedrock shall be considered as safety properties (i.e. functions) of the natural barrier that need to be characterised. The disposal depth is considered to act as a separate far-field property that provides protection against natural phenomena and human actions.

These requirements have been the basis for the characterisation programme extending over 25 years, that Posiva and its predecessor have been carrying out in Olkiluoto. In many respects Posiva has been one of the forerunners in high-level waste disposal site characterisation work and one of the few organisations that have extensively studied the crystalline hard rock disposal concept. As a consequence of this long-lasting continuous work, Olkiluoto is at present the most diversely studied and probably the best characterised volume of Finnish bedrock.

In many respects, Posiva's achievements to date in bedrock research and characterisation are at the level of state-of-the-art. Site evaluations for geological disposal have been developing for a few decades, and are still evolving, with questions often arising about the nature and stability of the deep geological environment over long periods into the future.

Crystalline hard rock

Posiva divides the geological model of Olkiluoto into ductile, lithological, alteration, brittle, and discrete fracture network (DFN) models (Posiva 2011-02). These are interrelated and Posiva has presented an aim of integrating the geological submodels more tightly (internal confidence in the geological model). The bedrock at Olkiluoto is typical of the, Precambrian supracrustal, high-grade metamorphic rock of Southern Finland. The major rock types identified are migmatitic gneisses, tonalitic-granodioritic-granitic gneisses and pegmatitic granites.

In many respects the *ductile deformation* model of Olkiluoto is a cornerstone to many other site modelling disciplines. The history and kinetics of ductile deformation are important in understanding and predicting the three dimensional lithological and alteration continuity and brittle deformation. Posiva identifies five different ductile deformation phases in Olkiluoto and divides the bedrock into three tectonic units that are bordered, or cross-cut, by deformation zones. Deformation phase D_2 is the most significant, and has pervasively deformed the whole site. Signs of other ductile deformation phases are variously visible in different units and zones of bedrock. The Selkänummi deformation zone (SDZ), at the border zone of Northern Tectonic Unit (NTU), and the Liikla Shear Zone (LSZ), at border zone of Southern Tectonic Unit (STU), have been strongly affected by D_2 and D_3. Parts of the Central Tectonic Unit (CTU) are intensively affected by deformation phase D_3, and also contain cross-cutting Flutanperä Deformation zone (FDZ), that was formed during D_3. The CTU is cross-cut by phase D_4 deformation zones $D_{4\text{-}1}$ and $D_{4\text{-}2}$. However, there are some ambiguities yet to resolve in Posiva's ductile evolution description. For example, the younger zones $D_{4\text{-}1}$ and $D_{4\text{-}2}$ clearly cross-cut the older LSZ, but not the older SDZ (Posiva 2011-02, Fig. 4-19). If SDZ is a dextral strike-slip fault that has also been active in D_4, then the kinematics of faulting would require that the southern counterpart of SDZ would exhibit similar features. Posiva does not present fold axes or lineation orientations related to different deformation phases. Consequently the kinematic justification of the deformation history remains inadequate. Posiva is, however, of the opinion that conceptual uncertainty related to the ductile deformation model would be low, if the eastern areas of Olkiluoto Island are excluded.

Posiva has characterised Olkiluoto *lithology* extensively from bedrock exposures, surface investigation trenches, underground tunnels and drill cores during the site investigations. Over the years, there have been some revisions of lithological terminology but, on the whole, it is judged that Posiva's current lithological understanding of the ground surface continuity of rock types is acceptable for the purposes of assessing the current license application. With respect to predicting the continuity of bedrock lithologies in three dimensions (e.g. pegmatites), especially for the planned repository volume, there is further work to be done. The three dimensional modelling of extent and continuity of various lithologies relies strongly on the conceptual understanding of the ductile deformation. Posiva considers uncertainties to be moderate in the central Olkiluoto area, yet concludes that the confidence to the lithological model is high in the central area.

Posiva includes in its *brittle deformation* model individual joints, veins and fissures, as well as single plane faults and deformation zones. Individual joints, veins and fissures without signs of movement should indicate a local extensional stress regime. Posiva has modelled major or medium size Brittle Fault Zones (BFZ; e.g. major BFZ019 and BFZ020 zones) and local sized Brittle Joint Zones (i.e. Brittle Joint Zone intersections – BJI) at Olkiluoto. Posiva divides brittle deformation zones into 1) site-scale brittle deformation zones (ground surface trace >1000 m) and 2) repository-scale brittle deformation zones (< 1000 m). BJIs occur only at the repository scale (WR 2010-70). Posiva has investigated the orientations of faults and zones kinematically (WR 2009-130). This research recognizes a set of SE dipping, low-angle faults showing prominent, reverse dip-slip movement related to ductile deformation stage shears and weakness zones. Another fault set recognised is subvertical and has strikes to the N-S and E-W. Compared to the earlier site description (Posiva 2009-01) Posiva has found 100 new BFZs, and has modified 48 previously identified zones. Posiva lists medium (fault core width, influence zones, brittle joints, and sequence of brittle events) and high (orientation, size, and spatial distribution of smaller zones) uncertainties for the brittle deformation model, but is nevertheless unclear when it states its confidence in the brittle deformation zones. Posiva 2011-02 claims that site-scale zones are inherently medium or high in confidence but, elsewhere, lists site scale lineaments that are low in confidence. Similarly, Posiva says that repository scale deformation zones are automatically set as low or medium confidence but, elsewhere, lists 35 zones that are high in confidence.

Posiva's *alteration model* identifies three different ages of alteration: retrogressive metamorphism (sericitisation, saussuritisation), hydrothermal alteration (illitisation-kaolinisation, sulphidisation, and carbonatisation), and surface weathering (goethite, hematite, oxyhydroxides, feldspar alteration at shallow depths and precipitation of fracture calcites). Hydrothermal pathways have been controlled by some of the existing brittle fracture or deformation zones, but also by zones that are now welded. The age of potentially relevant alteration-related mineralisation is < 1.57 Ga (Posiva 2011-02). The N-S and E-W striking faults in Olkiluoto tend to contain small sulphide enrichments and have consistent orientations with Eurajoki rapakivi granite related greisen veins. The porosity of altered rock is higher than that of fresh rock. Kaolinitised parts of the bedrock are found in the upper 200 metres. Illitisation is found at all depths, while sulphidisation is located in the upper 300 metres. Posiva indicates that the modelled extents of the altered rock volumes and the potential existence of unknown altered volumes have medium to high uncertainty, while identification of alteration degree has medium.

The *geological DFN model* divides Olkiluoto into six fracture domains (3 units, 3 zones). The fracture set orientations within domains are classified into global (3 sets), local (4 sets) and omitted (6 sets). 'Global' means that the orientation pattern is seen everywhere on Olkiluoto Island. 'Local' is seen only in specific lithologies or domains. 'Omitted' are seen only in deformation zones, in few lithologies, or are overlapped by global sets. Subvertical fracture sets do not exhibit depth dependence of intensity, but fracture sets concordant with foliation appear to exhibit some depth dependence. Based on Swedish studies (e.g. SKB R-07-46), Posiva uses a power law distributions to describe fracture sizes, but also recognises that its fracture-size model is quite poorly constrained. Posiva has tested two optional conceptual models for fracture sizes (Posiva 2011-02). The tectonic continuum model (TCM) is preferred because of a simpler formulation of the concept. Consideration of uncertainties in the geo-DFN model follows Posiva's earlier approach (WR 2009-77) and does not assign any levels to uncertainty sources. Uncertainties are simply ascribed to: conceptual uncertainty (division to populations), mathematical uncertainty (e.g. fractures simple disks vs. other options) and parameter uncertainty (fracture sizes, and distributions). The division of fracture orientations into 13 populations is detailed and it is likely that this detailed discrimination is not statistically meaningful and is also genetically questionable. Posiva recognises this, at least partially, and, in the hydro-DFN modelling, divides Olkiluoto into four fracture domains (see below). STUK considers that high uncertainty should be expected with respect to the fracture size modelling. Posiva agrees that the geological DFN model needs to be better integrated with other geological submodels.

Over the years, Posiva has developed its *uncertainty management* for crystalline hard rock at several stages. Currently, Posiva divides uncertainties into two categories: conceptual (related to conceptual models) and technical (related to modelling methodologies and data management). The significance of uncertainties is divided into three categories (low, medium, and high). However, Posiva does not use this management scheme systematically for all submodels (cf. geo-DFN) and, in some cases, the division into conceptual and technical uncertainties is not logical. For example, uncertainty related to depth extent of lithological units is conceptual, while the sizes of the units are technical. The concept of confidence overlaps with Posiva's uncertainty classification. There is further work to be done in assessment of uncertainties.

Posiva has also measured *reliability* of its crystalline hard rock models, using prediction-outcome (P-O) studies (Posiva 2011-02). The P-O studies include ductile deformation, lithological, brittle deformation and alteration predictions. According to Posiva, lithological and alteration predictions were only successful to a limited extent, while ductile deformation and site-scale brittle deformation zone predictions were mostly successful. Predictions underestimate significantly the number of repository scale brittle deformation zones. Predictions of fracture orientations are more successful, with more horizontal fractures than vertical ones. Based on brittle deformation zone predictions, Posiva states that it is almost impossible to identify Tunnel Cross-cutting Features (TCF), i.e. Full Perimeter Intersections (FPI), from the underground pilot hole data, because TCFs look similar in borehole data to any ordinary slickensided feature. This issue presents a significant challenge for Posiva's Rock Suitability Classification (RSC) methodology.

Conclusions
Posiva adequately describes ductile and brittle deformation, and lithology in the Olkiluoto central areas. However, Posiva also recognises that better understanding of ductile evolution, lithology, and brittle deformation history is required for the detailed-scale modelling work that it needs for the planned repository volume. The understanding of ductile deformation (history and kinetics) is important in understanding and predicting three-dimensional lithological continuity and brittle deformation. The critical primary data and justifications for the ductile deformation model should be presented more clearly. Posiva considers its alteration modelling results relatively uncertain. However, because of the mineralisation potential of hydrothermal alteration, there is an evident need to constrain and conclude the significance of alteration better. Posiva does not assign any levels of uncertainties for its geo-DFN modelling, but significant uncertainties should be expected. In general terms, Posiva has progressed significantly in assigning uncertainties for its hard rock models, but there is still further work to be done. Increasing the consistency between hard rock sub-models and uncertainty handling will increase confidence in the safety case.

Site hydrogeology
Posiva's groundwater flow models (WR 2012-32) are the basis of palaeohydrogeological evaluations, future site evolution and radionuclide transport considerations. Therefore, models need to represent reality adequately. Considerations of groundwater flow are based on division of the bedrock into hydrogeologically conductive zones and poorly conductive, sparsely fractured rock (SFR). A great part of Posiva's RSC method is also based on this hydraulic division of the bedrock. Conceptually, groundwater flow models need to have relationships to modelled brittle single-plane faults and deformation zones, as well as to geo-DFN models. Posiva's primary modelling approach for groundwater flow combines deterministic hydrogeological zones with stochastic hydro-DFN presentations that are applied to the SFR. Properties of hydrogeological zones and sparsely fractured bedrock are parameterised with data from single-hole Posiva Flow Log (PFL) tests (WR 2012-32).

Posiva says that site-scale *hydrogeological zones* are carefully evaluated against the brittle deformation model. However, the zones of the hydrogeological model are less complex than the zones described in the brittle deformation model. Brittle deformation zones have, in many cases, a larger extent than corresponding hydrogeological zones but, in some cases the hydraulic connections have larger extent than the corresponding brittle deformation zone. At the site-scale especially, hydrogeological zones larger than corresponding brittle fracture zones are contradictory. A practical example of the contradiction is provided by HZ19C, which is more extensive than BFZ019C. Posiva explains that HZ19C takes into account BFZ019C and a fault splay related to BFZ019C. If there are good grounds for the extent of HZ19C, then BFZ19C should also be modelled accordingly. Posiva states that the extents of the hydrogeological zones are based on hydraulic pumping test responses, overpressure tests, and various field activities. These interpretations should be utilised in the brittle deformation model as well. There appears to be some persistent discrepancy between the hydrogeological zone model and the brittle deformation model. Posiva may need to consider extending hydrogeological zones to ensure connectivity in flow model. Minimising the brittle deformation zone dimensions would preserve sparsely fractured rock in the repository volume. Posiva should consider common criteria for zone extrapolations for both disciplines and a more unified model for both flow modelling and repository layout design purposes. There is a reasonably clear definition of site-scale and repository-scale zones for the brittle deformation model, but similar classification for hydrogeological zones are ambiguous. Transmissivities for hydrogeological zones are broadly variable. This has been solved using a stochastic approach, taking into account hydrozone specific means, standard deviations and depth dependence. For certain structures at least, the depth dependence can be questioned (WR 2012-32). Posiva's hydraulic parameterisation also does not take into account the structural anisotropy that causes the hydrogeological anisotropy.

Posiva does not present uncertainty estimates for the structures in the hydrogeological zone model. However, it claims that confidence in the subhorizontal zone locations and their average hydrological properties is high in the central area, but agrees that the models are not deterministic in the areas where no borehole data are available (Posiva 2013-01). Most hydrogeological structures are compared to brittle deformation structures, but these comparisons are generally only simple justifications for the differences between the models.

The *hydro-DFN* model is based on a reduced number of domains compared to Geo-DFN model. According to Posiva, merging adjacent domains having similar characteristics is essential to achieve statistical significance in the PFL distributions that are used for model calibrations. There are other differences as well. While the Geo-DFN aims to summarise information from the whole fracture database, the main Hydro-DFN (Base case – case A) considers only open fractures. Cases with open and connected fractures (case B) and all fractures with internal heterogeneity (case C), are considered as variants. Case B and C fracture size models differ from the geo-DFN. In case B, the connectivity of fractures is ensured by using a log-normal distribution (in which large individual fractures are possible). Case C follows the global power law, but all fractures are considered utilising a "checker board" option, making them only partially open and connected. Conceptually, case C is the first time that Posiva has considered heterogenous fracture planes and attempted to downscale generalised hydraulic transmissivities into these. These same transmissivities were originally upscaled from individual heterogeneous measurements to generalised effective values. According to Posiva, within the SFR outside the hydrogeological zones, PFL conductive fracture frequency, as well as their specific capacity, decreases significantly with depth. This is confusing when compared to the conclusions about the geo-DFN fracture sets (see above), unless depth dependent channelling within fractures is hypothesised. However, Posiva is of the opinion that the depth zonation of hydraulically conductive fractures is in accordance with hydrogeochemical zonation at Olkiluoto. Posiva also makes assumptions on fracture size and transmissivity: correlated, semi-correlated and uncorrelated. According to Posiva, the semi-correlated relationship is the most effective method of reducing or removing inconsistencies from the hydro-DFN model. However, there appears to be no practical or literature evidence (from outside Olkiluoto and Forsmark) that a size-transmissivity relation exists within SFR outside site- or repository-scale hydrogeological zones. Posiva divides all hydro-DFN domains into four depth zones. The border between depth zone 3 and 4 should be justified better, since it is directly above the planned repository horizon.

While considering the hydro-DFN uncertainties, Posiva states that modelling is based on a large amount of data although, according to Posiva, ONKALO-based data should be used more for calibrations and there are uncertainties in conductive fracture sizes and frequencies. Posiva does not question the conceptual basis of the hydro-DFN modelling, although they have some concerns on the PFL method at the measurement threshold. However, the determinism of PFL observations can also be questioned with respect to correlations with identified fractures (Posiva 2011-02). A number of PFL observations are not correlated to any fractures. For hydro-DFN modelling purposes, a number of PFL observations have been assigned to the nearest (within ±2 m) identified fractures. The numbers of parameters or distributions needed in the hydro-DFN modelling are assumptions or judgements. These include, e.g., transmissivity distribution, fracture intensity-size relationships, flow porosity and transport aperture. Posiva has scoped some of the uncertainties related to these assumptions with sensitivity analyses and alternative models, but a great deal of these analyses cannot be verified without prediction-outcome studies.

Posiva uses equivalent porous medium (EPM) models to consider the evolution of hydraulic flow and solute transport at the site scale. The two important application areas are palaeohydrogeological models and P-O studies of ONKALO-induced disturbances. The EPM model at the site scale is based on the HZ model and upscaling of the hydro-DFN model. Upscaling has been done separately for each of the three different modelling cases (cases A, B, and C) to each of the four hydraulic domains and to each depth zone, in terms of effective conductivity (K_{eff}), porosity (φ_{eff}) and the anisotropy ratio (K_{hmax}/K_z). However, only the Base Case (case A) has been used for the applications mentioned. Posiva is confident regarding the effective properties (transmissivities and hydraulic conductivities) of the hydrogeological zones and the SFR in the EPM models and argues that the effective conductivity concept is valid for the characterisation of general flow conditions in the bedrock. However, Posiva accepts that local variations cannot be captured by EPM modelling. STUK agrees that this is probably the case, especially if channelled flow proves to be the correct conceptualisation at the disposal depth.

Uncertainties included in the EPM model are partially inherited from HZ and hydro-DFN models. While Posiva still has concerns with the hydro-DFN model at the measurement threshold of the PFL, it considers its EPM model rather reliable. Also, when a conductivity tensor (K) is assigned to a given block of the hydro-DFN model and then upscaled to a larger scale, the result may exaggerate the connectivity of the larger scale model. There is no guarantee that the SFR exhibits a similar character from one scale to another.

Conclusions

Posiva's groundwater flow modelling is among the leading-edge approaches in site-scale, crystalline hard rock research and is able to include critical factors and concepts that need to be accounted for. Given its state-of-the-art nature, STUK considers that the current framework is reasonable and the results calculated should be qualitatively acceptable. However, the modelling develops a complicated line of reasoning on the depth relations of fracture sizes, frequencies, specific capacities, and transmissivities. The input of the hydro-DFN is pre-processed in several ways and the conceptual correctness and its predictive power can be further upgraded and extended to include alternative assumptions on topics such as flow channelling and connectivity. There should be a better justification why the boundary between DZ3 and DZ4 lies at 400 metres. The repository is located directly below this boundary and on the lower hydraulic conductivity side of this zone division. The measurement results of the PFL tool are vital in setting up a hydrogeological flow model. However, there are concerns about what the PFL actually measures underground. Posiva should improve the evidence that the PFL tool works correctly in all the conditions it is used for, because the whole of the hydrogeological modelling starts from these measurements. The deterministic hydrogeological zone model needs a definite amount of connectivity to be capable to conduct water. There is a persistent difference in how Posiva justifies zone dimensions in brittle deformation and in hydrogeological zone modelling, although the disciplines share common discontinuity information on the bedrock. There should be more consistency between crystalline hard rock models and hydrogeological models, because these studies estimate the potential release pathways from the repository. Both consistency and strengthening the source data reliability will increase the confidence of the safety case.

Hydrogeochemistry of groundwater

Posiva's goal is to create a site-specific hydrogeochemical model that reliably describes groundwater composition, along with changes in composition and explanation of their causes. Posiva states (Posiva 2011-02) that it is necessary to characterise the current composition of the groundwater and assess the processes controlling its composition. Also, understanding the transient glacial-postglacial evolution in the Baltic Sea region during the Quaternary and the Holocene is vital when evaluating hydrogeochemical data, since they provide constraints for groundwater types that may occur in the bedrock. Both characterization work and process understanding provide the basis for modelling the future hydrogeochemical evolution of the site that is one of the most important starting points of the site performance assessment. Contrary to most other site research work, palaeohydrogeochemical modelling relies on widely diverse sets of variables. The sources of hydrogeochemical information are water samples (reliability-classified, based on success of the chemical analyses), electrical conductivity measurements, fracture mineral data, matrix pore water studies, and micro-organism research results.

The general *hydrogeochemical characterisation* of groundwater data leads to the identification of various groundwater origins at the site (WR 2014-06). The origin studies use several lines of evidence in interpretation of groundwater residence times. The stable isotope signature is the main evidence, but several radioactive isotopes have been used in addition (^{3}H, ^{14}C, ^{36}Cl). The possibility of using $^{3}He/^{4}He$ isotopes has not been utilised (not measured) though these data might contribute to interpreting deep groundwater residence times. According to Posiva (Posiva 2011-02), the oldest deep groundwaters are older than the latest glaciations and the upper groundwaters reflects the evolution of the Baltic Sea region during last glaciation and the Holocene: i.e., glacial melt water infiltration and mixing in groundwater, and penetration of the Littorina seawater and its mixing with the glacial and pre-glacial groundwater mixtures, which were already present in the bedrock. This mixing probably affected the groundwater composition more rapidly in the most conductive hydrogeological features: i.e., fractures and fracture zones.

The six different modern and relic sources of water (end-member waters) are considered by STUK to be well justified. Isotopic evidence indicates that Littorina seawater intruded the bedrock during the early saline Littorina stage. The depleted ^{14}C and the high rock-derived He contents indicate that glacial meltwater is distinctly older than Littorina seawater. The $^{36}Cl/Cl$ isotope ratios and He contents of saline waters support very long residence times for saline fluids. In order to solve the Holocene hydrogeochemical evolution of the site, Posiva has adapted an inverse geochemical mass-balance modelling approach, and has also defined *reference groundwaters*. A special case among these waters is the subglacial reference water that, according to Posiva, cannot contain Holocene glacial or postglacial water components because of its high Br/Cl-ratio and extremely low HCO_3^- and SO_4^{2-} contents (saline water characteristics). Confusingly, the reference groundwater definitions and terminology used in hydrogeochemical characterisation (WR 2014-06) are not compatible with the reference groundwater definitions and terminology that are used when considering the future evolution at repository depth (Posiva 2014-01).

Specifically, Posiva points out that there are several reasons for assuming an extremely long residence time for the deep saline groundwater. In particular, the stable isotope signature points to the elevated temperatures of the Palaeozoic times. The gradual dilution of saline groundwater as a function of decreasing depth is due to an older event and/or result of more ancient evolution. Based on isotopic evidence (especially δ18O), permafrost fractionation is also precluded. Subglacial reference water composition represents the most diluted component of the ancient dilution of the original brine prior to Weichselian glacial meltwater infiltration. According to Posiva (Posiva 2011-02), it can be assumed that saline groundwater has not been diluted by pure glacial meltwater.

In regard to *redox conditions* (as well as pH), Posiva argues that minerals in rock and fractures form the most extensive buffers against infiltrating reactive agents such as CO_2 and O_2, and stabilise redox and pH to reducing, near-neutral conditions (Posiva 2011-02). Manganese contents of near-surface, young calcites is higher than in the older generations and this has been interpreted to show that bedrock infiltration of reactive waters (low pH and/or oxygenated) has been limited, and that reductive conditions have been established already at shallow depths (< 10 m). This should indicate long-term stability (over the time span of glacial cycles) of the Olkiluoto bedrock that continues today (Posiva 2011-02). Unaltered pyrite and other iron sulphides are common and oxidation haloes around sulphides are restricted to less than 10-metre depths in fractures, indicating strong lithological buffering in bedrock against oxic waters over geological time. Uranium content of fracture minerals is higher near ground surface, indicating dissolution and precipitation by surficial redox changes. However, highly transmissive zones (e.g. HZ20A) have transported some surficial uranium down to depths of 300 metres during Littorina density inversion. Dissolved organic species and CH_4 and SO_4^{2-} in certain groundwaters also have the potential to form notable redox capacity. Posiva states that reducing sulphidic and methanic environments have fluctuated in the upper part of Olkiluoto bedrock over geological time. According to Posiva, microbiological observations generally correlate well with the different layers of the groundwater chemistry and high CH_4 and other hydrocarbon concentrations form an effective redox buffer that does not allow any oxidants to penetrate to greater depths. At present, the methanic environment is restricted to depths below 300 metres (abiogenic CH_4 becomes gradually dominant as depth increases). According to Posiva (Posiva 2011-02), the methanic environment was closer to ground surface at the beginning of the Holocene, before the SO_4^{2-}-rich groundwater infiltrated the system. This interpretation together with uranium transport observation down to depths of 300 m, indicates that the Littorina density inversion in highly transmissive zones has been rather abrupt and massive enough to transport oxidising conditions to depth. Posiva does not emphasise this, although it possibly means that seawater intrusions (density inversions) can be more relevant geological events than glacial melt water intrusions, causing abrupt redox changes in the bedrock. The present day microbial responses to hydraulic disturbances have been studied with an infiltration experiment (WR 2012-31). The results manifest very rapid oxygen consumption (O_2 penetration is even more limited than is the case for low pH) in the soil and in the very shallow bedrock, due to activity of heterotrophic bacteria.

In terms of *pH*, Posiva concludes that calcite is the major controlling factor and buffers groundwater effectively to a slightly alkaline level (pH 7–8.5). This is also likely to take place in the future. Well-preserved calcite crystals occur in the hydraulically active zones in the upper parts of the bedrock (< 10 m). Posiva states firmly that the general occurrence of calcite in shallow fractures without any significant dissolution structures and the great age of calcites, prove that not even the significant environmental and hydrogeological changes during past glacial cycles were able to destabilise the buffering capacity associated with calcite infillings. The occurrence of calcite in early glacial deposits (ground moraine) emphasises the buffering capacity of overburden during a glacial cycle. Posiva's monitoring results also indicate that high pH pulses due to the use of cementitious construction materials in disturbed open tunnel conditions even-out quickly (within years).

The hydrogeochemical characterisation results show the rapid increase of *ionic strength* of groundwaters after infiltration at Olkiluoto (Posiva 2011-02). Significant surface weathering and the early enrichment of all major ions have occurred in all Olkiluoto infiltrated waters during the Holocene. According to Posiva, there is a notable, weathering based, active source of solids that is readily dissolved during meteoric or glacial water infiltration. It is noticeable that all water infiltrated in Olkiluoto bedrock has already reached the 4 meq/l limit during infiltration into the upper bedrock. The 4 meq/l limit resembles closely the 0.4 g/l limit of total dissolved solids (TDS) that will be discussed in the future evolution of the site.

Posiva has described in detail the concentrations of some *safety critical species* (e.g. Fe^{2+}, HS^- and CH_4) for the Olkiluoto baseline groundwater (Posiva 2011-02). The HS- contents are shown to be at a low level at disposal depth. Posiva also lists NO_2^-, NO_3^- and NH_4^+ as canister-corroding agents (Posiva 2012-03), and K^+, Fe^{2+} and colloid formation as potentially harmful to buffer bentonite. These agents can be characterised in terms of the baseline conditions that have prevailed over extensive periods of time at the planned disposal depth. Posiva should make more thorough estimations and justifications of the baseline concentrations of redox sensitive species (e.g. DOC, H_2, S_{tot}, and CH_4) at the disposal depth. However, regarding DOC, HS^-, NH_4^+, CH_4 and K^+, Posiva has already presented some estimates for the first planned disposal panel area (Posiva 2012-23). Posiva notes that the exact SO_4^{2-} reduction mechanism is not clear and needs to be better understood, because of its importance to long-term safety.

Matrix pore water extracted from the SFR may act as an archive of the palaeohydrogeochemical and palaeohydrogeological history of the site. In Posiva's approach, porewater and its interaction with fracture groundwater is characterised with chlorine and bromine concentrations, Cl/Br ratio, and the stable isotopes ($\delta^{18}O$, δ^2H). At depths from 0–150 m, porewater sample distances to transmissive fractures are estimated to be metres while, in deeper bedrock, distances are estimated to be of the order of tens of metres. Shallow bedrock (0–150 m) pore waters are mixtures of Baltic/Littorina seawater and dilute meteoric water (Cl conc., and Cl/Br ratio): i.e., these pore waters have reached partial steady state with neighbouring fracture water. At intermediate (150–400 m) depths, Cl concentrations, Cl/Br ratio and stable isotopes indicate meteoric pre-Holocene pore waters of both cold and warm climatic origin. Cold climate fresh porewater might be comparable to the subglacial fracture reference groundwater. In deep bedrock (400–800 m) Cl composition and Cl/Br ratio indicate relatively dilute, possibly meteoric water origin. Stable isotopes indicate that these waters have been formed in moderate to warm climate conditions. The age has been interpreted to be hundreds of thousands to millions of years. The observed current transient conditions between pore water and fracture water at depths > 300 m suggest that saline groundwater may have been upwelling slowly, via the fracture system. This hydrogeochemical interpretation of the past is logical, but it contradicts Posiva's hydrogeological modelling work, which assumes significant matrix diffusion and some hydrogeological data that do not support the upward movement of saline water (Posiva 2011-02). Posiva has also studied the possibility of there being an effective regional hydraulic gradient to explain the upwelling hypothesis, but this leads to order of magnitude lower diffusivities than determined for the bedrock in laboratory experiments (WR 2014-27). Posiva also considers anion exclusion as a possible explanation for the pore water – fracture water discrepancy, which has been observed from the Olkiluoto SFR. Posiva agrees that the interpretation of dilute waters is contradictory at the moment (Posiva 2011-02).

In terms of representativeness and reliability, Posiva has graded its hydrogeochemical water sample data into four classes: quantitatively (B1) and qualitatively (B2) reliable samples for baseline conditions, samples representing temporary changes (T) and clearly uncertain samples excluded from interpretation (E). This is a good practise. Posiva is confident in its interpretations of water types, water type distributions, ranges of salinity, origin of groundwaters and the main hydrogeochemical reactions. According to Posiva, substantial differences between the matrix porewater and fracture water seem to be partially a problem of samples representativity, which it plans to resolve by increasing matrix pore water sampling.

Conclusions

STUK agrees that the justification for the interpreted hydrogeochemical evolution and the establishment of reference water types is mostly credible. The main results of the interpretations are adequate and are among Posiva's most firmly based findings regarding what can be expected with respect to Olkiluoto's future hydrogeochemical evolution. The characterisation of hydrogeochemical buffers regarding redox, pH, and against dilute waters are logical and well justified. However, Posiva omits discussion about the significance of abrupt seawater intrusion (density inversion) into the Olkiluoto bedrock and its effects on bedrock redox conditions. Moreover, certain characterisation results are in significant disagreement with Posiva's considerations of future hydrogeological evolution (to be discussed below). Although geochemical work indicates robust natural geochemical barrier conditions, there is a need to conceptualise and quantify the safety-critical hydrogeochemical processes. There are considerable uncertainties regarding the rate and history of interaction of SFR pore waters and waters in fractures. Clarification of pore water – fracture water discrepancy remains a significant open issue to be answered, because of its potential consequences for effective surface area assumptions and thereby its effects on radionuclide transport modelling results. The discrepancy also questions the sufficiency of current hydro-DFN models.

Rock mechanics

Posiva's Rock Mechanics Model (RMM) covers mechanical properties of both the SFR and the fracture and brittle deformation zones. The RMM also covers the in-situ stress state and thermal properties of the bedrock at the Olkiluoto site, especially at disposal depth. Posiva's rock mechanics studies are targeted to show that mechanical properties of bedrock are assessable and stable in the long-term. Posiva also points out that there is a strong link between the RMM and the rock engineering design. However, the discussion below points out that, in many respects, this link is not fully addressed in Posiva's documentation. Posiva states that the extrapolation of rock mass properties for SFR is difficult over any significant distance (POSIVA 2011-02). Part of the rock mechanical properties is also the irreversible mechanical damage induced in the rock by excavations (EDZ). These will be handled together with RSC in a separate Chapter below.

Posiva has attempted to define the in-situ stress state at Olkiluoto. There have been several, separate measurement methods in use, including hydraulic fracturing, overcoring, Long Strain Gauge (LSG) and Linear Variable Differential Transducer (LVDT) measurements. Supplementary information has been collected from acoustic emission measurements and from core disking and borehole breakout observations. However, Posiva still questions the effective stress regime at Olkiluoto and presents (Posiva 2011-02) two optional stress models. The older model takes into account all stress data available, while the newer model is based on LVDT and LSG results only. According to Posiva, if the Olkiluoto stress regime is a geological thrust environment, then all the results from the hydraulic fracturing are questionable. Both model options make a distinction between bedrock above and below the HZ20 structure. However, in the newer in-situ stress model, the stress field above HZ20 is unclear. For the regime below HZ20, the newer model provides the estimate for the major in-situ stress (ca. 34 MPa), which is horizontal and NW-SE oriented.

While presenting two optional in-situ stress models Posiva appears to agree that a great deal of older stress measurements are unreliable (Posiva 2011-02) and notes that these measurements have not been used for specifying the stress state in the newer model. Posiva does not present any quality classification for stress measurements but, apparently, currently considers only LSG and LVDT measurements as reliable for modelling purposes. Ranges of measurements and also the orientation of major principal stress contain uncertainties and Posiva intends to make further complementary stress measurements from the ONKALO tunnels, for the purposes of repository layout planning.

Strength and deformation properties of SFR, single fractures, and brittle deformation zones define, together with the stress field, the stability properties of the bedrock. In its strength studies Posiva approximates the SFR as “intact rock” and has measured strength properties of various rock types in the laboratory. The results indicate that diatexitic gneiss is strongest in the compressive stress field, while veined gneiss is weakest. The tensile strength of pegmatitic granite turns out to be lowest in the tensile stress field. In general the measured strength variation for metamorphic rocks is large, varying between 58 MPa and 161 MPa (95% confidence). However, Posiva concludes that the spatial distribution of “intact rock” strength in ONKALO is not determined by rock type, alteration or ductile domains. Instead, the parts NE from the ONKALO centre area seem to have lower strength than those of the SW sector. There is only a loose connection between the rock mechanistic modelling of fractures and the geo-DFN-modelling. With respect to deformation zone properties, Posiva concluded that the data collected are imprecise, have low spatial coverage, and do not summarise the internal characteristics of brittle fault zones reliably (Posiva 2011-02).

Posiva has measured the success of its RMM with P-O studies (Posiva 2011-02). Most of these spalling/stability studies have been done in the ONKALO ramp and in a rock mechanics research niche (POSE). Posiva states that the rock is more resistant to spalling than predicted: i.e., P-O modelling results predict exaggerated amount of spalling incidents compared to observations. The P-O studies do not predict the damage locations well. In this sense, the predictions are unsatisfactory. According to Posiva, observed damage is a result of a more diverse set of factors than are taken into account in the modelling. Rock quality and spalling predictions are not reliable due to rock heterogeneity and, frequently, the loss of stability occurs not as spalling, but as rock fall. Erroneous parameterisation (spalling strength higher; stress state different) of the models has also been proposed as an explanation of model inaccuracies (Posiva 2011-02). Due mainly to rock heterogeneity, rock quality predictions based on pilot holes are also not notably successful. This is a concordant observation with the large fracture identification (TCF/FPI) difficulties and may have implications to the RSC methodology. Finally, STUK notes that the POSE niche is located in a more pegmatitic bedrock compared to the average Olkiluoto gneissic bedrock, and is situated some 100 m above the actual disposal depth. Posiva also agrees that the mechanical properties of altered rocks are inadequately known and this may affect the construction of underground facilities.

The *thermal properties* of the rocks are controlled by the properties of the migmatic rock, with a lower conductivity gneissic part and a higher conductivity pegmatitic part. In addition, anisotropy in the rock has a significant effect, with the direction of foliation being the most conductive. According to Posiva, modelling of thermal properties in the depth range 350-550 metres is based on lithological continuities that have been included in RMM v. 2.0. At shallower depths, average thermal properties have been used, based on veined gneiss values. Alternatively, Posiva also uses a repository panel calculator to optimise deposition hole locations at the panel boundaries, based only on the averaged thermal properties of repository near-field bedrock. The thermal properties of various rock types are based on laboratory studies. The uncertainty of laboratory measurements leads to ± 10% uncertainty in calculated diffusivity. This value increases with increasing uncertainty in rock type determination. Further uncertainty is created by rock anisotropy and uncertainty related to the lithological model. Posiva has not measured the relationship between the temperature rise and the change of rock mechanical properties. The temperature relationships of various rock types are solved using literature values. Posiva concludes, however, that uncertainties related to the thermal properties of Olkiluoto bedrock are relatively well bounded.

Posiva calculates thermal increments of the in-situ stresses (WR 2014-32), indicating that the maximum in-situ stresses in the central areas of the repository panels would be around 40 MPa, which correlates with the areas of maximum temperature increase. An earlier estimate (Posiva 2012-23) indicated around 50 MPa maximum in-situ stress (thermal increment –29 MPa). All Posiva's stress calculations contain several simplifications for schistose, heterogeneous, and fractured bedrock. It is assumed that bedrock is continuous, homogenous, isotropic and linearly elastic. In any case, based on modelling results for the central tunnels of the first repository panel, crown damage will be likely during the thermal period, if the tunnel is open. Posiva relies strongly on the tunnel backfilling preventing further rock damage. The counter-pressure generated by tunnel backfill swelling is much smaller than the thermal increment. Consequently, there is a need to obtain further confirmation on rock behaviour during the thermal period of repository. At the deposition hole scale, Posiva relies almost entirely on the thermal P-O studies of POSE hole 3 in evaluating the consequences of heating on the rock stress state and the temperature rise in the surrounding rock. Posiva claims the results to be relatively good, although the experimentation is limited.

Conclusions

Although there are continuing difficulties associated with the in-situ stress measurements, the data gathered are considered to be adequate for qualitative stress estimations in Olkiluoto. However, further confirmation is needed. There is a need, in the near future, to supplement rock stress measurements with reliable data and improve the current rock stress models. The rock stress model is among the principal sources of information that Posiva uses to plan and justify the orientations of deposition tunnels. There is also a longer-term need to characterise rock and fracture zone strength and stability properties. The stability predictions for tunnels to be excavated need further improvements. Currently, models predict the tunnel stability rather qualitatively. The discrepancies are caused by the well-developed schistosity, the changes in tunnel profile, local fracturing, the variation of the rock types and possibly other factors. In the view of thermal properties, the shallow depth generalisation raises the question of robustness. Average values for veined gneiss should be shown to be conservative. Uncertainties of thermal property measurements exhibit relatively high variability, as a result of, e.g., heterogeneity and anisotropy within samples. Apparently this variability could be diminished by increasing the sample size. Adequate understanding of baseline rock stress and stability conditions are of primary importance, because they are among the key factors guiding the design and construction of the repository.

Transport and retardation properties of the bedrock

Posiva considers flow resistance (F) as the dominant flow-related factor in modelling radionuclide transport through the bedrock (Posiva 2012-24). However, as long as the majority of engineered barriers perform as intended, the main long-term confidence in limiting radionuclide releases rests on the EBS. Posiva also regards matrix sorption and diffusion in the bedrock as significant retention processes that affect radionuclide transport. In the case of non-sorbing radionuclides like I-129 and Cl-36, diffusion is the only process potentially affecting their transport. In scenario analyses, Posiva adopts conservative or pessimistic approaches, where it is assumed that some of the repository EBS properties have been lost or degraded for some reason. In these cases the geochemical retention properties of the bedrock are argued to be of significance (Posiva 2012-24). In addition to the geochemical retention processes affecting transported solutes, the transport of radionuclides associated with colloids that are mobile in the advective groundwater flow field also needs to be considered.

Posiva studies *flow related transport* in the repository block and at the site scale. Flow related transport considers three main aspects: 1) conductive fractures act as the main conduits, whereas the rock matrix plays a role as a stagnant reservoir of water, 2) flow takes place along distinct flow paths and 3) the flow is channelled according to the connectivity of the network and the in-plane heterogeneity. The hydraulic characteristics of mobile zones are determined by the conductivities and the connectivity of the fracture network. The results of the site scale simulations indicate that the majority of the transport resistance along the release paths is accumulated in the background fracturing of the repository near-field and Posiva recognises that the long-term performance and containment/isolating capacity of bedrock rest foremost on the small-scale hydrogeological characteristics of the repository near-field SFR. In the repository block scale, Posiva argues that the exact character or style of fractures in the repository near-field rock cannot be uniquely defined and a statistical DFN-approach is used. Based on all hydro-DFN modelling options (cases A, B, and C), about 20–30% of the deposition holes would be hydraulically connected to DFN. STUK considers that these percentages are likely to turn out to be high if the stochastic flow model were to be conceptualised as a hydraulically sparsely channelled network (SCN), rather than as a hydro-DFN (cf. Black & Barker, Water Resour. Res.; in press). There is a continuing need to demonstrate that the chosen hydro-DFN modelling approach adequately represents actual flow behaviour.

Based on five different repository block scale calculation cases, Posiva presents the results of 40 hydro-DFN realisations, for 25 deposition holes (Posiva 2011-02). According to the simulation results, transport resistance varies mainly in the range 10^5 years/m to 10^8 years/m, while the median of the F-values is around 10^6 years/m in the repository near-field. Posiva also states that realisations of the whole repository are expected to result in much lower variation between realisations compared to the cases presented. Posiva has compared its current modelling results to previous hydro-DFN modelling results presented in OSD2008 (Posiva 2009-01). The present F-values are significantly higher than those presented in 2010. According to Posiva, this can be explained mostly by the lower effective conductivity of the SFR in the newer modelling exercise.

Uncertainties in transport modelling are related to the hydro-DFN modelling. Posiva is confident in the site-scale hydrogeological zone model (flow paths) and the topography. Posiva is mostly concerned with determining the ratio of open and flowing fractures to all fractures. The variability in open fractures strongly affects connectivity. Posiva has some concerns related to the lower detection limits of underground measurements with the PFL, but trusts the derived F-value interpretations and says that palaeohydrogeological simulations (to be discussed below) support the transport resistance calculations.

The quantification of *total retention properties* requires an estimation of both the flow distribution of the mobile zone (F) and the immobile zone rock matrix retention properties along the flow paths (porosity, diffusivity, K_d). Therefore, bedrock is defined in terms of 1) rock matrix and 2) properties of the fracture flow field. The heterogeneity of the rock matrix is conceptualised with immobile zones of fractures that are divided into four simplified transport classes (clay, calcite, slickensided and others). The thicknesses of zones, porosities and diffusivities vary between the classes. However, the total pore volume of the rock is available for matrix diffusion, although diffusion values are low, beyond a few mm from a fracture surface. Three of the four categories cover 58% of the studied fractures. Consequently, 42% of the identified fracture types are lumped together and their characteristics are omitted in the transport characterisation. The porosity and diffusion properties of the class “other fractures” equal those of the unaltered rock. Based on transport class, hydraulic domain, depth zone, and fracture orientations, the PFL fracture data are divided into hydro-DFN fracture sets, each having unique properties. In summary, in its transport modelling, Posiva attempts to conceptualise extensively the characterised matrix properties of the bedrock.

In principle, the sorption properties of the four transport classes are based on Olkiluoto experimental data. These sorption (K_d) data have been measured and collected from crushed samples and appropriate scaling procedures have been applied. Crushing and scaling is, however, prone to several uncertainties and Posiva points out that there is uncertainty about whether laboratory data (crushed samples) are biased, compared to in-situ data. There are, however, few site-specific data on the migration properties of the rock matrix or the heterogeneities of fracture planes. It is also unclear how well the four transport classes, invented later than the crushing experiment results, can be assigned to the laboratory results. Moreover, in some cases, there are no Olkiluoto specific sorption data available. The Cation Exchange Capacity (CEC) estimations for rock types are based on biotite content or on surface area estimations, based on scaling of experiments. Posiva identifies the understanding of detailed-scale migration properties and the site-specific rock matrix properties as the key remaining issues for future research.

Posiva has made limited investigations related to *natural colloids in bedrock*. In the ONKALO samples, Posiva has measured colloid contents in the bedrock at around 0.2–0.7 mg/l and, at greater depths (613-618 m), as lower than 0.2 mg/l. The concentration of dissolved organic carbon (DOC) is estimated to be around 5–10 mg/l at the repository depth (Posiva 2011-02) and only a few mg/l in deep groundwater. Posiva also concludes that DOC content may be high in shallow groundwater but, due to microbial activity in the groundwater, large organic compounds are broken down and at depths of 100–300 m (brackish SO_4^{2-} -rich groundwater) DOC contents are already at a low level. The measured colloid content and DOC levels apparently represent long-term equilibrium conditions in the bedrock. However, because colloid transport is considered a potential radionuclide release mechanism, further confirmatory measurements and scoping calculations are relevant.

Conclusions

Posiva provides a credible argument and support for the significance of the repository near-field rock in providing the long-term performance and isolation capacity of the natural barrier. Although the role of the natural barrier has been shown adequately for the construction license, the flow-related transport is strongly dependent on the modelling concept utilised. Consequently, potential uncertainties related to the hydro-DFN are inherited by the transport calculations. For example, the connectivity of the hydro-model can be overestimated and bedrock retardation underestimated if the bedrock being modelled is not correctly parameterised. The bedrock could behave more as a SCN than in the way that it is conceptualised in the current DFN-model. The hydrogeological conceptualisation and parameterisation of the repository near-field is important and needs to be confirmed with further P-O work and model comparisons. The understanding of detailed scale migration and retention properties for the rock matrix and the heterogeneities of fracture planes remain as key issues for future research.

Overall consistency and unintegrated data

Posiva considers the consistency between disciplines (geology, hydrogeology, geochemistry, and rock mechanics) as a factor for developing overall confidence in its site characterisation work. Consistency in the crystalline hard rock submodels has already been discussed. To assure consistency, Posiva looks for support from its future modelling work, e.g., from radionuclide transport calculations, in which respect Posiva has also characterised the Olkiluoto biosphere and surficial hydrogeology extensively. During recent years especially, Posiva has worked on integrating the surficial hydrogeology with the bedrock hydrogeology. In eastern Olkiluoto, Posiva's characterisation work is not at the same level as in the central area. Posiva also collects monitoring data that is not, at present, directly integrated with its characterisation work.

Palaeohydrogeological modelling is at the centre stage in finding internal consistency between the most important safety-relevant site characterisation disciplines. The integration work is mostly about finding consistency between hydrogeological and hydrogeochemical baseline observations, but is also about integrating brittle deformation model and SFR properties in a compatible way in the model. Posiva recognises the need to use palaeohydrogeological modelling and sees it as 1) a verification tool for the upscaled properties of the hydro-DFN model and 2) a basis for predicting the future evolution of the disposal site. Modelling palaeohydrogeological evolution is of particular importance while evaluating the hydrogeochemical stability of the site for long-term safety analyses.

Posiva discusses extensively the boundary conditions for palaeohydrogeological modelling of the site (Posiva 2011-02). Important boundary conditions are that 1) the modelling starts from the beginning of the Littorina Stage (ca. 8000 BP), 2) modelling takes into account transient changes in shoreline and seawater salinity, 3) the simulation begins with variable, depth dependent brine, glacial, and subglacial mixtures within fracture zones, 4) modelling has been done with hydro-DFN case A fracture size-frequency distributions and 5) in addition to previous conditions, there are many model parameters based on repository block model upscaling, fracture zone characterisation and annual recharge.

Posiva recognises (WR 2012-32) that key parameters for the palaeohydrogeological evolution are hydraulic conductivity in the top 100 metres and the fracture surface area, affecting both rock matrix diffusion and the amount of matrix that can be accessed in a given time. In summary, according to the hydro-DFN modelling, there is significant connected fracture surface area (and consequently significant matrix diffusion) at all depths in the bedrock. Posiva emphasises that the hydro-DFN modelling results are in good agreement with fracture water evolution of the site. The model is able to capture the main, end-member water distributions of the site, though it slightly overestimates glacial water fractions, underestimates Littorina infiltration and overestimates the meteoric water infiltration depth. On meteoric water infiltration, a conclusion is made that the overestimation is a consequence of the properties of hydrogeological zones in the centre of the island. However, the hydro-DFN modelling results are in direct conflict with the matrix porewater interpretations (Posiva 2011-02). This, together with contradictory results from the independent modelling of upward movement of saline water (WR 2014-27), questions whether the hydro-DFN is correctly conceptualised and calls for scoping work using alternative approaches for conceptualising the groundwater flow. Posiva has made a preliminary simulation exercise (Hydro-DFN case C) with heterogeneous hydrogeological zones, but ends with the confusing conclusion that the mean gradual transmissivity depth trend of hydrogeological zones and stochastic heterogeneous realisations of hydro-zones are considered more or less optional (Posiva 2011-02).

Posiva has studied input parameter sensitivity of its hydro-DFN model (case A). The results show that rock matrix diffusion is a key process in modelling the geochemical evolution. This underlines the essence of the dual porosity assumption that Posiva utilises in its safety assessment work (e.g. WR 2012-35). The changes in conductivity of the overburden indicate that some of the discrepancies between models and data could be explained by variability in overburden properties. As an additional key uncertainty, not evaluated in the palaeohydrogeological simulations, Posiva names the hydraulic heterogeneities within the rock mass and within the hydro-zones.

Posiva does not assign any reliability for its palaeohydrogeological model, although it has a great significance in the safety assessment. However, with respect to the hydro-DFN modelling especially, Posiva has scoped some alternatives for the SFR (e.g. Posiva 2013-01). Considerations have been made of three fracture size distributions (cases A, B, and C) and three fracture size vs. transmissivity assumptions (correlated, semi-correlated, and uncorrelated).

Posiva handles biosphere-geosphere interactions briefly in the Olkiluoto site description. Extensive terrain and ecosystem modelling, as well as biosphere assessment, have mostly been developed separately from the bedrock characterisation work. According to Posiva, between the oxygenic, photosynthetic surface biosphere (surface zone) and the anaerobic, reduced deep geosphere (deep biosphere) there is a shallow intermediate zone (near-surface zone) that is located in the depth range around 0–25 metres. This intermediate zone receives contributions from both the biosphere (oxygen, organic and inorganic material) and the geosphere (methane, hydrogen). Microbial populations are hypothesised to be more diverse in the shallow zone than deeper in the bedrock. In this intermediate zone, e.g., oxygen is practically totally consumed from water before further infiltration to depth. The processes causing this are said to be likely to continue to occur in the future. The pH values in shallow groundwater vary from 4.9 to 8.0. Very low pH values are considered to result from mixing of surface meteoric waters. Posiva has assigned hydrogeochemical uncertainties related to overburden properties in its infiltration experiment (Posiva 2011-02). The results seem to confirm strong bio-geochemical buffers against oxygen, low pH and very low ionic strengths during the early infiltration of meteoric waters.

The *surface hydrogeological model* deals with surface water balances at Olkiluoto and links together vegetation processes in the biosphere, flow in unsaturated and saturated soils in the overburden, and groundwater flow in the bedrock. The model compiles these layers together into one continuous flux system. The surface characterisation emphasises hydrogeological properties of the sediments and overburden water balance (precipitation, runoff, recharge, transpiration). The computation of 1) vertical upward flux to the root zone or to peat layers, 2) horizontal water movement in overburden towards the stream network, and 3) vertical flux rates at the interface between bedrock and overburden are named as major uncertainties that need to be verified by direct or indirect evidence. As indicated in the sensitivity studies of the hydro-DFN model, the properties of the overburden significantly affect modelling success. Posiva's attempts to integrate Olkiluoto surface and subsurface hydrogeological characteristics are reasonably successful (Posiva 2012-30). The available input data were divided into model calibration and model validation sets. Both datasets were utilised successfully, which indicates a well-constrained, integrated model. Most parameters and boundary conditions extracted from the model are for biosphere assessment, but parameters such as water fluxes to depth (as a function of time) are of use in the bedrock hydrogeological modelling.

According to Posiva, the characterisation of *Olkiluoto eastern areas* has been significantly improved, compared to the earlier summary presentation (Posiva 2009-01). The brittle deformation model has been upgraded, based mostly on reflection seismic surveys. Although the extrapolations of gently and steeply dipping structures with geophysics are a step forward, the internal properties of these zones remain to be investigated. Posiva is also continuing to study the area with investigation trenches and deep boreholes. However, studies of topics such as ductile deformation, alteration, rock mechanics and hydrogeochemical characterisation of the eastern area are currently at a preliminary stage. The extrapolation of lithological units is based heavily on the aeromagnetic maps. The extent of tonalitic-granodioritic-granitic (TGG) gneiss is interpreted from aeromagnetic minima, but based on bedrock exposure checks. Posiva also postulates a higher grade of anatexis (diatexitic gneiss) for the eastern areas than for the central area (veined gneiss). However, this higher-grade area does not coincide with the tectonic unit division presented for Olkiluoto. The eastern areas of Olkiluoto are less well characterised and Posiva is committed to further investigations there. At the current stage, the rather unintegrated nature of the eastern area characterisation is justified, since the disposal plans (e.g. Posiva 2012-23) state that the eastern areas will be the last ones needed for disposal. At the moment (Posiva 2011-02), Posiva assigns high uncertainties to sizes, boundaries and depth extensions of lithological units for eastern Olkiluoto. For the purposes of overall consistency of the site model, there is a continuing need to gather further data from the eastern area and add to the confidence in the interpretations that have already been done.

At present Posiva collects *GPS measurements* from 18 stations at and around Olkiluoto. The network of stations is connected to the GeoSatakunta GPS and to the Finnish permanent GPS network (Posiva 2012-01). The purpose of the networks is to detect and monitor active brittle deformation at the Olkiluoto scale, as well as at the larger scale. Contrary to most other Posiva monitoring work, these data do not contribute in a clear manner to any of Posiva's site characterisation disciplines, or to tracking underground construction consequences. There are small but measurable differential movements of rock blocks at Olkiluoto, but Posiva argues that the movements are not proven to be associated with any specific fault (Posiva 2012-21). STUK considers this to be an understatement, as there are statistically significant movements between stations (WR 2012-36) and these movements are likely to be focused on selected brittle zones in the bedrock. Moreover, there are detectable regional movements between other permanent stations in Finland. The results of these measurements should be used for regional tectonic stress regime considerations. After beginning the ONKALO construction work, Posiva also made some *precise levelling* campaigns at Olkiluoto. These measurements indicate small vertical movements at Olkiluoto which, together with GPS results, prove that there are kinematic movements at Olkiluoto, hence establishing questions about their origin.

Conclusions

There is a continuous need to look for consistency, especially between the most safety critical modelling disciplines, and Posiva has recognised this as an important way to increase the credibility of the safety case. Integrating hydrogeological and hydrogeochemical modelling in a consistent palaeohydrogeological model has a central role. Further confidence building also requires consideration of independent integrated model conceptualisations. At a smaller scale, the internal consistency between, e.g., crystalline hard rock submodels, will inevitably increase robustness of the performance assessment. Similarly, showing consistency between the brittle deformation and the deterministic hydrogeological zone models will increase confidence. Further characterisation of the Olkiluoto eastern areas is needed for consistency building in the models used in the central area, but also because of the future disposal plans for the area. The GPS measurements monitored at and around Olkiluoto represent a rather unintegrated area of Posiva's studies. Evidently, the movements detected provoke questions that will need to be answered. There is possibly an important connection between the Olkiluoto tectonic stresses and the observed movements.

Future evolution of the site

Posiva expects that the repository near-field bedrock will, with the exception of incidental deviations, retain its favourable properties over hundreds of thousands of years (Posiva 2012-22). The key external drivers for future changes in the disposal system are climate evolution and seismicity, and processes related to those. Identification of these external drivers leads to several, separate modelling tasks (Posiva 2013-01). As a starting point, there need to be models describing climate evolution, post-glacial crustal uplift and seismicity. For hydrogeological evolution (surface water and groundwater), Posiva has modelled shoreline evolution, with the assumed climate conditions taken into account as boundary conditions. The assumed climate conditions are also among the input data in permafrost modelling. According to Posiva, assessment of the geochemical evolution of the site is based on understanding of the past evolution of the site, as well as on reactive transport modelling. A part of the rock mechanical evolution is related to the stress evolution and rock stability during a glacial cycle (with reference values from climate modelling) and shear displacements induced by earthquakes, while other parts of mechanical modelling concentrate on excavation disturbances and thermal loads generated in the repository.

Posiva has estimated *future climate evolution* for Olkiluoto at three different time-scales: 1) the operational period during the next 130 years (Posiva-STUK-10373), 2) climate and sea level scenarios for the next 10,000 years (Posiva 2012-26) and 3) climate scenarios on a time-scale of 120,000 years (Posiva 2011-04). The first two reports also consider potential sea-level changes under extreme regional weather and global climate conditions. According to recent calculations, Posiva expects that, by the end of this century, average global sea level may rise by 3080 cm and, according to an extreme scenario, by up to one metre. Posiva states that this average global sea-level rise will continue for centuries or even some millennia. Posiva also recognises potential abrupt events (melting of Greenland Ice Sheet and West Antarctic Ice Sheet), but notes that the gravitational effects of increased ocean volume are uneven globally, so sea-level rise is uneven globally and estimation of regional sea-level in the Baltic Sea would not be simple (Posiva 2012-26). The net sea-level rise is also dependent on post-glacial land uplift at Olkiluoto. According to Posiva's studies, the potential sea level rise occurring later than a millennium after closure of the repository would not change the results of the current safety evaluations. However, Posiva has not fully analysed temporal sea level changes in the Baltic Sea, especially, possible abrupt ice sheet events and extreme scenarios of climate evolution during the repository operational period and the early stages after closure of the repository. These should be evaluated in more depth. For example, site characterisation data indicate that abrupt seawater intrusion may change redox conditions in highly transmissive zones of bedrock significantly. Posiva should also scope the possibility that its available models could utilise information from global Holocene geological sea-level records outside the post-glacial uplift areas as the boundary conditions of future evolution models are adjusted. The third report concentrates on far future climate evolution at Olkiluoto and utilises CLIMBER-SICOPOLIS simulations on a global scale. One of the main inputs is the evolution of atmospheric CO_2 concentrations. As a greenhouse case, Posiva assesses a 400 ppm atmospheric CO_2 concentration for 120,000 years into the future. The value chosen is close to the present level and does not seem cautious, compared to Posiva's pessimistic estimation of over 900 ppm by the year 2100 (Posiva-STUK-10373). The summary suggests confidence in the climate models is rather low. As an example, there are large uncertainties related to the evolution of atmospheric chemical composition (Posiva 2013-01). The uncertainties are mentioned as a reason to limit continuous modelling to 50,000 years. An independent expert panel reviewed Posiva's long-term climate scenarios (Posiva-STUK-10396). The review yielded some criticism of the general modelling structure, as well as of the extensive ice-covers depicted during the Weichselian, compared to geological records. The criticism related to climate modelling led Posiva to omit parts of the climate evolution calculations and to create a schematic time-line with consequential periods of temperate, permafrost and ice sheet conditions that Posiva claims to be a conservative alternative for more quantitative future climate forecasts.

In its schematic time-line for reference evolution, Posiva assumes (Posiva 2013-01) that the first future cold period could start at 50,000 years AP and, after the first reprise of the past Weichselian cycle, these cycles would be repeated into the far future. The general approach, whereby the Weichselian glacial is repeated into the future is justified on the basis that by far the most knowledge and geological records of past ice ages are related to the latest part of the Quaternary glaciations. However, the starting time for the next glaciation is almost arbitrary. Starting the cold period at 50,000 years AP leads to a first glaciation at around 90,000 years AP. This does not appear to be a conservative choice for consideration of potential releases from the repository at that stage. There needs to be more solid argumentation why the first future glaciation will not end until 100,000 years AP. While it can be agreed that reproduction of the Weichselian cycle is a defendable and a robust choice to represent possible future climate, it is a significant simplification. Some experts suggest that the Weichselian glaciation was perhaps unique among Quaternary glaciations in some important respects (SGU Research Paper C836). Posiva assumes that, for future glaciations, the maximum ice thickness would be 2–2.5 km. This is in line with independent expert judgements presented on the maximum Weichselian ice sheet thickness in Finland. However, STUK notes that SKB has estimated over 3 km maximum ice thicknesses for an area just 200 km W-SW from Olkiluoto. Furthermore, it has been estimated (Boreas 35, 539–575) that during an earlier Quaternary glacial phase (Saalian) the maximum glacial thickness would have been over 4 km (140,000 years BP). These highly varying ice sheet thickness values give different isostatic load values if free hydraulic pressures are assumed from the ice sheet surface to disposal depth. Evidently, Posiva needs further clarification of its argumentation on how the barrier system (near-field rock and EBS) adapts mechanically and hydrogeologically to extreme load conditions. Therefore, instead of simply replaying the temperate and Weichselian glacial conditions in its future climate considerations, Posiva should explore more thoroughly the extremes of various climatic conditions. Although Posiva has used arguments for the start of the next glaciation based on analysis of Milankovitch cycles, evaluation of earlier and much more delayed start times of glacial cycles would provide more robust confirmation of the resilience of the repository to climate change. Posiva should also scope various temperate climate intensities (Nordic boreal vs. Mediterranean climate) and time-spans. There needs be better argumentation on the consequences of extensive periods of temperate conditions. The Eemian-interglacial, before the Weichselian did not last more than about 15,000 years. This is a short length of time compared with the extensive temperate climate period estimates proposed to result from anthropogenic CO2 releases.

Postglacial land uplift modelling is based on a semi-empirical approach that utilises individual shore level dating points. This is a quite well established external driver, although there are some uncertainties related to the sparse measurement network. On the whole, the model provides a good representation of palaeo-uplift and the tools to predict future land rise.

Posiva's evaluation of *seismicity* is not fully connected with its climate considerations. It does not distinguish between glacial, postglacial, and interglacial seismic conditions. The seismicity evaluation does not take into account inferred future tectonic or glacial evolution of the site, but is based directly on available, observed historical data (see Ch. Seismic activity). However, Posiva acknowledges that increased seismicity in Fennoscandia might be connected with glaciations (Posiva 2013-01) and points out that high earthquake (EQ) moment magnitudes could be possible in postglacial conditions. Posiva does not consider increased frequencies of postglacial earthquakes. Posiva's seismic analyses of potential fault movements and EQ magnitudes are based on the BFZ model and they omit both high magnitudes and increased frequencies. Within Olkiluoto, this can be justified only if the dimensions of BFZs are correctly estimated, seismic movements do not induce new fractures and older ones do not propagate. According to Posiva, Olkiluoto is located within the Southern Finland Quiet Zone (SFQZ), but there is no consideration of how persistent this zone could be in future. For example, the Aranda rift within the SFQZ has been postulated to have been active after the Weichselian deglaciation. The lineaments surrounding Olkiluoto are discounted on the basis of lineament size-distance relations. However, there are ambiguities in Posiva's lineament interpretations. Posiva also discusses possible optional methods of assigning seismic parameters for the seismicity. In this approach, observed seismicity, geology and Moho depth are combined to form an estimate of seismic activity (Posiva 2013-01). Posiva should extend its seismicity studies with data available from compressional stable continental regions, with post-glacial geological records available from Fennoscandia and other formally glaciated northern areas, and with data and records available from the Olkiluoto region. To complement its seismicity studies, Posiva should also perform quantitatively constrained, probabilistic seismic hazard analyses (PSHA) and consider distributed faulting related to potential EQ zones. The latter would lead to probabilistic assessment of fracture and fault displacement hazards (Probabilistic Fault Displacement Hazard Assessment – PFDHA) throughout the rock volume at the site. These techniques have been more broadly applied in the field of seismic hazard analysis.

To address seismic hazard to the repository, Posiva calculates the number of critical canister positions (N_{crit}) that might experience shear displacements (Posiva 2013-01). Critical positions are based on the assumption of large fracture intersections with tunnel and deposition holes. Two cases were considered: 1) the formal FPI criterion and 2) the modified FPI criterion (a deposition hole is not used if a FPI fracture intersects at least 4 holes, or a fracture intersects at least 6 holes). For case 1) the N_{crit} was 35 canisters; for case 2) the number was 78 canisters, out of a total 4500 canisters. Posiva considers these estimates as reasonable upper estimates for the number of deposition holes that might be intersected by large fractures and not correctly detected using the RSC.

Based on Posiva's approach (Posiva 2012-34), EQs during the first thousands of years of the repository evolution are as probable as those during the later evolution. Posiva has not analysed fault displacements during the thermal period of the repository although, after a request of additional information, Posiva assessed (Posiva-STUK-10270) potential dose rates related to an early seismic shear event that would lead to a loss of canister integrity. Posiva makes an overall conclusion (Posiva 2013-01, Posiva 2012-04) that canister failure by fault displacement is highly unlikely in the planned repository, although faulting has been included in Posiva's scenario studies (pre- and post-glacial cases considered). However, this requires successful application of the RSC.

Posiva models *hydrogeological evolution* of the site up to 50,000 years AP (Posiva 2012-04). These modelling exercises are closely related to Posiva's palaeohydrogeological modelling from 8000 BP until the present. Simulating the 50,000 years of temperate conditions leads to gradual but, in geological terms, fast dilution of groundwater salinity in the bedrock at disposal depth. According to Posiva, after 25,000 years there will be dilute waters (< 0.4 g/l or 4 mM) at disposal depth and, after 50,000 years, about 2% of the total length of deposition tunnels will experience these dilute conditions. In accordance with these results, it can be assumed that, with further extension of temperate conditions, there would be more and more dilute water at disposal depth. However, there is a significant drawback in this modelling approach. The calculations assume conservative infiltration into the bedrock and conservative mixing of dilute meteoric waters with groundwaters. Posiva has recognised that the water-rock interactions will inevitably cause rising salinity values of infiltrating meteoric water and plans to evaluate the consequences of water-rock interactions in research period 2013–2015. Otherwise, Posiva considers modelled hydrogeochemical boundaries for the temperate climate conditions to be well constrained (Posiva 2013-01). However, as pointed out above, Posiva should evaluate more fully the consequences of varying intensities, abrupt changes and time-spans of temperate climate conditions.

Posiva estimates separately the potential hydrogeological drawdown and up-coning effects under the conditions that will occur at a future ice-margin. The results of these calculations were variable and Posiva recognises that they are highly sensitive to the location of the ice margin and other assumed boundary conditions (WR 2012-35). In a pessimistic case, an ice margin remains over Olkiluoto for 1000 years and the modelled maximum salinities at disposal depth rise from an initial value of 16–17 g/l to a level of 30 g/l, while minimum salinities could drop to a few grams per litre. Posiva notes that the boundary conditions for the retreating ice sheet are speculative and cannot be verified. Posiva builds confidence by using conservative assumptions and sensitivity analyses, but the only method for model validation is the available geological evidence from existing ice margin areas in Arctic and Antarctic regions.

Permafrost modelling requires a relatively diverse set of input values. However, the main boundary condition for modelling is the mean annual air temperature (–9 to –1 °C) that leads to sub-zero ground temperatures (Posiva 2013-01). According to Posiva's results, a 10,000 year periglacial period (–5 to –10 °C) would lead to maximum permafrost depths from 60 to 240 m. The same analyses indicate that the permafrost would reach disposal depth (400 m) if a dry periglacial period continued for about 100,000 years. The areal distribution of permafrost is also strongly affected by snow cover, lakes and peat areas. In addition, all the uncertainties related to climate modelling are inherited by the permafrost modelling. Despite these uncertainties, Posiva concludes that it is highly unlikely that permafrost would reach repository depth, though the reference calculation based on 10,000 years seems not to be robustly justified. In its schematic climate time-line, Posiva assumes that the future cold period would start at 50,000 years AP, which leads to glaciation at 90,000 years AP. Although the climate fluctuations during the 40,000 years are logical, they are hard to justify, although Posiva assumes these to occur (Posiva 2013-01). In the view of potential consequences, Posiva argues that permafrost has a relatively limited effect on the rock, but, at the same time, observes (Posiva 2012-07) that some uncertainties exist about the consequences for the engineered barriers.

The *hydrogeochemical evolution* of the site is to a large extent dependent on the evolution of the hydrogeological system. Based on palaeohydrogeochemical evidence, Posiva judges (POSIVA 2011-02) that *"the host rock characteristics at the repository level will be stable or predictable to at least several thousands of years, and that the range of geological changes which occur thereafter, particularly due to the large scale climate changes, are estimable"*. Posiva agrees that it is at least equally important to predict the evolution of the groundwater composition and the geochemical buffering capacity of the groundwater flow system, as is the ability to predict the transport of radionuclides. Based on its characterisation work (see Chapter above), Posiva claims that the dissolution of calcite and silicates forms a significant buffer against acid intrusion into the bedrock, and this situation will also exist in the future. Similarly, Posiva is confident that fracture mineralogy, dissolved aqueous species and microbial activity form a strong buffer against oxic waters over geological time scales. However, this conclusion apparently also assumes that seawater intrusions into hydraulically highly conductive zones are not expected in the future. There is also no indication that glacial meltwater intrusion would have led to strong dilution of groundwater at disposal depth (Posiva 2011-02) but, as noted above, the extremes of various climate conditions should be evaluated more carefully.

Posiva has also estimated groundwater evolution over the next 10,000 years with a simulation exercise (WR 2014-09). The species concentration results mostly mimic baseline characterisation observations, although there are apparently some unrealistic or incomplete (e.g. rates and processes related to organic reactions) boundary conditions. The simulations also lack thorough process understanding regarding, e.g., anoxic sulphate reduction, rate of production and consumption of dissolved sulphide, and role and origin of dissolved gases in redox processes. Simulations, however, indicate that after closure of the repository the near neutral (pH ~7.5–7.8) reducing conditions (Eh ~ –2005…–170 mV) will be restored quickly at disposal depth. Regarding many safety critical species concentrations (e.g. DOC, NO_2^-, NO_3^-, NH_4^+, and H_2). Posiva does not make comprehensive estimates of their fate or evolution in the longer term. Similarly, thermal effects are omitted in the information presented (WR 2014-09).

In its recent hydrogeochemical simulations (WR 2014-09), Posiva makes controversial assumptions regarding the future deglaciation period. Posiva assumes that a single porosity model for bedrock fractures would apply for the glacial melting period, although it is stated that the assumption is extreme and unrealistic. Currently, the reasoning behind this model variation is not well justified, because the dual porosity assumption is among the main boundary conditions in Posiva's transport calculations. Posiva considers matrix diffusion as a key hydrodynamic process at the Olkiluoto site. Use of the single porosity model reflects Posiva's current difficulty in resolving how best to combine its hydrogeochemical matrix porosity studies, physical porosity measurements (autoradiography studies) and the porosity assumptions used in transport simulations.

Although Posiva presents multiple lines of evidence on geochemical stability in the bedrock, it also defines the hydrogeochemical evolution of the site with a complex set of reference groundwaters and bounding groundwaters (Posiva 2014-04). According to Posiva, the reference groundwaters represent the expected groundwater conditions at repository depth, and bounding groundwaters bound the expected range of water compositions (e.g. salinity and pH) at the repository depth during different time periods. While the assignment of reference groundwaters is justified by the site characterisation work (Posiva 2011-02) and consistent geochemical modelling, the justifications of bounding groundwaters (Posiva 2014-04) are not based on the evaluation of past or future behaviour but on Posiva's requirements (target properties). Evidently, the bounding water compositions originate from EBS materials considerations (Posiva 2012-03). Posiva's performance assessment and modelling work does not show the times at which many of the bounding groundwater conditions would be met at repository depth and they therefore look artificial from the viewpoint of the site evaluation. Posiva needs to clarify its terminology. If reference groundwaters take their justification from the site performance assessment, then these waters are, logically, representatives of long-term targets. Similarly, if bounding groundwaters are justified with the requirements of the EBS, then these waters should be representatives of conservative requirements to be fulfilled at all times. There is some further terminological confusion, as the reference groundwaters used in the palaeohydrogeochemical interpretations (WR 2014-06) are not comparable with the terminology used for future evolution.

Posiva continues the vague definition of the bounding waters by stating (Posiva 2014-04) that the groundwater compositions are collected from the site, although brine water is partially (and glacial melt, completely) based on hydrogeochemical data from the Swiss Alps (Nagra database). Posiva also says that bounding waters are defined taking consideration of site disturbances. However, this definition of disturbance has no direct relation to disturbance scenarios (Posiva 2012-08), unlike the reference waters, which can be related to the expected evolution and to Posiva's Base Scenario (Posiva 2012-08).

The *rock mechanical evolution* considerations of Olkiluoto cover various topics. The general stress evolution and rock stability considerations during the onset and main stages of glacial times are inadequately justified. There are no estimates or sensitivity studies that address how the repository near-field rock would respond, e.g., to various potential ice thicknesses or isostatic hydraulic pressures. Some studies are available (cf. Rock mechanics Chapter above) on how the early thermal evolution may affect the repository near field rock (e.g. Posiva 2012-23, WR 2014-32). However, Posiva has not covered in its future evolution studies the mechanical evolution of the near-field bedrock during the first thousands of years after closure of the repository. Thermal issues and construction effects for the repository near-field bedrock are discussed further below.

Posiva evaluates seismically induced postglacial fault displacements analytically. It is assumed that fracture displacements (WR 2011-13, WR 2012-08) in deposition holes will be induced by postglacial seismic events in nearby deformation zones (BFZ100, BFZ021/099, BFZ214 and BFZ39). The displacement studies assume perfectly planar deformation zones and rupturing in the entire zone. These are considered as conservative assumptions. Simulations resulted in maximum moment magnitudes in the range M_w = 4.3–5.9. Magnitudes are based on static phase shear stress properties and on the modelled zone areas. These are somewhat ambiguous assumptions because, e.g., the depth dimension of zones seems rather arbitrary (cf. BFZ099 is quite elongated rectangle). The selection of zones and limited depth dimension could be non-conservative and is not fully justified. Similarly, fault rupture was initiated at a pre-defined hypocentre and programmed to propagate outwards with a specific velocity. Compared to present day seismological observations, the assumed hypocentre depths are shallow, although the chosen depths likely cause maximum movements on target fractures. The target fractures were assumed to be planar discs with a constant "critical" radius (75 m) with centres located at the disposal depth (420 m). Three target fracture distances (100m, 300m and 500m) were considered, perpendicularly from the primary fault. The rock mass around the fractures and zones was assumed to behave elastically. Otherwise, the rock properties were assumed to be isotropic, homogeneous and continuous. These are significant simplifications, but can be seen to be partially conservative assumptions (seismic attenuation occurs due to inelastic deformations in rock).

Posiva concludes that the displacement studies can be taken as reasonable upper bound estimates of fracture shear induced by end-glacial EQs. Simulations produced maximum target fracture displacements (about 30 mm) in a gently dipping fracture at 100 m distance from BFZ100. However, taking into account the simplifications (e.g. material properties) and uncertainties (e.g. evolution of glacial stresses and pressures, BFZ dimensions) involved, earthquake consequences are not evaluated as convincingly as they could be. Posiva agrees on this (Posiva 2013-01) by acknowledging that the displacement modelling has been done in a schematic way. However, Posiva provides supportable arguments that most simplifications act conservatively in the modelling, suggesting that increasingly realistic simulations would result in smaller and smaller calculated displacements. This is possibly not the case. There are also novel techniques, such as particle flow code (PFC) modelling (SSM Technical Note 2014:59), that lead to heterogeneous conceptualisations of BFZs, which in turn question the relations between the EQ and the deformation zone sizes, the EQ and the displacement magnitudes, and "critical" target fracture sizes and displacements.

Conclusions

Posiva's approaches to evaluation of future climate give an insight into the future evolution of the site but raise questions, which is unsurprising in this complex and developing area of science. One issue is how robust the climate scenarios need to be in order to provide a convincing safety case. Analyses relating the full range of potential variations of glacial conditions to the response of the release barrier system are needed. There is much geoscientific information available from the Quaternary that Posiva could apply in estimating future lines of evolution, because this is the most valuable argumentation for site stability. Posiva should analyse the possibility of a more varied, abruptly changing, and prolonged global temperate period and compare these analyses with available palaeosea-level records. There is also a need to evaluate further the various possibilities related to onset and extent of future permafrost conditions. Posiva's present estimate of future hydrogeological conditions is overly pessimistic, since there is no coupling to the TDS regulating hydrogeochemical reactions. In hydrogeochemical considerations, Posiva assumes future boundary water conditions that do not get much support, either from the site characterisation work, or from geochemical modelling work. In hydrogeochemical modelling, Posiva also uses porosity assumptions that are in contradiction, e.g. with the transport modelling work. Posiva should extend its seismicity analyses with geologically and seismologically more realistic PHSA and PFDHA methodologies. Posiva has studied potential consequences of postglacial EQ shear with deterministic analyses that are bound to the BFZ model concept (uniform continuous structures). To gain more realism, Posiva should consider also more heterogeneous conceptualisations and alternative techniques (e.g. PFC) to analyse the potential movements.

Quality of the site characterisation

Posiva states (Posiva 2011-02) that it applies the ISO 9001:2000 management system for the production of site characterisation reports. The system is intended to ensure that the documentation is traceable and transparent with respect to data, assumptions and calculations. Posiva says that the composition and quality management of reports and the recruitment of expert reviewers are controlled according to respective guidelines (unpublished documentation). ISO 9001:2000 is based on the principle of "management by processes". In line with the standard, a process owner checks and approves the data and a quality controller (QC) checks and approves the procedure. In general, this is also the case in Posiva's site data production and handling. Posiva has divided its research work into sub-processes that are supervised by the main process "Development of the Disposal System". Each process has its owners. For example, the owner of the main process is the "Development Manager". The other guideline Posiva claims to pursue is the "graded approach" (Posiva 2012-03). According to Posiva, a graded approach Posiva means that *"the primary emphasis in QC is placed on those parts of the assessment that have direct bearing on the arguments and conclusions of the long term safety of disposal."* However, in conformance with the graded approach, Posiva does not specify (e.g., in Posiva 2011-02) what parts of the site related safety arguments are at the primary QC level and what arguments are at some standard control level. Related to the safety argumentation, uncertainty handling of site characterisation should also be managed in accordance with the graded approach. This means identification of key uncertainties and recognition of uncertainties that are not so critical to the safety case. According to Posiva, the audits of the site characterisation were concentrated on the handling of data, the requirements of alternative explanations and interdisciplinary consistency (Posiva 2011-02). It seems that audits related to the safety-case production process have been between Posiva and its contractors. However, this process needs to be expanded, with the possibility of future STUK oversight.

To date, an area of quality control that has been rather unconstrained by Posiva is work that requires expert elicitation. According to definition, expert elicitation is used in cases when the understanding or data basis is conflicting and consensus is needed for the selection of key data. The members of an elicitation group are supposed to be independent scientists, representatives of leading-edge knowledge of their research disciplines. The goal of elicitation work is that these experts independently contribute to a data range that fully captures and qualifies best estimates and uncertainty.

The quality of elicitation depends largely of the delimitation of work and the number of experts in the group ultimately defines whether the group can come up with constructive independent estimates. Attempts to force consensus views may lead to increasing disagreements or the group may begin to act more like a review group. Despite Posiva's unsuccessful experiences there is a use for expert elicitation. The appropriate approach is a Cooke method where the target is not to reach a consensus view but quantify the uncertainty around a credible estimate by giving weights to expert opinions (c.f. Nature 463, p. 294). There are prominent disciplines of science where independent approaches could be used, e.g. climate change, seismic hazard studies, hydrogeological conceptualisations and effective porosities (cf. matrix pore water studies).

Conclusions

The practices of QC are not as transparent as Posiva presents them to be. The site characterisation and reporting mostly avoids assigning any safety significance to the results found, although some characterisation results should certainly be put at the primary QC level. Similarly, uncertainty handling of characterisation results calls for handling with a graded approach. Posiva needs to specify more clearly how data, models, analyses and uncertainties are classified into safety importance grades that designate their significance to the safety case conclusions. In certain fields of science, the use of formal expert elicitation should be explored further. The elicitation work should be targeted on defining uncertainties around estimates, rather than trying to reach precise results from controversial and frequently deficient data.

3.5.2 Site suitability

At the high level GD 736/2008 requires that any area with a feature that is substantially adverse to safety shall not be selected as the disposal site. Together with the requirement for favourability, these two aspects practically define the suitability of the site. As indicated in YVL D.5 408 and 412 the suitability vs. unsuitability consideration often follows the principle of dualism. According to YVL D.5 412 the site is unsuitable at least in the cases when 1) the bedrock is likely unstable (high stresses compared to strength), 2) high seismicity can be expected, 3) groundwater characteristics will be potentially adverse for the concept, or 4) the site or its surroundings contain exploitable resources for future humans.

It is required that the favourability of the repository near-field bedrock that acts as a natural barrier (YVL D.5 407) of the disposal concept shall be stable and assessable during the oncoming several thousands of years (YVL D.5 413). The range of subsequent geological changes, especially caused by major climate changes, shall be evaluated and these changes shall be taken into account in specifying performance targets for the disposal site near-field bedrock. The location of the facility and the disposal depth (YVL D.5 414) shall be selected taking into account properties indicating suitability (YVL D.5 408), mitigating adequately above-ground natural phenomena and unintentional human intrusion.

Posiva has arranged its safety argumentation on site suitability into two approaches. The first line of reasoning is Posiva's argumentation on the site performance and consequently the suitability is based on site characterisation, palaeohydrogeology, and evaluated future evolution of the site.

Posiva's second approach defines first the KBS-3 safety concept for nuclear waste disposal, then the safety functions, performance requirements for the bedrock, i.e., general requirements and performance targets ("target properties" as termed by Posiva) (Posiva 2012-24, Fig. 3-1; Posiva 2012-03, Fig. 6-1), and finally the design requirements and specifications for bedrock. In many cases the detailed long-term performance targets for bedrock stem from the needs of the Engineered Barrier System (EBS).

Performance

In accordance with the KBS-3 safety concept, Posiva defines that, with respect to the bedrock, the concept relies on: *"a sufficient depth for the repository, favourable and predictable bedrock and groundwater conditions and well-characterised material properties of both the bedrock and the EBS"* (Posiva 2012-22). At the same time, the safety function definition says only that bedrock should *"provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers, and limit and retard the migration of harmful substances that could be released from the repository"* (e.g. Posiva 2012-24). Then again in definition of performance requirements, Posiva states on bedrock suitability that *"host rock shall, with the exception of incidental deviations, retain its favourable properties over hundreds of thousands of years"* (e.g. Posiva 2012-22, Posiva 2012-03). It appears that this definition refers only to the repository near-field bedrock. Similarly, it seems that the general requirements (e.g. Posiva 2012-03, Fig. 6-1) refer to the repository far-field bedrock, i.e. to mitigation of the impacts of above-ground natural phenomena and human actions.

Posiva lists its performance requirements for the disposal site bedrock in Posiva 2012-03. The disposal depth is the only general requirement that been related to the repository far-field bedrock (site bedrock in general). Posiva omits the aspect of proximity of natural resources, which should also be considered as a general requirement.

Posiva wishes to make a link between its defined target properties and the repository near-field bedrock performance targets required in YVL D.5 409. STUK agrees on this but notes that many performance targets for bedrock do not derive from the site bedrock performance analysis (characterisation and modelling), but from the requirements set, e.g., by EBS (canister corrosion, buffer and backfill performance) and radionuclide solubilities. The performance targets defined by Posiva, presents a dilemma that should be resolved (bedrock performance targets set vs. properties to be preserved). Reasonable design requirements and specifications should be possible to be deduced from the performance targets. The service life of the repository near-field bedrock is stated to be hundreds of thousands of years. There can be occasional short-term conditions in the near-field that conflict with the natural properties of bedrock, but these conditions cannot dominate the near-field during most of the planned service life. Obeying the design specifications should guarantee that the performance targets set will be likely reached and maintained in the expected evolution of the repository. However, if the implementation of design specifications assures that only the expected bounding conditions will be met in the long term, it evidently does not imply that the favourable and natural near-field bedrock properties, described in performance assessment, are preserved adequately during construction and will thereafter perform sufficiently for the whole service life of repository.

There is considerable confusion with the performance targets compared to Posiva's site assessment work as can be seen below. STUK is in the opinion that the bedrock near-field performance targets (target properties), representing boundary conditions always to be fulfilled, and the properties to be preserved, based on the site assessment and describing the expected evolution at repository depth, need to be clearly separated.

For *hydrogeochemistry* Posiva presents extensive and multiple performance targets for bedrock (Posiva 2012-24). In many cases, the performance targets are not compatible with each other. Regarding groundwater salinity, Posiva specifies three different performance-targets: Cl^- concentration of less than 2 M in L3-ROC-11 to avoid corrosion of canisters by Cl^-; total charge equivalent of cations of less than 4 mM in L3-ROC-14 to mitigate chemical erosion of the buffer and backfill; and a TDS of less than 35 g/l (less than 70 g/l during the early evolution) in L3-ROC-15 to ensure high enough a swelling pressure for the buffer and backfill. These targets are considered collectively by the design specification L5-ROC-19. The criterion in the performance target L3-ROC-11, which equals to a concentration of 100 g/l (TDS), is seen to contradict with the criterion in L3-ROC-15. Of the presented criteria, the 35 g/l criterion can be justified as a future short-term extreme condition with Posiva's hydrogeological modelling calculations. The *minimum salinity* criterion (ionic strength) presented is overly cautious (see discussions above). In the view of Posiva's site performance arguments it is also questionable if this lower limit criterion is relevant for describing long-term conditions.

STUK's YVL D.5 412 requires *reduction capacity* from the repository near-field. Posiva sets two optional long-term performance targets regarding redox conditions: L3-ROC-10 for anoxic groundwater conditions at the reposity depth and L3-ROC-29 for reducing groundwater conditions. Only the latter has support from the site assessment studies. The qualitative definition of redox-state is not consistent with the critical importance of maintaining stable clearly reducing conditions for long times in the repository near-field.

Considering potential *pH-ranges*, Posiva defines three competing long-term intervals for the repository near-field bedrock performance targets. pH of greater than 4 in L3-ROC-11 to avoid corrosion of canisters by Cl^-; pH of 5–10 (5–11 locally during the early evolution) in L3-ROC-16 to ensure chemical stability of the buffer and backfill; and pH of 6–10 (6–11 locally during the early evolution) in L3-ROC-30 to ascertain adequate radionuclide sorption. All of them conflict with the expected long-term, slightly alkaline balance of the bedrock, and none of them is supported by the site assessment studies. Posiva defines performance targets for several safety-critical species (*HS^-, NO_2^-, NO_3^-, NH_4^+, acetate, DOC, H_2, S_{tot}, K+, and Fe_{tot}*) that may occur in groundwater. However, no quantitative criteria are presented for them, although the long-term significance of some has been assessed in the site characterisation work. Some of these species are bound to be relevant initially and their long-term relevance should be shown more clearly. A common feature to most hydrogeochemical performance targets is that the presented values are based on EBS requirements.

Posiva set only a few *hydrogeological* performance targets for the repository near-field bedrock. The most important of these is the performance target L3-ROC-19 for saturated flow in a fracture intercepting a deposition hole not exceed 1 l/m·year. This also appears to be a feasible performance target, but it is not clear how and from where in the site assessment this criterion has been extracted. Furthermore, Posiva has not shown that obeying the corresponding design requirement L5-ROC-62 (inflow criteria 0.1 l/min) will guarantee that the performance target will be reached and maintained in future. According to POSIVA-STUK-10115, a local inflow of less than 0.25 l/min into a deposition tunnel during backfill installation (L5-ROC-54) will fulfil L3-ROC-21 that, however, does not specify long-term flow conditions in the tunnel surrounding fractures. In Posiva-STUK-10337, the notion "vicinity of the deposition hole" is clarified to represent a distance of about 10 m from a deposition hole. Posiva should link this to the RSC methodology and define terms such as "local" and "initial" in a similar way and to consider the revised definitions in actual targets and requirements in order to diminish their ambiguity.

Regarding *radionuclide transport*, Posiva sets a few performance targets for the repository near-field bedrock, L3-ROC-20, L3-ROC-33 and

L3-ROC-31. The most important is the *transport resistance*, L3-ROC-20. According to Posiva, the L3-ROC-20 criterion should, in general, be larger than 10,000 years/m for the repository near-field bedrock, but much lower values are accepted as well. The criterion set is much lower than the results based on the bedrock characterisation based calibrated models. As a requirement, the lower, conservative value is acceptable. However, the corresponding property should get its justification from the evaluated site performance. Moreover, in an earlier review, STUK criticized the simplified single value presentation of transport resistance, because a broad deviation exists in calculated distributions. In the site assessment, Posiva also identifies *geochemical retardation* properties of the bedrock (e.g. Posiva 2011-02, Posiva 2012-24), but the performance target L3-ROC-33 for the near-field rock are completely qualitative. Posiva's approach in regard to *colloids* is similar. The performance target L3-ROC-31 for colloid and DOC concentrations is qualitative.

The only *mechanical stability* performance target Posiva sets for the repository near-field bedrock is the likelihood for shear displacement exceeding 5 cm (L3-ROC-23). The origin of this specific number was unknown and a request of additional information was sent to Posiva. The maximum displacements Posiva has been able to simulate in its site assessment studies are 3 cm. However, uncertainty still remains over statistical consideration of primary faults hosting an earthquake. In particular, Posiva should present sensitivity analyses in which the interplay between primary and secondary faults is considered more comprehensively. Also, a description should be given of how uncertainties are perceived to translate from primary faults to secondary faults in such analyses. Finally, the analyses should be coupled more intimately with the understanding of an impact a canister is able to withstand without failing. Posiva does not set any stability criteria for long-term stability of the excavated rooms, although, loss of stability will occur in various parts of the repository (e.g. the crown area of deposition tunnels; deposition holes). Spalling and fallen rock blocks will affect buffer and backfill performance and likely increase available groundwater pathways at repository depth. Similarly, Posiva does not present any performance targets for the thermal performance of bedrock. Consequently, there are apparently no rules for thermal dimensioning in design requirements.

Conclusions

The performance assessment conducted by Posiva shows that according to expected evolution, the favourable properties of the rock surrounding the disposal facilities will continue to evolve in a stable and predictable manner, and the requirements imposed by Posiva on the bedrock are likely to be fulfilled by a large margin. According to results presented in safety case this basis is credible.

At present the connection between the performance targets and design specifications remains unclear. Consequently, it is difficult for Posiva to construct the facility and demonstrate its acceptability so that the requirements by para. 508 of YVL D.5 will be fulfilled. The EBS related performance targets are conservative bounds that need to be fulfilled for EBS at all times. Before the start of the underground construction activities, Posiva needs to introduce the essential, site performance assessment based; properties to be preserved in the bedrock, in addition to the EBS based performance targets that are already available, and their relationship to design requirements. There also remain further needs for development towards the operating licence application regarding both performance targets and requirements of the bedrock. Before submission of the operating licence application, Posiva needs to reconsider its safety functions and performance targets on the whole and to all barriers. This means improving and clarifying argumentation and removing internal inconsistencies from the performance in the target specifications.

Stability of bedrock

Based on the rock stresses and strength at Olkiluoto (Posiva 2011-02), Posiva claims that bedrock at the repository level is stable. Information from the POSE experiment and ONKALO construction experiences lead Posiva to deduce that there will be no major stability concerns in the planned repository, although it observes that rock noises and spalling events increase with depth and in locations where a change of tunnel profile occurs. The reasons for rock damage/failure are well identified, but these give little information for rock stability predictions. Compared to practical excavation experiences, Posiva has had considerable difficulties in measuring, predicting and understanding the prevailing in-situ stress conditions within the bedrock. Rock strength is measured from samples in the laboratory and is easily biased by heterogeneity and anisotropy of the samples. Posiva admits that predicting the strength (and rock mass properties in general) of sparsely fractured bedrock over any significant distance is difficult and stochastic strength predictions have to be accepted. Despite the uncertainties, Posiva states that its confidence in the properties of sparsely fractured rock is high, while admitting that determining the rock stresses and rock strength for estimating rock mass stability (of the fracture zones and the sparsely fractured) is one of the key remaining issues for future research. As a preliminary conclusion, it is said, however, that the stress levels in relation to the strength of the rock are not abnormally high at Olkiluoto (Posiva 2011-02).

An area where there is little practical experience is the long-term effect of rock stress increments as a result of thermal load. Most of Posiva's experience on predictions of underground room stabilities during ONKALO construction are based on unheated conditions. Thermal load will affect the stability of excavated rooms during the operational time, but questions on the long-term performance of the repository near-field bedrock have been raised as well. The large scale thermal response of the rock mass from repository to ground surface is not well understood and there is no analogous experience in heating such a large body of rock at relatively shallow depth. It is, e.g., possible that thermal expansion of bedrock will lead to small displacements in near-field bedrock fractures, causing irreversible hydraulic conductivity increases in the near-field rock. A potential scenario that might lead to significant consequences is an earthquake during the thermal phase of the closed repository, which, in turn, may cause significant displacements in deposition holes. Posiva also says little about deposition and central tunnel crown space evolution after the closure of tunnels. The lack of clarity related to tunnel crown space evolution is shown in Posiva's RN-transport calculations, where it is simply assumed (without justifications) that, in future, a 10-cm thick crown space will have hydraulic conductivity of 10^{-3} m/s (Posiva 2013-01). Apparently, this highly conductive layer is not taken into account in the performance assessment related hydrogeological evolution calculations (i.e. WR 2012-35).

Conclusions

Based primarily on Posiva's practical experiences during excavations, it can reasonably be assumed that the bedrock around the disposal tunnels and holes will be adequately stable. However, taking into account rock heterogeneity and the current level of understanding of in-situ stresses especially, it is clear that rock mechanical conditions require more work. From the viewpoint of understanding and optimising long-term safety, Posiva's bedrock stability argumentation, concentrated on the possibility of abnormally high stresses, is not adequate (POSIVA 2012-24). This is also acknowledged by Posiva and further work is suggested, e.g., in POSIVA 2013-01.

Seismic activity

Posiva justifies the seismic stability of Olkiluoto based on the collected historical and measured earthquake records from Northern Europe (FENCAT database years 1375–2010). The first mechanical seismographs became available at the beginning of the last century (Sweden, Norway). However, more and better-quantified data are available from the 1960s onwards, when the first electromagnetic seismographs became available. As a result of detailed analyses of the FENCAT database, Posiva has divided South and Central Finland into three domains. Olkiluoto is located close to the border of the SFQZ, just north of the seismically more active Åland-Paldis-Pskov (Å-P-P) zone. From the measured and interpreted seismic events, Posiva has extracted a magnitude-frequency distribution of earthquakes for the Olkiluoto target area. This justification is relatively well established. However, it is evident that it concerns only the current conditions of Northern Europe and Olkiluoto, several thousands of years since the last ice cover melted, with consequently diminished post-glacial unloading responses in the bedrock. Moreover, although the FENCAT database represents the state-of-the-art in Northern Europe seismic investigations, it covers a short time-span compared to the time-scale of long-term safety assessment.

From the geological viewpoint, Posiva justifies the seismic stability of Olkiluoto using broader knowledge on the seismic stability of deeply cratonized, stable continental regions. Posiva disclaims this generalisation only in the case of earthquakes that can be associated with the retreating ice sheets, but states that *"it cannot be conclusively determined whether or not end-glacial faulting should have occurred in the Olkiluoto region during last glacial period"* (WR 2011-14). This statement omits the clear indications of postglacial faulting at the bottom of Eurajoki Bay (e.g. STUK-A222). Instead, Posiva considers that future seismic activity in the Satakunta area will concentrate in the Å-P-P belt and the Aranda rift (Posiva 2011-02). To a degree, Posiva apparently overlooks recent postglacial faulting research in, e.g., southern and central Sweden (Geology 42, 379–382; Int. J. Earth Sci. 103, 1711–1724), and northern Germany (Quat. Sci. Rev. 38, 49–62). Evidently, Posiva needs in future to strengthen its seismic hazard analysis with more data (e.g. lineaments around the Olkiluoto, neotectonic evidence, strain budget modelling of GPS data, BFZ dimensions and stabilities, and EQ magnitude – frequency evolution). This should lead to a more constrained post-closure PSHA.

Posiva recognises that the extent of fault movements in Olkiluoto might correlate with ice thicknesses (Posiva 2012-21). Available geological records from Northern Europe are related to the most recent Weichselian glaciation and consequently the use of this information is most justified for future glaciation estimations. However, as indicated above (future climate evolution) there is a need to justify and assess the potential variation related to ice sheet thicknesses.

Conclusions

It is evident that the FENCAT database is a valuable source of seismic information for Northern Europe. The main drawback of all seismic databases is their short history and, to compensate for this, a global approach to seismic records of cratonized compressional areas would increase confidence. With respect to long-term safety, Posiva's seismic stability justifications should be based more on geological observations, models and records than on historic event databases. Geologically, most information available in Northern Europe is related to the Weichselian glaciation. The potential consequences of more extreme conditions should be evaluated, to confirm the robustness of the chosen conceptualisations.

Groundwater flow

Posiva claims that disposal tunnels and holes can be selected so as to avoid locations with unacceptably high flow. This justification relies on the successful implementation of the RSC, which means correct identification of Layout Determining Features (LDF's) and correct determination of respect volumes of LDF's and identified large fractures. This justification emphasises the expectations related to the prediction capability of the RSC.

Posiva's other arguments on low groundwater flow at disposal depth needs better formulation and/or further justifications. Posiva claims that, within the site-scale hydrogeological zones, hydraulic transmissivity generally decreases with increasing depth, together with a decreasing trend of fracture intensity (Posiva 2011-02). The observation is perhaps true on the average, but may not give a complete picture of the phenomena. Apparently, there can be significantly conductive fractures in fracture zones at greater depths as well. Regarding certain individual hydrogeological zones (e.g., HZ19, HZ20, and BFZ100), the transmissivity conclusion is overly optimistic. The measurement results manifest the internal heterogeneity of hydrogeological zones rather than the depth relation of transmissivity. For certain structures at least (WR 2011-32), the statistical regressions presented on the transmissivity vs. depth relationship do not represent physical reality, for safety assessment purposes.

With respect to the sparsely fractured bedrock outside the hydrogeological zones, Posiva makes significant assumptions related to fracture sizes and their transmissivity. While calibrating the DFN models to the observed PFL inflow densities, Posiva has developed fracture size vs. transmissivity relationships (WR 2012-32). The semi-correlated relationships especially have been found effective in calibrations that force the transmissivity of smaller fractures to the PFL detection limit, but still retain their modelled fracture sizes. However, it appears that there is no practical evidence to support these relations, especially in the SFR.

Posiva's conceptualisations of groundwater flow and solute transport is based on the concept of dual porosity. In this approach the walls of fractures and fracture zones are considered somewhat porous, enabling diffusion of solutes in flowing fracture waters into stagnant matrix waters (matrix diffusion). The concept is quantified, e.g., in Posiva's transport classification of fractures (hydro-DFN). The dual porosity assumption has a large significance: e.g., in the success of the palaeohydrogeological model calibrations. The porosity assumption is logical and should be correct (fracture walls are porous), although there are some concerns, as discussed below.

Conclusions

In general terms, Posiva's arguments on low hydraulic conductivity at the disposal depth in Olkiluoto are justified. The suitability of bedrock for disposal is predicted and detected with Posiva's RSC. The hydrogeological design requirements are in a central role in this classification and the success of the RSC is a cornerstone of hydrogeological favourability justifications. Posiva also supports hydraulic favourability with hydrogeological measurements and observations, and implementation of these in its modelling work. Some boundary conditions used in the modelling work have been questioned by hydrogeological experts and need to be better justified in future.

Hydrogeochemistry at the disposal depth

High salinities detected deep in the Olkiluoto bedrock and the significance of sulphate, methane, sulphide and iron contents around the disposal depth need to be evaluated, in particular, while assessing the favourability of the site. With regard to salinity evolution considerations, Posiva relies on palaeohydrogeochemical interpretations and conservative hydrogeological transport modelling calculations. Regarding the general assessment of potential hydrogeochemical evolution of the site, Posiva relies on inverse palaeohydrogeochemical modelling and forward reactive transport modelling calculations.

Based on the general understanding of palaeohydrogeochemisty of the site, Posiva suggests (Posiva 2011-02) that, after the retreat of the Weichselian ice sheet, at the beginning of Littorina stage (8000 BP), the groundwater TDS at the Olkiluoto disposal depth was around 11–12 g/l. Based on the Olkiluoto baseline observations, Posiva concludes that salinity differences between fractures with varying transmissivity cannot be found below depths of 300–400 metres. This indicates that the past glaciation was not able to develop sufficiently high gradients to disturb the deep saline groundwater volume of Olkiluoto. Posiva recognises that the current fracture groundwater TDS values in the repository near field are at a level of 10–12 g/l (Posiva 2012-03). Posiva also argues that the porewater composition of the rock matrix indicates that the bedrock has been exposed over long time periods (in the order of 10^5 to 10^6 years) to stable hydraulic conditions, with dilute groundwater in fractures (Posiva 2011-02).

As previously indicated, Posiva's models on conservative (i.e. no water-rock interactions) infiltration of meteoric water into the bedrock are overly pessimistic, because geochemical reactions cannot be avoided during infiltration. While Posiva's simulation results are open to interpretations and could readily be made more realistic, there is little evidence of extensive melt water intrusions in the past evolution of the site.

Posiva has characterised in detail, e.g., SO_4^{2-}, HS^-, Fe^{2+}, and CH_4 contents in groundwater for Olkiluoto baseline conditions (Posiva 2011-02). The origin of certain species (SO_4^{2-}) is clear, while others can be challenged (CH_4). Regarding the EBS performance, HS^- and Fe^{2+} concentrations are shown to be low at present, and K^+ concentrations not critical at disposal depth. At disposal depth, the identified baseline characteristics can be reasoned to be a result of post-Weichselian, long-term stabilisation covering the previous 10,000 years.

Posiva justifies the stable and reducing nature of future geochemical conditions at disposal depth several times in its safety assessment. These statements are based both on the site characterisation work (e.g., Posiva 2011-02, and Posiva 2012-24) and on the forward modelling work (WR 2014-09). Both suggest that calcite is likely to endure for extended periods in shallow bedrock, even under intense recharge conditions. However, Posiva still plans to conduct confirmation studies on geochemical processes and site-specific matrix properties related to, e.g., radionuclide migration. This is sensible, because there are several uncertainties and incompatibilities between hydrogeochemical characterisation (e.g. matrix porewater studies), hydrogeological simulations (e.g. dual porosity assumptions) and hydrogeochemical modelling. Moreover, there are still deficiencies in the hydrogeochemical process understanding.

Conclusions

Currently, the hydrogeochemical stability indications at the planned disposal depth are convincing. Results of the palaeohydrogeological baseline characterisation at Olkiluoto are Posiva's strongest evidence for stability. However, the explanation of historical salinity evolution, as well as potential future evolution of salinity, needs to be improved and justified because of the lack of water-rock interactions and its relationship to the hydrogeological modelling concept chosen. Furthermore, Posiva still needs to improve its geochemical process understanding, in order to improve the confidence in the hydrogeochemical buffer capacities of the bedrock that ensure the general geochemical site favourability. There is a specific need to understand in detail how the species concentrations that are defined as critical for release barriers (EBS and near-field bedrock) behave in the various geochemical environments considered possible in the future.

Natural resources

Posiva handles only briefly the potential proximity of natural resources that might affect site suitability (e.g. Posiva 2012-24, Posiva 2011-02). Posiva argues that there is no evidence of ore or other rare natural resource potential at Olkiluoto. Posiva's primary argumentation is based on its site characterisation work. The more general areal evaluation of ore potential is based on a three-decades old report and on the Fennoscandian Ore Deposit Database available from the Geological Survey of Finland. After delivery of the licence application, Posiva complemented its natural resource evaluation with a separate summary (Posiva-STUK-10272).

The European Union (EU) recently updated its list of potential natural resource candidates that may turn out to be critical within the EU in the future. Out of the 54 candidates, the EU assigns 20 materials as being critical for present society. Regarding Olkiluoto, the nearest known identified (Sn-W-Be-Zn) mineral occurrence is located in Eurajoki rapakivi. The studies of this occurrence are some 40 years old. Comparing the general ore potential of rapakivi granites to the recently updated list of critical materials in the EU, 6–7 elements (or groups of elements) have a potential to be enriched in the late phases of formation of a rapakivi granite intrusion. Posiva agrees that (e.g. POSIVA 2011-02) greisen veins, fracture bound or related hydrothermal alteration and small enrichments of rare metals detected (Pere 2009) at Olkiluoto can be assigned to the intrusion of nearby rapakivi granites. There are also seismic reflection survey indications that blind rapakivi intrusions might exist under the Olkiluoto site. Against this background, Posiva should continue evaluation of economic mineralogy contemporaneously with future excavations and characterisation work, and integrate the Olkiluoto alteration and economic mineralogy history better into its overall, integrated geological interpretation of Olkiluoto and its surroundings.

After delivery of the licence application, Posiva also clarified (Posiva-STUK-10272) whether the Olkiluoto groundwater reserves might interest future humans. Based on the definitions of various Finnish environmental authorities on the significance or otherwise of meaningful groundwater reserves, Posiva concludes that Olkiluoto is not located in any of those areas. Regarding the domestic usage of groundwater, Posiva also argues that groundwater, even at shallow depths at Olkiluoto, contains rather high amounts of chloride, iron and manganese, making potential drinking water ill-tasting.

Posiva delivered a GSF statement to STUK regarding the geothermal potential of Olkiluoto bedrock (Posiva-STUK-10272). The statement concludes that, in a broad sense, the thermal properties of Olkiluoto bedrock are comparable to most bedrock areas in Finland. However, Posiva does not consider the situation after closure, decommissioning and remediation of the site.

Conclusions

Olkiluoto is unlikely to have resource interest for future human populations. However, Posiva should continue to evaluate the economic mineralogy of Olkiluoto and its surroundings as construction continues. Regarding all respects of natural resources, Posiva should justify more rigorously that Olkiluoto is comparable to any other supracrustal gneiss area in Southern Finland.

Disposal depth

Posiva describes general hydrogeological, geochemical and rock mechanical conditions at the disposal depth in report Posiva 2012-24. Both Posiva 2012-05 and Posiva 2012-24 state that the depth of repository is selected in accordance with the Government Decision-In-Principle (DiP 2000), which required: *"The repository shall be located at a minimum depth of 400 metres"*. Posiva's Safety Case did not give a clear view on how the bedrock properties that variously contribute to long-term safety affect the chosen disposal depth (400–450 m).

After delivery of the licence application, Posiva clarified in a separate memorandum (Posiva-STUK-10211) that, in the original KBS-3 concept description, aspects regarding 1) ground erosion, 2) glacial impacts, 3) other above-ground activities or phenomena, 4) hydraulic conductivity of bedrock and 5) groundwater chemistry, should be taken into account while selecting the disposal depth. However, 6) rock mechanical and stress properties of bedrock, 7) temperature rise as a function of depth and 8) increased difficulties of research as a function of depth may also restrict suitable depth. According to the original description, the fulfilment of these conditions leads to a disposal depth of 400–500 metres, although it was considered that the depth will not be problematic, as long as it is less than 1000 metres. The original description also states that the selection of disposal depth is ultimately an optimisation task that considers both long-term favourable and engineering properties of the bedrock as functions of depth.

The memorandum refers to a DiP-stage report (Posiva 2000-08) that concluded, on the basis of rock mechanic properties, that the constructability of bedrock would be normal up to depths of 500 metres. Because Posiva also wanted to keep a two-tier repository option open, and the distance between the two storeys should be at minimum 100 metres (Posiva-STUK-10211), the upper storey was designed to be at a depth of 400 metres. However, in 2008, Posiva decided to apply for a construction licence for a single storey repository, but this did not lead to reconsideration or re-optimisation of disposal depth. Based on the memorandum, it is evident that simple adjustment of disposal depth does not significantly change the likelihood of inadvertent intrusion by future humans into the closed repository.

Conclusions

Posiva's explanations on the chosen disposal depth are adequate. Posiva also describes qualitatively how various properties of the bedrock vary as functions of depth, and it concludes that the chosen depth is favourable for high level waste disposal. Posiva's original treatment gave the impression that the disposal depth was selected by the Government in its 2000 decision. In future, Posiva should describe more clearly how the site properties affecting disposal safety vary at the disposal depth. Also, the gradients towards unfavourable conditions should be described more clearly.

3.5.5 Rock classification

According to GD 736/2008, the disposal site shall contain sufficiently large, intact rock volumes that facilitate the construction of the waste emplacement rooms. It is also required in YVL D.5 414 and 507 that any structures and other characteristics of repository near-field bedrock that can have importance regarding the locations of emplacement rooms and in terms of long-term safety shall be defined and classified. This classification shall consider favourability of groundwater flow conditions, potential for rock movements, and other possible aspects of bedrock that have long-term safety consequences.

It is also required (YVL D.5 507) that Posiva shall be ready to make modifications to its layout plans of the repository if the quality of the host rock surrounding the foreseen emplacement rooms turns out to be unfavourable.

Posiva's answer to these requirements is the RSC methodology, which uses selected observable parameters reported in the design requirement and the design specification level (VAHA levels 4 and 5) of the Posiva's requirement system. In principle, Posiva started developing rock classification methodology from the beginning of the ONKALO excavations (autumn 2004). However, the methodology was revised in 2006 and the current methodology has common interfaces with the SKB methodologies. According to Posiva, the development of the RSC methodology is still an ongoing task and Posiva intends to present further developments of the methodology in future. For application of the RSC, Posiva divides it into four different scales: 1) repository, 2) repository panel, 3) deposition tunnel and 4) deposition hole. In each scale, bedrock is evaluated with scale-specific criteria.

The RSC methodology

Posiva states that *"by applying the stepwise RSC approach, deposition tunnels will, therefore, be constructed in bedrock volumes where no large and highly conductive hydrogeological zones exist"* (Posiva 2012-24). Regarding canister integrity, the main motivation of the RSC is to limit mechanical damage for long times in the deposition holes. Maintaining favourable hydrogeological properties in the near-field rock volumes into the far future and controlling the hydrogeological properties of excavated rooms during operational time of repository are also key aspects of the RSC methodology.

In the repository and repository panel stages the proper *determination of LDFs* is essential, in order to identify the usable rock for waste disposal. The leading principles in LDF identification are the potential for mechanical shearing (seismic influence) and the potential for hydraulic disturbance. According to Posiva, a rock mechanical LDF is a brittle deformation zone or a lineament with surface length of 3 km or more. A hydrogeological LDF has a vaguer definition. According to Posiva, a hydrogeological feature is a LDF if it has a transmissivity value ≥ 10^{-6} m^2/s, or can be judged as a LDF based on expert analysis. Interpretations and analyses aim to mitigate hydrogeochemical disturbances and evaluate, e.g., the likelihood of saline or dilute water intrusion into the repository volume (Posiva 2012-21). Both hydrogeological definitions are open to interpretation, as the heterogeneity of hydrogeological structures has shown (see discussions above). Posiva assigns respect volumes around LDFs, and has defined multiple terms to describe these volumes. In the case of mechanical LDFs, the terminology starts from the damage zone (mechanically weak). The next step towards respect volumes is influence zones, which include both mechanically, damaged zones and hydrogeologically affected and/or geochemically altered zones. According to Posiva, the minimum respect volume in most cases equals the width of the influence zone (Posiva 2012-21) and, in general, a 20 metre distance from LDF cores is sufficient (Posiva 2012-24). This means that respects volumes are at least as extensive as influence zones/volumes, but can be more extensive, based on expert judgment.

While considering LDFs, Posiva finds an empirical relationship between brittle deformation/fault zone dimensions (zone length) and damaged zone thickness (Posiva 2012-21). Usually, fault zone dimensions are geological interpretations, while the damage zone thicknesses are based on drill hole and ONKALO observations, whenever possible. Based on Posiva's own experience (Posiva 2012-24), it is also claimed that damage zones of faults are narrower at Olkiluoto than would be indicated by the general scaling laws (cf. linear scaling law by Scholz 2002, Cambridge Univ. Press), but all 'deterministic' observations (increased fracturing, degree of alteration, and anomalous transmissivities) from drill cores are basically the judgments of experts. It is also clear that influence zones projected in unexcavated rock volumes may prove different in character to observations based on drill cores or from ONKALO walls. Uncertainty in the 'deterministic' influence zone estimations is easily generated by 1) variations in rock type, 2) unexposed cross-cutting brittle deformation/fault zones and 3) number of influence zone observations for an individual LDF, at least.

Posiva justifies the hydrogeological definition of LDF respect volume based on potentially higher bedrock permeability, which may lead to harmful changes in the near-field groundwater chemistry and lower transport resistance for radionuclides in the near-field. This long-term starting point is well justified. However, the effects of this on practical classification and on measures to retain the favourability of the near-field bedrock are inadequately shown. Posiva says only that the identification of respect volumes will contribute to high transport resistance of radionuclides (Posiva 2012-21). Posiva also notes that the determination of hydrogeological respect volume is largely based on expert views and experience (Posiva-STUK-10388). Posiva also indicates that LDF definitions are work in progress.

In addition to the terminologies above, Posiva also uses terms such as 'process zone'. Posiva and SKB have different definitions regarding the respect volume. As opposed to Posiva's deterministic approach, SKB assigns a 100-metre respect distances to those fault zones (LDFs) that may host earthquakes, in order to take into account influence zones and modelling uncertainties of the zones. SKB's approach is perhaps over-conservative, and Posiva clearly dissociates itself from this interpretation (Posiva 2012-21), but also states that the analysis of influence zones needs further development. However, Posiva should consider some conservative uncertainty measures for its ‘deterministic’ approach as well.

Posiva is still reconsidering the practical expert analysis of hydrogeological zones. One of their considerations is related to situations when a zone does not have brittle deformation indications (Posiva 2012-21). Apparently, this consideration may mean that if a hydrogeological zone is arguably mechanically deformed, it would only then be a hydrogeological LDF. This contradicts the argumentation of mitigation of hydrogeochemical disturbances. Posiva notes that non-deformed hydrogeological zones are merely indicators of a complex fracture network (c.f. discussion on Transport properties of bedrock), but do not explain, e.g., how the slightly or practically not deformed hydraulically conductive splay structures of a major mechanical deformation zone are taken into account. There is a need to provide more self-consistent definitions to the ‘deterministic’ LDF approach. These considerations should possibly also be connected to considerations of how the frequent discrepancies between the hydrogeological and brittle deformation models should be resolved (see discussion on Site hydrogeology).

According to Posiva (Posiva 2012-21), *uncertainties in LDFs* originate from model uncertainties (geological and hydrogeological) and determination of influence zone widths. For brittle deformation zones, there is a semi-quantitative methodology to identify zone uncertainty (low, medium, and high), but the discussion on hydrogeological zone uncertainties does not conclude with any clear idea of uncertainty classification. Similarly, discussion on influence zone uncertainties does not conclude with any clear or practical classification of uncertainties that would be of real help in defining LDF uncertainties.

At the deposition hole scale, the FPI definition and the *critical fracture size* have a central role when considering the mechanical stability of the deposition hole. In Posiva’s approach, there is a relationship between a FPI and a conservative estimate of the actual FPI fracture size. However, the fracture size discussion is poorly addressed and Posiva tries to avoid the topic with the requirement that *“potentially large fractures shall not intersect the canister”* (Posiva 2012-24). In practise, this requirement means that 1) a FPI fracture whose diameter is unknown and 2) a fracture whose diameter is unknown and cannot be followed from tunnel or other deposition holes, cannot intersect the whole perimeter of a deposition hole at a canister position (i.e., the respect distance is 0.5 m). The second requirement concerns, specifically, the corner and edge areas of a repository panel. However, Posiva also relaxes these requirements by stating that, if a known fracture diameter is less than the critical fracture size, it can intersect the canister position over the whole perimeter of a hole. This is a poorly constrained definition. It leaves the arguments for underground fracture size justification open where extrapolations into unexcavated bedrock are, in any case, difficult (cf. uncertainty of DFN models related to the size distributions of simulated fractures).

Based on DFN modelling with Forsmark data, SKB justified a solution where 96% of FPI fractures are less than 200 metres in diameter and 86% of FPI fractures are less than 100 metres in diameter (SKB R-06-54). For its own studies, Posiva has chosen the critical fracture size to be 150 metres and this value has been used in Posiva’s deterministic seismic assessment studies (e.g. WR 2012-08). Posiva does have some concerns related to the critical fracture size and, for RSC demonstration purposes in the ONKALO (ONK-PH10 studies), Posiva has also adapted the critical fracture size to be less than 200 metres in diameter (POSIVA 2012-24), which is more design-constraining than 150 metres.

In Posiva’s deterministic BFZ mapping, and seismic modelling it is assumed that new fractures are not formed and the old ones do not propagate in future seismic events. It is also assumed that movements in fractures smaller than the critical size are not a threat to long-term safety. These assumptions might be challenged with alternative modelling approaches (e.g. PFC), which do not conceptualise either fractures or brittle deformation zones as individual planes. The heterogeneous fracture zone approach (cf. SSM Technical Note 2014:59) might also question the relationship between the individual plane size and the potential displacement at many repository scales (cf. discussion on Future evolution of the site). An additional view of the conceptualisation discussion can be taken from the illustrated fractures presented in the ONKALO DEMO-area deposition tunnels and deposition holes (Posiva 2012-24). Correlations of individual fracture traces between tunnels and holes can be speculative, even at short distances. Posiva also presents an ambiguous case from DEMO-tunnel 1 (DT1). A long fracture (LF6) forms a FPI structure in the tunnel and its extrapolated extension was expected to be found in experimental deposition hole 8 (EH8). However, neither the pilot hole nor the full boring of EH8 confirmed unequivocally the cross-cut of LF6 in the full perimeter of the hole. Instead, a controversial, three-quarter cross-cut was found and, since no full perimeter intersection was found, Posiva concluded EH8 to be suitable. Several points of this deduction could be questioned if the determinism that was followed were to be supplemented, e.g., with discontinuity assumptions within faults and distributed faulting.

The prediction capability of pilot holes is an important aspect of the RSC methodology. For rock classification purposes, Posiva uses pilot holes especially for predicting rock mass quality, groundwater flows and brittle deformation structures for tunnels and holes planned to be excavated. For fulfilling these purposes Posiva is committed to execute 1) geological, 2) geophysical and 3) PFL loggings, as well as 4) water injection tests and 5) single hole interpretations from every pilot hole. Posiva has done systematic pilot hole P-O testing in the access ramp (ONK-PH10) and in DEMO area (DT1 and DT2) along about 350 metres of tunnel. Moreover, in the ONKALO access ramp Posiva has carried out FPI investigations and usability ratio exercises over about 800 metres of tunnel. As a Posiva-SKB co-operation, there have also been 'large fracture' investigation exercises in the selected areas of the access ramp. However, compared to the complete amount of excavated tunnel (over 5000 metres), it is clear that the prediction capability of pilot holes is inadequately verified. The P-O studies done between pilot hole observations and findings from the tunnel walls, as well as from experimental holes, have shown discrepancies (Posiva 2012-24). The pilot hole prediction capability (P-O technique) needs to be improved. Posiva concludes from its access tunnel FPI investigations (ONK-PH11 and ONK-PH12) that drilling of additional pilot holes into a tunnel profile should also be considered as a research method for RSC.

Posiva apparently has informal, expert judgement based, hydrogeological limits for pilot hole inflows. As an example, Posiva made a decision to shorten the planned length of DT1 because of high inflow from pilot hole ONK-PH17. Posiva presents (Posiva-STUK-10388) some design acceptance criteria for a deposition tunnel. However, these criteria concern only tunnels that are already excavated (cf. also Posiva-STUK-10216). Posiva should show more clearly the role of pilot hole inflows while identifying planned tunnel acceptability and the role of potential hydrogeological FPI's. Posiva's brittle deformation structure predictions start from the detailed scale (DS) geological model predictions and, after the drilling of pilot holes, predictions are made again (Posiva 2012-24, Posiva-STUK-10370). There are no clear criteria for how to assess rock mechanical acceptability of the planned tunnel or rock mechanical FPIs from a pilot hole. However, Posiva has proposed that, if a fracture contains "slickensided" or "grain-filled" features, it is likely to be a rock mechanical FPI (Posiva 2012-24). Moreover, large fracture investigations indicated that scoring of geophysical logging results might show correlations to large fractures (WR 2012-12).

Posiva presents some exact observational *hydrogeological criteria* for excavated deposition tunnels and holes that are applied in the RSC. The importance of hydrogeological characterisation and control is shown in Posiva's RSC demonstration work (Posiva 2011-24), which concentrates entirely on the hydrogeological and rock mechanical properties of near-field rock. For deposition tunnels, Posiva sets a point-wise or a fracture-related inflow limit (0.25 L/min) to apply during backfill installation. According to Posiva's criterion, an inflow ≥ 0.25 L/min from a single fracture would lead to the rejection of a tunnel section. However, Posiva reserves the possibility to inject various grouts (low-pH cements, silica) to control the inflow as needed. Moreover, Posiva says that this criterion will be reviewed in future, as the details of the backfilling concept become available. The tunnel inflow criterion does not constrain the number of point inflows or total inflow into a deposition tunnel. In the performance assessment calculations, Posiva assumes that the average hydraulic conductivity in SFR surrounding the repository is at a level of $3.0 \cdot 10^{-11}$ m/s (WR 2010-25). Posiva also states (Posiva 2012-03) that the original hydraulic and chemical conditions in the host rock should be gradually restored after closure of the repository. At present, it is clear that the argumentation presented for tunnel inflow (Posiva-STUK-10216) is not properly integrated with assurance of the long-term targets and the general rock quality for the tunnel near-field.

For deposition holes, Posiva sets a criterion 0.1 l/min for open hole inflow and says that no grouts, or fractures that have grouts, or indications of them, are allowed in deposition holes. Posiva does not indicate when the inflow is measured, which may have a vital effect on the representativeness of the results and thus the acceptability of the deposition hole. Practice has shown that tunnel inflows tend to diminish with time, due to pressure loss and, e.g., clogging of hydraulically connected fractures. The hydraulic head-field may alternate vigorously during excavations in underground facilities. The connection to the criterion of the corresponding long-term target (1 l/m·year) was questioned earlier in this report. Nevertheless, Posiva states (Posiva-STUK-10216) that the 0.1 l/min criterion should lead to a transport resistance of 10,000 years/m. Posiva also points out that there are additional uncertainties regarding the long-term performance, even though the inflow criterion is initially met. Possible future rock shear incidents might increase the average conductivity of SFR by opening previously closed fractures and by changing the apertures of existing conductive fractures (Posiva 2012-24). This is a relevant consideration, especially regarding the early thermal phase of the repository. The rule for grouts can easily be used subjectively, as difficulties in fracture trace correlations in the DEMO area have shown.

Posiva considers the *thermal properties* of repository near-field bedrock from the viewpoint of degree of utilisation. Schematically, Posiva assigns the thermal properties of bedrock to the RSC, although thermal criteria are not included in the RSC. Posiva delivered (Posiva-STUK-10273) to STUK a panel calculator that includes an optimisation algorithm based on heat production of canisters, average thermal properties of bedrock and deterministically identified brittle deformation features of bedrock. The optimisation target is that as many canister hole surfaces as possible would meet, but not exceed, the assigned maximum temperature for bedrock. However, as has been indicated above (Site characterisation) the assumptions of thermally continuous, homogeneous, isotropic and linearly elastic bedrock at tunnel and panel scale are major simplifications. Besides optimisation considerations, the understanding of mechanical properties of bedrock at tunnel and repository scale also has a long-term stability aspect. For the stability evaluation, the assumption of average thermal properties is too general and optimisation should be conformable with Posiva's RMM. More detailed assessment of long-term heating of bedrock should be considered and possibly also implemented in the RSC. If it can be shown that, e.g., the effects of thermal discontinuities and anisotropies can be mitigated by deposition hole location selection, implementation of suitable thermal parameters into the RSC should be considered.

Posiva also presents *hydrogeochemical criteria* for RSC utilisation (Posiva 2012-24). The practical implementation of the observational criteria is unproven, however. The criteria have not been used in any of the demonstrations that Posiva has implemented. Posiva has copied the hydrogeochemical RSC criteria from the controversial long-term targets (discussed above). Posiva's presentation gives the impression that observable hydrogeochemical criteria would be equally relevant at each RSC scale. This can be questioned. The deposition holes should present the tightest parts of the SFR surrounding the repository. Certain hydrogeochemical criteria, if ever violated in an open deposition hole, would indicate exceptionally fast connections to greater depths or directly to the ground surface (cf. [Cl-] > 2M, ionic strength < 4 mM). However, some criteria might have use at the deposition hole scale. If high pH values are observed in the deposition hole, this would clearly indicate direct connection to a grouted area and would be a basis for hole rejection. Hydrogeochemical criteria should be given more thought. Their significance as a measure of operational disturbance, together with the RSC scales at which disturbances are relevant to measure, should be correctly identified. The hydrogeochemical RSC criteria should also be closely connected to the hydrogeochemical monitoring criteria.

Posiva does not include any *mechanical stability criteria* into the RSC other than the consideration of LDFs, FPIs and the respect volumes related to these. On the whole, LDFs and FPIs tell rather little about the future mechanical stability of deposition areas that may affect repository performance. In the closed repository, the crown areas of deposition tunnels and walls of deposition holes (for example) will be prone to spalling or rock disintegration (cf. Posiva 2012-23 and 2013-01) that will be stimulated first by the thermal pulse created. Then, during the complete service life of the repository, there is high possibility of low and intermediate magnitude EQs. Posiva is also uncertain about the long-term significance for the bedrock of excavation-induced damage (EDZ). At present, in its base case RN-transport calculations, Posiva assumes transmissive ($T_{EDZ} = 10^{-8}$ m^2/s) EDZ patches in deposition tunnel floors to take into account performance reduction caused by excavation damage, but sensitivity case calculations also consider a continuous tunnel floor EDZ. Studies done by Posiva support the view that blast-induced fracturing would not form a continuous, connected network over larger distances along deposition tunnel (Posiva 2013-01). However, this conclusion could be optimistic if the early evolution stage thermal pulse is added to the damaged rock. Posiva's POSE experiments already indicate that heat-induced micro-fracturing occurs around the walls of an experimental deposition hole (WR 2012-60, WR 2013-39). Criteria utilising estimates of thermally reduced wall stabilities (e.g., based on bedrock lithology and anisotropy) should be scoped as part of the RSC. In the safety case, there should be more extensive (than simply EDZ) degradation estimations available for the long-term mechanical performance of deposition areas.

Conclusions

In the near future, Posiva needs to develop the RSC further and verify the pragmatic applicability of the methodology. Posiva applies a 'deterministic' approach to define LDFs, FPIs and respect volumes, and much of this determinism is based on expert judgements or point-wise observations. Posiva relies on an individual plane conceptualisation in describing bedrock discontinuity features. Difficulties in discontinuity mapping at many scales prove this to be a significant simplification. The plane conceptualisation can also be an over-simplification and alternative approaches should be scoped, because unexpected results and relationships may arise. Many of the RSC criteria need further development and there should be consistency between overall design requirements and the monitoring work to be implemented in the repository. Also, the extent of the methodology should be re-considered. Rock classification methodology is meant to take into account all the aspects that can affect long-term performance of the bedrock (YVL D.5 507). At present, Posiva does not present any criteria for how the probable suitability of unexcavated bedrock is deduced from pilot hole studies. The effective criteria for each RSC scale and for each step of RSC application need to be identified more clearly.

Utilisation of the RSC

During the construction of the repository, Posiva approaches the acceptable deposition volumes of bedrock in a scale-wise manner. This is in accordance with YVL D.5 806. At the repository scale, the main targets of the suitability classification are to define the available rock volume of the repository within the LDFs and plan and design locations for 1) access routes, 2) auxiliary subsurface rooms and 3) central tunnel locations for repository panels. Government decision 478/1999, which was later replaced with Government decree 736/2008, required that the disposal facility host rock shall be characterised at disposal depth before submission of a construction licence application. This was further elaborated in Guide YVL 8.4, which required construction of an underground research facility at the planned disposal site. For this reason, steps 1) and 2) of the repository scale are already built in to Olkiluoto. According to Posiva, the RSC methodology is actually tested for panel, tunnel and hole scales, and for these Posiva presents rather detailed summary flowcharts (Posiva 2012-24) and detailed RSC decision sheets (Posiva-STUK-10388). In principle, each RSC scale should contain three steps where suitability considerations are made: 1) DS model evaluation before drillings, 2) studies after drilled pilot holes, and 3) studies from the walls of excavated areas. This order of focusing of studies was also followed by Posiva in the DEMO-area excavations, with a few exceptions: Posiva never drilled a pilot hole into the tunnel profile that presently imitates the central tunnel of the DEMO-area and, e.g., experimental hole EH7 was bored without a preceding pilot hole.

In the *summary flow charts* Posiva has assigned the starting point of each RSC scale to the drilling of the pilot holes (POSIVA 2012-24, Fig. 6-2). To a degree, this is a matter of choice, as Posiva points out, because the previous RSC scale ends with an update of the DS model. Posiva also illustrates a *general outline of repository construction* process, where the previous stage does not end with the update of the DS model (Posiva 2012-24, Fig. 7-2; Posiva-STUK-10388) but with an update of the planned layout. There is a need to update the published summary flow charts to conform better the general outline process, because only the summary flow charts attempt to show what kind of investigations Posiva intends to make within each RSC scale of the general outline. Currently, e.g., the iterative feedback in the summary flow does not point to the same location in the previous scale as in the general outline charts. According to the summary flow charts, Posiva assigns three updates of the DS model into each RSC scale, while in the general outline there are only two DS model updates within each scale. From Posiva's decision-making and STUK's inspection point of view, the latest update of the DS model and the results of suitability analyses are natural decision points regarding the adequacy of information from an unexcavated area where pilot holes are to be drilled. Moreover, the general outline does not show the iterativity related to "excavation rounds", where probe-holes and the walls of the excavated area are investigated after each excavation round. Here, there are natural decision points, as the summary flow charts indicate well. There should also be a process description for data transfer to general site characterisation work. The DS model updates will also produce information for the Olkiluoto site scale model that will be needed when the new panel areas are started.

Posiva also presents detailed RSC decision sheets on how the method should be utilised (Posiva-STUK-10388). These instructions try to clarify the decision rules for how the panel locations, deposition tunnel orientations and lengths, and deposition hole locations are found in practise. Within each RSC scale, the RSC decision sheets concentrate on three last steps (DS and DFN update, suitability assessment, and update of planned layout) of the general construction outline. The RSC decision sheets end with consideration of acceptability of either the planned or implemented layout. According to Posiva, if criteria based acceptance is not met, the general outline of construction leads to a previous RSC scale. This may mean reconsideration of panels at repository scale, reconsideration of tunnels at panel scale, and reconsideration of deposition holes at tunnel scale. This iteration process seems acceptable. However, criteria guiding acceptance still need to be considered, as indicated above. In defining the decision rules, an essential part of the instructions is also how to conduct unequivocally the reconsiderations and modifications to the initially planned design. The readiness to change plans is also mentioned in YVL D.5 507.

In connection with the RSC process, Posiva has introduced rock suitability classes (Posiva 2012-24). The suitability classes are to be considered at different RSC scales, as well as in different steps of RSC application. Currently, Posiva classifies potential deposition tunnel sections based on pilot hole data as 1) possibly suitable (TUNps) and 2) possibly not suitable (TUNpns). After excavation, a deposition tunnel is classified based on wall observations to 1) suitable (TUNs) and 2) not suitable (TUNns). The pilot hole classification illustrates Posiva's current difficulties with pilot hole data and emphasises the need for better pilot hole investigations and formulate RSC criteria for pilot hole investigations. Posiva does not consider this classification in its RSC instructions (Posiva-STUK-10388), although it is extensively evaluated in Posiva 2012-24.

For Posiva, a primary concern in layout planning is the degree of utilisation of a planned disposal area. Posiva expected earlier that the degree of utilisation will be at a level of 75 % (Posiva 2008-01) to 90 % (WR 2009-131). At the moment, Posiva takes into account a risk that 20 % of the hole positions will be rejected (Posiva 2012-23). In connection with degree of utilisation, Posiva has also defined a closely, but complexly related term, called degree of suitability. In the DEMO area, measurements of rock quality have mostly concentrated on measures of the degree of suitability. However, the degree of suitability in the DEMO-area rock is low. This indicates that concepts related to utilisation and suitability can be still subject to quick changes.

Certain *rock engineering actions* will have distinct effects on observations that are made for defining long-term safety properties of near-field bedrock. Nearby excavations may affect hydrogeological observations in the investigation area. Thus, e.g., deposition hole inflow can be affected by excavations done elsewhere. To support the inflow measurements, there should be a routine hydraulic head monitoring programme that is more suited for revealing the hydraulic connections in the excavation area. Rock engineering plans and actions should be taken into account in the RSC utilisation. The excavation damage consequence and mitigation considerations should be part of RSC utilisation. Before the start of construction operations for the first panel, Posiva should present detailed engineering plans for the panel and tunnel scale, because 1) the number of deposition tunnel and deposition hole pilot holes drilled at one time, 2) the number of deposition tunnels and deposition holes excavated at one time and 3) the number of deposition and deposition holes closed at one time, will all affect the RSC suitability interpretations from nearby pilot holes and excavated area walls. These engineering plans should be interrelated with the monitoring and the RSC utilisation plans, which may also contain methodologies for how damage is mitigated.

Because the RSC methodology development is work in progress, Posiva needs to commit itself to further updating and testing of the RSC in connection with hydrogeological pilot hole P-O work, and the testing and monitoring programme, as required above. Posiva will continue RSC development as construction proceeds to the first tunnels of the first planned deposition panel. However, this work is also inevitably going to contribute to confidence building and continuous improvements to the RSC methodology should be expected during the years of repository operation.

Conclusions

Posiva presents summary flow charts on the RSC decision process for three different scales. Some improvements to these should be considered. The summary flow charts should be updated to match the general outline chart of construction. Posiva has also drafted detailed decision sheets showing how it intends to assure the design specifications and requirements. Updates will be needed to the criteria in the detailed decision sheets as Posiva revises its VAHA system. The RSC work and the hydrogeological P-O, measurement, testing and monitoring work are intimately related and a routine programme to implement both should be presented. Modifications to hydraulic connections as a result of construction actions need to be monitored more carefully (e.g. with hydraulic head measurements) and included into RSC decisions. Continuous development of both RSC and DFN models are necessary for building confidence on chosen conceptual models and site performance.

3.5.4 Long-term effects of construction activities

The legislation requires (GD 736/2008, YVL D.5 508) that the favourable properties of the near-field bedrock shall be maintained, as far as possible, during the excavation and construction of the repository. Special care has to taken for example, that 1) the excavation methods limit caused disturbances to as low level as reasonably achievable, 2) detrimental substances from reinforcements and injections cannot significantly affect the engineered barriers and 3) intrusions of organic, oxidising, or other detrimental agents into the closed parts of the facility shall be minimised. It is also required that the emplacement rooms shall be backfilled and closed as soon as feasible.

The construction activities will inevitably affect the repository near-field bedrock properties. However, YVL D.5 411 requires that the disposal concept is not sensitive to these changes. The consequences of construction activities are required to be monitored (YVL D.5 506) in order to mitigate the construction disturbances and to collect supplementary information for long-term safety argumentation.

During ONKALO construction, Posiva has gained experience with the Drill & Blast (D&B) excavation method. To manage inflows, Posiva has adapted available conventional methods, but has also been developing more customized injection methods for leaking fractures. Short-term effects of construction activities have been followed up with a monitoring programme. Posiva also proposes a new monitoring programme for the period before repository operations. This monitoring plan is dealt with in Section 2.3 of this report.

Mechanical long-term stability

Posiva says that the central tunnels will be excavated by the D&B method (Posiva 2012-23). Posiva considers that possibilities for fine tuning of explosive usage and developments in rock support methods are still developing and that further development of the D&B method is possibly the most robust way to implement repository tunnel excavation.

Excavation induced *mechanical damage* surrounding the repository openings is among the primary concerns and mitigation of construction disturbances is considered. Posiva agrees that excavation methods do induce fracturing into the tunnel (Posiva 2011-02) but claims that this fracturing does not form a continuous, conductive fracture network. Posiva states (Posiva 2012-22) that the thickness of the EDZ caused by the D&B method used for tunnel excavation can be controlled to some extent by the design of the blasting technique (separation and placement of holes and amount of explosives used). However, Posiva argues that the thickness of EDZ is not the critical issue: the important factor is how hydraulically conductive it is and whether it provides a continuous transmissive pathway. According to some Posiva results, the EDZ seems to extend typically up to 30 cm below the tunnel floor (Posiva 2013-01) but, in the DEMO area, Posiva allowed for a maximum EDZ thickness of 40 cm (Posiva 2012-23). Posiva is testing various methods for mitigating the EDZ, e.g., using roadheader and chain sawing methods to minimise the tunnel floor EDZ. With respect to deposition holes, Posiva states that, using the "upside down" raise boring method, the EDZ is not a critical issue. Similarly, the raise boring method has been used in the ONKALO elevator and ventilation shafts, and, according to Posiva, the EDZ has been almost completely avoided in these excavations. Nevertheless, based on POSE experiment results, Posiva assumes in its RN-calculations that there will be a 10 cm thick EDZ around the deposition holes, where an anomalous transmissivity of $0.23 \cdot 10^{-8}$ m^2/s is assumed (WR 2012-42). In summary, there do not appear to be clear conclusions available yet on the relations between EDZ intensity, EDZ thickness and EDZ hydraulic conductivity. It also appears that EDZ continuity in the deposition tunnel floor is an open question. Because of the small amount of data available, Posiva considers uncertainties related to EDZ to be high (Posiva 2013-01). Consequently, Posiva uses conservative estimates for EDZ to handle this uncertainty, but in the tunnel floor the EDZ is concentrated in noncontinuous patches (Posiva 2012-09, WR 2012-42). Moreover, Posiva considers removing the damaged rock from the tunnel floor and argues that the EDZ is not the major pathway in backfilled deposition tunnels. This argumentation does not represent the state-of-the-art of EDZ studies. Therefore, more investigations related to tunnel floor EDZ should be expected in the future.

As has been indicated previously, the *large-scale thermal response* of the rock mass from repository to ground surface is not well understood and there is no earlier experience available in heating such a large body of rock. It is possible that stress changes occurring in the bedrock will trigger shear movements within repository near-field fractures. Movements may also occur at the repository scale, within the repository rock volume surrounding the BFZs. Small to medium magnitude earthquakes will possibly affect repository stability from the first decades of operation to 1000 years after closure of the repository. This might also have some long-term consequences. Regarding bedrock thermal response, Posiva has made one study in the POSE niche where a heated disposal hole is monitored with acoustic sensors (WR 2013-41). This experiment shows that heating generates further fracturing, in addition to an EDZ, and the possibility that long-term heating produces a continuous fracture network cannot be excluded. Thermally induced fracturing seems possible around both the deposition holes and the deposition tunnel. These novel studies related to EDZ propagation show that understanding of long-term rock mechanical damage is still at an early stage. Consequently, prediction of future impacts and identification of methods to mitigate them remain a challenge.

Conclusions

Owing to the small amount of data available, the consequences of the EDZ that will result in D&B excavations continue to be questionable, although STUK agrees that induced fracturing does not question the viability of the disposal concept. Posiva is still considering various possibilities of mitigating, e.g., the deposition tunnel floor EDZ. Posiva has not thoroughly justified its arguments on the hydraulic conductivity of the EDZ, especially if further mechanical damage is developed in the tunnel perimeter EDZ during the thermal phase of the repository. Therefore, it is still necessary for Posiva to continue both EDZ and thermally induced fracturing investigations.

Hydrogeological and hydrogeochemical perturbations

Posiva expects that the site's groundwater circulation system will almost recover its former natural state soon after the repository is closed (Posiva 2013-01) and the deeper groundwater regime will return to a state that corresponds to its natural characteristics in the longer term (Posiva 2011-02). Similarly, Posiva says that the repository operational phase will make temporary perturbations to the site groundwater hydrogeochemistry as a result of disturbances and the replacement of excavated rock by materials with different characteristics (Posiva 2013-01). However, in the longer term, the hydrogeological and hydrogeochemical system will have a strong resistance to external changes (Posiva 2011-02). Posiva has done little work on the consequences of the thermal pulse for the repository near-field bedrock hydrogeochemistry and hydrogeology.

Posiva has both measured and predicted *hydrogeological impacts* of ONKALO construction (Posiva 2011-02). Grouting, in order to limit inflow to the underground rooms, has had a strong additional effect on the hydrogeological disturbances. Even in non-grouted areas a positive and unpredictable skin factor appears to limit inflow into tunnels. According to observations, ONKALO construction (2004–2010) has only produced a small drawdown in the free groundwater surface of the site. This is in accordance with groundwater table simulations (Posiva 2011-02). Posiva states that the growing history of measurements will give possibilities to refine these computations and the related parameters further but, in general, disturbances of the free groundwater surface are not too sensitive with respect to the disturbance evaluation. Therefore, Posiva has also assessed hydraulic head drawdown of 27 packed-off deep borehole sections. Over 10-metre drawdown has been observed in 19 packed-off sections (Posiva 2011-02). According to Posiva, the P-O results of packed-off sections correlate relatively well with measurements, although in certain cases, modelling predicts less drawdown than is observed while, in other cases, the situation appears to be vice-versa. According to Posiva, drawdown occurs 1) due to proximity of ONKALO (general conductivity from sparsely fractured rock) or 2) due to good hydraulic connection to ONKALO (longer distance). In many cases, there are discrepancies between model results and observations, indicating that all essential features of the bedrock are not captured in the hydrological model. These discrepancies are related to the consistency of the safety case credibility discussions above. According to Posiva (Posiva 2011-02), one of the success criteria for the Olkiluoto long-term hydrogeological model is that it has to be able to reproduce the short term disturbances as well. This is a conclusion with which STUK agrees, and further testing and qualification of the hydrogeological model has been discussed earlier (see e.g. Transport and retardation properties of bedrock). The observed disturbances also emphasise the importance of backfilling and closing parts of the repository as soon as practicable.

Based on *hydrogeochemical monitoring* observations and modelling calculations Posiva concludes that the open tunnels draw groundwater from all directions from the bedrock and the excavations are likely to cause an increase in the mixing of water types (Posiva 2011-02). However, the interpretation of the early site monitoring results (years 2001-2011) has led Posiva to conclude that, to date, the disturbed condition observations are mainly similar to the Olkiluoto baseline data (WR 2012-44) and the results do not show any dramatic changes over the years. Salinity decreases slowly in and above HZ19 and in HZ20, whereas there is some salinity increase at a depth of 430 m related to HZ20B. The deep parts, e.g. around HZ21, have remained stable. Posiva concludes that the groundwater at repository depth is of Na-Ca-Cl type with a salinity (TDS) range from 8.5 to 15.5 g/l, pH of water around 8 (i.e., slightly alkaline) and SO_4^{2-}, Mg^{2+}, and NH_4^+ concentrations negligible in terms of being a threat to cement performance (Posiva 2012-23). Regarding the operational future, Posiva predicts groundwater composition for the first repository panel area. The conditions are initially very similar to the baseline conditions. Posiva also says that the conditions may change during the time when the panel is open, but is of the opinion that open tunnel conditions will mainly result in drawdown of upper water layers that causes increases in alkalinity, sulphate and sulphide. Posiva separately points out that the expected initial TDS levels are far below the limit (70 g/l) required by the proper functioning of the backfill and buffer (Posiva 2012-23). This statement is a clear and welcome contribution to the VAHA initial and short-term requirements, and to the long-term targets and requirements. However, Posiva omits from its discussion and modelling consideration of how the thermal pulse caused by previously disposed waste might affect near-field hydrogeochemistry during the operational period and during the first thousands of years after closure.

Posiva has also considered more broadly the consequences of construction activities for the site's groundwater system (WR 2010-25). These studies are based on the previous site model (OSD2008) and evaluate the possible disturbance caused by the complete time-span of disposal operations (i.e. 110 years). In addition to the operational period, the simulations cover the first 2000 years after closure of the repository. This previous flow model makes more extreme predictions than the current flow model (Posiva 2011-02) and some of its results are summarised below. The base case of the 2008 study predicts that the maximum salinity at repository depth might be met below the access tunnel and the shafts after about 100 years of operation. The initial value of TDS (~16 g/l) would then rise to a level of 42 g/l. The maximum salinities in the repository panel areas might rise to 25–30 g/L, the average values remaining at around 20–25 g/l. The 2008 flow model study contained twelve sensitivity calculation cases. Decreasing the flow and diffusion porosities, reduction of longitudinal dispersion lengths and reduction of porosity values all tend to increase both maximum and minimum salinities in the repository volume, although the average of salinity of the repository volume remains around 12 g/l. Contemporaneous adjusting of several parameters leads to the most extreme salinity changes. In the sensitivity cases, the maximum salinities varied between 41–80 g/l, the highest also giving always the lowest minimum values (0–4 g/l). In the base case calculations and in most of the sensitivity cases, a rather fast recovery towards initial salinity levels begins immediately after closure of the repository.

The modelling results of the 2008 flow model are unverified. So far, Posiva does not see any significant disturbances in the immediate vicinity of the ONKALO tunnels (Posiva 2011-02). The modelling and its results also provoke once more the question of the conceptual hydrogeological approach and hydrogeological parameterisation, discussed earlier in this report. It is clear that the hydrogeological P-O studies discussed will contribute to these disturbance considerations. Besides the salinity evolution, Posiva does not consider the evolution of safety critical geochemical parameters, or temperature effects on hydrogeochemistry during the operational period and beyond. Posiva points out the possibility of present-day seawater intruding into the open repository facilities (Posiva 2011-02). This is also a relevant consideration and should be evaluated. Posiva should consider how it might mitigate such an event, if it were to occur during the repository operations. Moreover, Posiva does not discuss the fate or evolution of safety-critical foreign species concentrations during the operational period and beyond. There should be more quantitative descriptions of how the disturbed system finds its way back to, or close to its baseline equilibrium state.

Conclusions

The mitigation of hydrogeological and hydrogeochemical disturbance has been considered by Posiva. However, these considerations do not cover the complete extent indicated in YVL D.5 508. In addition to salinity evolution, Posiva should show more quantitatively how extensive the hydrogeological and hydrogeochemical perturbations are expected to be during the years of repository operation and how the disturbed system will find its way back to, or close to, its baseline equilibrium state after closure of the repository. Posiva also needs to evaluate how the repository near-field responds hydrogeologically and hydrogeochemically to the thermal pulse caused by the SNF.

3.6 Sealing structures and closure

3.6.1 Characterization and suitability

Based on YVL D.5, Posiva should identify the relevant properties of each closure material to be characterized. Emphasis in the characterization should be put on properties affecting the long-term durability, performance and mutual suitability of each (sealing/closure structure) material. Closure materials used must be stable in repository conditions (temperature, ground water chemistry, pressure) and must sustain their performance (performance targets) in space and time. Closure materials used must not jeopardize the performance of other barriers, i.e., the backfill, buffer and canister (not to contain materials that directly or indirectly affect on other barriers).

Posiva has considered the topic of material characterization and the suitability of sealing and closure structures in various documents: Design, Production and Initial State of the Underground Disposal Facility Closure report, Posiva 2012-19, Backfill Production Line 2012 report, Posiva 2012-18, Description of the Disposal System 2012 report, Posiva 2012-05.

Posiva has presented only a brief description of the materials used in the sealing and closure structures (closure backfill, plugs). This is due to the fact that closure is not going to start until 50 to 60 years after the present day. Consequently, there is sufficient time to study and optimise the plans and materials for the closure. Despite the relatively long time horizon until the onset of closure and the uncertainties in the materials that will actually be used, Posiva should have provided a clearer account of its expectations of the long-term performance of the closure.

Posiva's approach is that, depending of the depth and local water conductivity of the rock, different materials with different properties will be used. At the repository level, materials similar to the deposition tunnel backfill are used and the characterization procedure is, in principle, the same.

Posiva has identified both a lack of understanding and characterization methodology in its disposal concept development programme and has presented plans to deal with the topic.

Posiva states in Posiva-STUK-10236 (POS-018517) that the maximum concentrations of substances considered harmful to the EBS have not been determined. Posiva considers that accurate limits are not necessarily needed because the use of different harmful substances is controlled and accepted by means of a safety analysis.

Conclusions

Posiva's characterization approach is currently under development and understanding of material properties of clay materials affecting the performance of the barriers is limited. However, Posiva has acknowledged the situation and does have plans to improve the understanding of the material properties. Given the long time before closure systems are likely to be deployed, STUK considers that the understanding is sufficient for this licensing phase but requires more work in the period before an operating licence application. There is time to develop the characterization approach, based on the experience gathered from buffer and backfill materials.

The modular approach developed provides a procedure to select the correct materials and components for various closure parts in the repository, depending on the performance requirements of the closure at each location.

3.6.2 QC

Posiva should (YVL B.2, YVL D.5) classify the barriers as systems and structures to safety classes and determine the relationship between the system, structure or device and the inspection class.

Posiva should develop or accept the necessary guides, instructions and system specific quality manuals in order to carry out the QC procedures (YVL D.5) properly. The QC procedure covers the fabrication (material, conditions, devices, personnel, documentation) and emplacement phases (compliance with the requirements, documentation).

Posiva has considered the topic of quality control in Posiva 2012-17, 2012-18 and 2012-19. In these reports, QC is embedded in all phases from material selection/approval and manufacturing of components to emplacement of system components, up to the verification of compliance with the requirements. The QC chain is comprehensive and continuous for the whole process described.

Posiva has not described clearly how the instructions, manuals, method and process description needed to manage the QC process are to be developed. However, Posiva is currently in the process of writing the quality manuals for each barrier.

Posiva (2012-19) also states that the quality control of the closure backfill, as well as the various plugs to be installed, will follow the principles set for quality control of the deposition tunnel backfill. Further, quality control of the deposition tunnel backfill is described in detail in Posiva 2012-18.

Conclusions

Posiva's description of QC activities in connection with producing systems and system components is sufficient for this licensing phase. There remains work to be done in producing the necessary documentation for various parts of the process.

3.6.3 Performance

Guide YVL D.5 requires that performance targets be specified for each safety function based on high-quality scientific knowledge and expert judgement. In doing so, account shall be taken of the factors affecting the disposal conditions during each assessment period as well as their combined effects. In defining performance targets for the safety functions of the closure, account shall also be taken of the quantities and half-lives of radioactive materials.

According to Guide YVL D.5, conceptual models shall be constructed to describe the safety functions of the closure and the factors affecting them.

Posiva 2012-07 presents the description of each factor (FEP) considered by Posiva to be reasonable likely to affect the development of the disposal system. Such descriptions are intended to address relevant interactions between a specific factor and all the other factors influencing it. As such they serve the purpose of providing the basis for conceptual models constructed to describe the safety functions and the factors affecting them. The objective of Posiva 2013-01 is to describe the conceptual models used and their main assumptions. Presentation of the reasoning and rationale for the derivation of the performance targets is a key aspect of Posiva 2012-03. Posiva's assessment of the fulfilment of the performance targets is presented in Posiva 2012-04.

Posiva has specified performance target L3-CLO-6, according to which the closure shall restore the favourable, natural conditions of the bedrock as well as possible. According to design requirement L4-CLO-10, hydraulic connections from disposal depth to the surface environment through the closed tunnels, shafts and investigation holes should not provide easier transport paths than through existing natural fractures and fracture zones. A hydraulic conductivity of $\leq 10^{-9}$ m/s in central tunnels and vehicle connections, of $\leq 10^{-8}$ m/s above –200 m, in technical rooms and lower shafts, and of $\leq 10^{-7}$ m/s in other positions, are stated to ensure the fulfilment of this target.

The rationale for L3-CLO-6 is reported in Posiva 2012-03 to be that the hydraulic conductivity of the materials and structures used in the closure shall be close to those of the host rock at the same depths. However, the hydraulic conductivity of central tunnels and vehicle connections presented in performance target ($\leq 10^{-9}$ m/s) is nearly two orders of magnitude higher than that shown in Posiva's working report 2012-09 for sparsely fractured rock at repository depth ($3.0 \cdot 10^{-11}$ m/s).

The performance target assumes that the hydraulic conductivity of the closure is less than 10^{-8} m/s down to a depth of 200 m, in the technical rooms and in the lower shafts. In other positions, the target is to have a hydraulic conductivity of less than 10^{-7} m/s. However, it is seen from Posiva WR 2012-19 that hydraulic conductivity down to a depth of 200 m is estimated at about 10^{-7} m/s. The target for the hydraulic conductivity of the technical rooms and the lower shafts is also about 10^{-7} m/s. In other parts of the closure at a depth of 200–420 m, except for fracture zone HZ20, the target hydraulic conductivity is 10^{-8} m/s. WR 2012-09 reports that, down to a depth of 200 m, the hydraulic conductivity of the sparsely fractured rock varies between $1.0 \cdot 10^{-7}$ m/s and $1.3 \cdot 10^{-10}$ m/s, being up to two orders of magnitude lower than that presented in the performance target and up to three orders of magnitude lower than presented in Posiva 2012-19. Also, the hydraulic conductivity of the sparsely fractured rock presented in Posiva's WR 2012-09 for a depth of 200–420 m is found to be two orders of magnitude lower than in Posiva 2012-19. In summary, consideration of the performance target in terms of the hydraulic conductivity of the closure is found inconsistent.

Posiva 2012-07 presents the factors affecting chemical degradation of the closure. The effects of some of these factors are considered only at a general level (e.g., chemical composition of groundwater) or not at all (e.g., temperature). It is stated that the long-term impact of microbial activity on cement degradation is not well understood; yet Posiva 2012-04 suggests that there are no major uncertainties in the evolution of the closure components during the first 10,000 years after closure.

If the central tunnels, or any other part of the closure, will be backfilled with a material with an EMDD less than about 1300 kg/m^3, microbial activity is considered likely therein. WR 2012-09 states that the density achieved in the backfilled section of the shaft plug has a dry density of 1750–1850 kg/m^3, corresponding to an EMDD of 1030 kg/m^3. As the EMDD is considerably less than the threshold value of 1300 kg/m^3, microbial activity is foreseen to be likely in the backfilled section of the shaft plug.

POSIVA-STUK-10115 states that current uncertainties in the fulfilment of this performance target are taken into account in groundwater flow modelling, without explicitly identifying what these uncertainties are and where the relevant analyses have been reported.

According to performance target L3-CLO-7, the closure shall prevent the formation of preferential flow paths and transport routes between the ground surface and deposition tunnels/deposition holes. A hydraulic conductivity of $\leq 10^{-9}$ m/s in central tunnels and vehicle connections, of $\leq 10^{-8}$ m/s above –200 m, in technical rooms and lower shafts, and of $\leq 10^{-7}$ m/s in other positions are stated in design requirement L4-BAC-12, which is seen to be quantitatively identical to L4-BAC-10, to ensure the fulfilment of this target. According to design requirement L4-CLO-11, hydraulic isolation of sections in the underground openings intersected by highly transmissive zones (such as HZ20) from other facility sections is also required to ensure the fulfilment of L3-CLO-7.

The justifications of the performance target and, consequently, the review findings as well, are largely the same as for L3-CLO-6. For L3-CLO-7, Posiva 2012-03 states additionally that the access routes down to the estimated permafrost depth of 300 m (Posiva 2012-03) should withstand the effects of freezing and thawing without compromising the safety of the repository. However, Posiva 2012-03 does not explain what this means in terms of the performance of the closure. Posiva 2012-03 also states that the sealing at the zones where the shafts and access tunnel intersect some major hydraulically conducting fractures needs special consideration, without elucidating what is meant by "special consideration".

Posiva 2013-01 states that the possible degradation of closures has been taken into account in the groundwater flow modelling presented in Posiva 2012-04. However, no explicit account appears to have been taken of the effects of degradation of closures on groundwater flow. In Posiva 2012-04, the degradation of closure plugs is stated to be uncertain, but even if pessimistically assumed to have happened during the first 100,000 years, gravitational sealing is assumed by Posiva to ensure low permeability through the access tunnel and other spaces filled with closure materials. The process of gravitational sealing is found to be inadequately described. On the other hand, the consequences from the degradation of cementitious closure plugs after hundreds of years are stated to have been taken into account in the groundwater flow calculations by considering cases with an increased hydraulic conductivity for the backfilled tunnels. It is unclear where these groundwater flow analyses have been reported, as no explicit literature reference is given in either Posiva 2012-04 or Posiva 2012-19 to support this statement. Also, it is unclear which values of increased hydraulic conductivity were considered in the calculations.

In Posiva 2012-04, it is stated that there are no major uncertainties in the evolution of the closure components during the first 10,000 years after closure; yet, Posiva is prepared for the effects of declined performance of the closure plugs occurring after hundreds of years only.

Posiva does not appear to have considered the effect of earthquakes on structural integrity and performance of the closure. While Posiva has concentrated in the potential of an earthquake with a moment magnitude (M_w) of >5 to induce rock shear displacements significant enough to breach a canister during a post-glacial period, it does not, however, seem to have considered the potential of earthquakes with $M_w < 5$ to impair the performance of the closure and to create relatively short transport paths to the surface environment already soon after closing the disposal facility.

Posiva 2012-03 states that the radionuclide transport analyses have not taken directly into account transport in the underground openings, because shorter transport paths have been found. Posiva does not discuss the role of the underground openings and these "shorter transport paths" in contributing to radionuclide transport in terms of their relative transmissivities, especially if the former does not perform as expected. Consequently, Posiva appears not to have assumed the declined performance of the closure in any of the radionuclide transport analyses. Also, plugged investigation drillholes might pose a greater radiological risk than anticipated in the safety case, through formation of relatively short transport paths to the surface environment.

According to performance target L3-CLO-8, the closure shall not endanger the favourable conditions for the other parts of the EBS and the host rock. According to POSIVA-STUK-10115, fulfilment of this target rests foremost on a proper choice of materials and design.

Posiva 2012-03 states that a major risk for the EBS, especially the buffer, is constituted by high-pH leachates from the concrete. Posiva 2012-07, 2013-01 and Posiva 2013-04 present a conceptualization for the leaching of cement from auxiliary components. Based on the information reproduced in these reports, Posiva's level of understanding of this issue is difficult to assess.

According to design specification L5-CLO-14, the amounts of organics, oxidizing compounds, sulphur and nitrogen compounds in the closure components should be limited. The set of potentially harmful substances is extended in Posiva 2012-03 and 2012-19 to include iron and hydroxide ions. However, no information about the maximum amounts of these substances that would fulfil the performance target can be found in Posiva's safety case. Indeed, in POSIVA-STUK-10236, it is stated that no criteria that would limit their amounts in the closure have been specified. Table 1 in POSIVA-STUK-10236 assumes that nitric, sulphur and organic compounds in the closure do not have adverse effects on the favourable conditions of the buffer, backfill, closure and host rock.

Conclusions

Although there are several areas identified above where Posiva will need to provide further argumentation in future work and because the implementation of the closure is not foreseen until the second half of this century, STUK considers that Posiva has described and justified the performance of the closure adequately at this licensing phase. In particular, in moving towards an operating licence application, there are requirements for further developments with respect to the performance of the closure, especially as many of the performance targets lack a criterion or are fairly ambiguous in their specification. Before submission of the operating licence application, Posiva should reconsider the safety functions and performance targets critically, in order to improve and clarify their argumentation and to remove internal inconsistencies in the target specifications. Due to the ambiguities in argumentation and lack of criteria, it is difficult to assess at present if some of the performance targets are based on sufficient, high-quality scientific knowledge and expert judgement. Posiva should form a more coherent view of the expectations of the performance of the closure at the operating licence phase.

There is also a need to develop FEP descriptions further to address all the relevant interactions within and between barriers more clearly and comprehensively and to construct a conceptual model for each safety function of the closure and the factors affecting them. This contributes to a more robust specification of the performance-target criteria. Posiva's progress in its RD&D work regarding these issues will be followed by STUK.

4 Demonstrations, manufacturing and installation tests

4.1 Description of demonstrations and their targets

Posiva should demonstrate compliance with the requirements of the whole construction, manufacturing and emplacement process of the KBS-3V concept. In this licensing phase (CL) it is enough to demonstrate the technological readiness and available plans (YVL D.5, YVL B.1). For an operating licence application, the whole process must be demonstrated as part of the (non-nuclear and nuclear) commissioning tests.

Successful demonstration of emplacement devices, manufacturing of EBS components (separate systems), emplacement of EBS components, attainment of the initial state requirements, together with credible quality control and documentation, would indicate the feasibility of the concept.

Successful demonstration of excavation and construction of repository rooms (central tunnels), deposition tunnels and deposition holes, under the guidance of the RSC process, would indicate Posiva's readiness to proceed to the construction of the first central tunnel and first deposition tunnels (preparatory stage, panel 1).

Monitoring of ONKALO and future demonstrations and commissioning tests is planned and described in Posiva's monitoring plan (Monitoring at Olkiluoto – a Programme for the Period Before Repository Operation, Posiva 2012-01). This programme is described in Chapter 2.3.

Excavation and construction of the repository

Posiva has developed the excavation and construction methods to produce the necessary underground rooms for the repository. The process is described in the following reports: Underground Openings Production Line 2012, Posiva 2012-22 and Site Engineering Report, Posiva 2012-23.

Posiva has excavated five kilometers of access tunnel, large technical rooms, investigation niches and four, short demonstration tunnels. Posiva has also bored four deposition holes for development and demonstration purposes. Posiva is currently in the process of boring 3+3 additional deposition holes in Demonstration Tunnel 2.

Demonstrations have also been presented and discussed in Posiva's Licensing Plan (PSAR, POS-014722 Luvitussuunnitelma) and Preliminary Commissioning Plan (PSAR, POS-014698, Alustava käyttöönottosuunnitelma).

Manufacturing of EBS components

Canister

The canister consists of the copper tube and lid, and the cast iron insert. Posiva has developed a pierce and draw method (Posiva's reference method) for the canister tube manufacturing. The lid will be made using a hot forming process. In terms of the canister insert, Posiva has developed a casting process. Posiva has presented the current status of the canister production development work in its Canister Production Line 2012 report (Posiva 2012-13) and its references.

Buffer

Posiva has studied the manufacturing processes of buffer components made of bentonite clay. The buffer is composed of buffer blocks (rings and disks) and pellets. The current knowledge of material, fabrication and emplacement has been documented in the Buffer Production Line 2012 report (Posiva 2012-17) and its supporting reports.

Posiva's current reference method for buffer block fabrication is isostatic compression. Posiva is also carrying out tests to compare blocks and their properties, manufactured with both methods (uniaxial and isostatic). Posiva has not yet demonstrated the fabrication of full-scale buffer blocks.

During autumn 2014, Posiva has tested the buffer installation machine (BIM), which is a demonstration machine. Tests have been carried out in the Test Hall at ONKALO. Tests will be carried out in the ONKALO demonstration tunnels in early 2015.

Posiva has not yet demonstrated in full scale the use of a copper plate at the bottom of the hole, together with the rubber membrane. Testing is possible in the Test Hall at ONKALO.

Backfill

The backfill is composed of clay blocks, bentonite pellets and a foundation layer constructed of crushed bentonite. The current knowledge of material, fabrication and emplacement has been documented in the Backfill Production Line 2012 report (Posiva 2012-18) and its supporting reports. Posiva has studied the manufacturing process of a backfill made of Friedland clay.

Posiva's current reference method for block fabrication is uniaxial compression Posiva has made fabrication tests with full-scale blocks, but the results have not yet been published. Thus the fabrication of full-scale backfill blocks has not been demonstrated yet.

Posiva is subcontracting the manufacturing of a backfill installation machine, which will also be a demonstration machine. Currently the FAT tests are being carried out. Site tests (SAT), at ground level, will continue until summer 2015 and continue after that in ONKALO.

Plug

Posiva's reference plug has earlier been a so called "wedge" plug. It has been documented at a general level in Posiva's working report "Principle plug design for deposition tunnels", WR 2009-38. Currently, Posiva's reference plug (as stated in Posiva 2012-18) is similar to SKB's reference plug (Dome plug), described in SKB report TR-10-16. SKB has studied the use of low-pH concrete in plugs in a later report (R-11-04).

Posiva is participating in the EC 7th Framework Programme project, DOPAS, in which Posiva is constructing a low-pH concrete wedge plug in ONKALO Demonstration Tunnel 4 to demonstrate its construction.

Closure

The closure is composed of buffer blocks (rings and disks) and pellets. The current knowledge of material, fabrication and emplacement has been documented in Posiva 2012-19 and the supporting reports.

Because closure will happen in the distant future, Posiva's idea is to utilize the principles and experiences that will be gathered from deposition tunnel materials and plugs during the operational period. Therefore, there are no detailed plans for demonstrations for the closure.

Demonstrations

Posiva recognizes the need to demonstrate the feasibility of the concept before the decision concerning the construction licence application is made. The demonstration principles have been presented in a working report "Testing and demonstrations in ONKALO – Aims and needs" (WR 2009-24). Posiva's "Nuclear waste management programme" (YJH-2012) presents the updated principles and various demonstrations that have been planned for the period 2013-2015 and also up to the operational phase. The previous TKS-2009 programme contained a limited number of plans for demonstrations.

It is particularly important for Posiva to show the feasibility and the practicality of implementing (engineering) the disposal concept and its design and to show that it can be made to work and perform in the manner envisaged in the safety case.

Posiva is late with some aspects of the demonstrations and some of the plans and timetables in YJH-2012 were not clear enough. STUK requested Posiva to gather, schedule and clarify the contents, timetables and safety significance of the planned testing, research and demonstration activities. Posiva has delivered an additional document "Disposal concept development programme / Loppusijoituskonseptin kehitysohjelma" (Posiva-STUK-10215, POS-018285, in Finnish), which contains most of the information requested, presented at varying level of details. This programme does not cover the demonstration of the underground rooms: for example, the production of deposition tunnels and holes.

In terms of the manufacture of the EBS components, Posiva's technology readiness level is highest for the canister components. According to its documentation related to the canister, Posiva can manufacture full-size canister components whose mechanical properties (e.g. tensile strength, elongation) fulfil the requirements that it has set.

The development programme contains a large amount of testing and demonstration, thus making up a large part of Posiva's RTD activities. The programme tries to link tests and demonstrations to the performance targets. STUK identifies some shortcomings: parts of the project are described on a general level, concrete project plans are missing and the criteria and decision making processes have not been described. The programme is not explicit and timing of the projects is not detailed enough and seems optimistic. Posiva is aware of the project risks, especially concerning the timing.

Parts of the demonstrations are planned to be carried out in Äspö, Sweden, as co-operation activities with SKB. Information dealing with these projects is sparse. Posiva should focus its future R&D into areas for which reduction in current uncertainties will have the greatest impact on improving and assuring post-closure safety.

Monitoring is discussed in section 2.3.

Conclusions

STUK considers that the most important, near-term priority for Posiva must be early demonstration of its ability to reproducibly emplace its engineering barrier system at their intended initial state, preferably in underground conditions. According to the PSAR decision (1/H42241/2012) this has to be done before the starting of the construction of the preparatoty phase (panel 1).

STUK sees that the emplacement of barriers will need almost real-time quality control and an instantaneous decision-making procedure. The information received so far from the demonstration machines and related software does not confirm readiness for this.

Posiva is late with the demonstration programme and is not able to demonstrate the feasibility of the concept even at the system level. If the demonstrations with canister and buffer can be carried out successfully then it can be expected that the whole concept will be feasible. However, there remain uncertainties due to the fact that the feasibility of some other barriers (backfill, including plug, deposition hole (bottom) and nearby rock) remains to be shown.

There also remains work to be done for the commissioning phase of the facility (commissioning plan, both non-nuclear tests and nuclear tests after getting the OL).

Despite these specific issues, Posiva's overall intentions and approach to demonstration activities are reasonable and credible from the CLA point of view. However, STUK has concerns about clarity and precise timing, which will affect the feasibility and schedule of the project. The plans presented in Posiva's "Development programme" would, however, be sufficient in proving the feasibility of the concept, if successfully carried through.

4.2 QC

Posiva should develop or accept the necessary guides, instructions and system specific quality manuals in order to properly carry out the QC procedures (YVL D.5). The QC procedure covers the fabrication (material, conditions, devices, personnel, documentation) and emplacement phases (compliance with the requirements, documentation).

The QC procedures that Posiva has used during the concept development period, before the CLA, and will use during the forthcoming demonstrations, have been stated in the Management System Manuals.

Posiva is in the process of producing quality manual for each barrier component (technical or natural). The QC procedures during manufacturing and emplacement activities of each barrier have also been described extensively in a related production line report.

Posiva has recently updated the requirements for QA and QC tasks and personnel competence and taken them into account in the task specifications and in the manufacturing and installation of clay based components.

In previous and current demonstrations, Posiva has applied suitable technology and procedures (for example laser scanning) to verify the successful construction of rooms and structures. New demonstration devices will be equipped with modern positioning and quality control instruments. It will also be possible to follow the emplacement from direct video transmission, or check it from video recording.

The main emphasis of Posiva's current work is to construct the demonstration machines and the necessary development of process descriptions has been delayed.

Conclusions

QC activities dealing with the previous or current demonstration activities of the technical barriers are at a sufficient level for this licencing stage.

4.3 Relevance and expected outcome

There are no direct requirements for demonstrations in any of the regulations. However, the requirements (YVL B.1) state that the solutions and methods chosen during the course of the design shall be based on proven technology and operating experience, and they shall be in compliance with the applicable standards. In addition, the design shall strive for simplicity and, if new solutions are proposed, they shall be validated through tests and experiments.

Demonstrations, manufacturing and installation tests are described and discussed in both the CLA material and other related documents. A first, comprehensive presentation was given in Posiva WR 2009-29.

Demonstrations have also been presented and discussed in Posiva's Licensing Plan (PSAR, POS-014722 Luvitussuunnitelma) and Preliminary Commissioning Plan (PSAR, POS-014698, Alustava käyttöönottosuunnitelma).

The latest document describing these activities is the Disposal Concept Development Programme (POS-018215). It contains a description of all EBS-related tests and demonstrations that Posiva will carry out up to the commissioning tests. Posiva is currently preparing a detailed research plan for every test. These research plans define the targets, expected outcome and safety significance in detail.

Posiva's CLA describes the role of demonstrations as a part of the development and licensing processes. Posiva has also decided that the operating licence will only be applied after the required demonstrations, especially the commissioning tests, have been successfully carried out.

Demonstrations have also been presented and discussed in Posiva's Licensing Plan (PSAR, POS-014722 Luvitussuunnitelma) and Preliminary Commissioning Plan (PSAR, POS-014698, Alustava käyttöönottosuunnitelma) .

Demonstrations will be used to show the feasibility of the initial state of each barrier. Posiva and STUK are aware of the possibilities and limitations provided by the demonstrations and monitoring and have started discussions dealing with performance confirmation. Demonstrations and/or monitoring cannot, on a large scale, be used to verify the performance of the barrier system and the attainment of the target state, because few areas of the repository might evolve to the target state during the operational period.

Conclusions

The demonstrations planned and described in the development programme are relevant from the feasibility and post-closure safety point of view. However, STUK has not yet made a detailed review of the development programme.

The planned demonstrations are late and Posiva is thus not able to show the feasibility of the concept, either at the system level or at the concept level, before STUK's statement. However, Posiva's demonstration activities, both for development and feasibility purposes, are at a sufficient level for this licencing stage.

5 Post-closure safety

5.1 Analysis of the safety concept

5.1.1 Safety functions and performance targets

GD 736/2008 11§ requires that the long-term safety of disposal shall be based on safety functions achieved through mutually complementary barriers so that a deficiency of an individual safety function or a predictable geological change will not jeopardise the long-term safety.

It is also required that safety functions shall effectively prevent releases of disposed radioactive materials into the bedrock for a certain period, the length of which depends on the duration of the radioactivity in the waste. For short-lived waste, this period shall be at least several hundreds of years and, for long-lived waste, at least several thousands of years.

YVL D.5 states that performance targets shall be specified for each safety function, based on high-quality scientific knowledge and expert judgement. In doing so, account shall be taken of the factors affecting the disposal conditions during each assessment period, as well as their combined effects. In an assessment period extending up to several thousands of years, it can be assumed that the bedrock of the site remains in its current state, taking account, however, of the changes due to the disposed waste and predictable or foreseeable processes, such as land uplift and excavations.

Further, Guide YVL D.5 states that in defining performance targets for the safety functions provided by means of engineered barriers, account shall be taken of the quantities and half-lives of radioactive waste. The point of departure for the disposal of SNF shall be that the safety functions provided by the engineered barriers will effectively limit the release of radioactive substances into the bedrock for at least about 10,000 years. Respectively, the duration of the effective containment provided by means of engineered barriers shall be at least about 500 years for short-lived waste disposed of in the bedrock.

According to YVL D.5 the design of the safety functions shall aim to provide a disposal concept that is not sensitive to changes in the bedrock. Another design objective shall be that the characteristics of the engineered barriers in the disposal facilities will not change over time in a way that may have adverse effect on the safety functions, with due consideration given to the reduction of the importance of engineered barriers over long periods of time.

Posiva has defined safety functions and performance targets for the safety functions in Posiva 2012-03. In general, Posiva does not explain which safety functions the performance targets are specified for. Hence, the linkage between Posiva's safety functions and performance targets remains unclear. Posiva states that safety functions are implemented in the proposed design through a set of technical design requirements, which are based on performance targets. The link between performance targets and the design remains unclear.

Due to the general and broad scope of Posiva's safety functions, as concluded section 2.2 of this report, it is unclear how the declined performance of a safety function is handled in Posiva's assessment.. Guide YVL D.5, A05 requires the extent to which the performance of a safety function may decline to be addressed.

The performance targets Posiva has specified are also safety-objective-like notions, rather than measurable or assessable characteristics of the barriers as required in the final version Guide YVL D.5. Only a few performance targets are found to include a measurable or assessable criterion. Posiva has presented a criterion only for such performance targets that it considers a criterion to be definable for. Posiva appears to have perceived performance targets as requirements for the barriers, the associated criteria of which may not necessarily provide sufficient flexibility for the design once specified. Instead of this rigid view, Posiva should consider the performance targets as actual targets for the performance (of a barrier), instead of requirements. Then, whether these targets are met or not, the possible effects on post-closure safety would be assessed through scenarios to demonstrate that an adequate level of post-closure safety can be maintained. In POSIVA-STUK-10337/13.10.2014 (36/H42252/2014), STUK's request to consider performance targets as targets instead of requirements has been acknowledged by Posiva, who now plans to revise the specification of the performance targets accordingly.

In defining performance targets, Posiva suggests that it has considered all the factors that have the possibility to influence system evolution. Posiva has explored a large number of factors, as indicated in Posiva 2012-03. However, in Posiva 2012-12 it is suggested that "In the definition of the performance targets and target properties, all the lines of evolution and expected loads that are judged reasonably likely to occur (based on current understanding and previous findings) are taken into account". Here, Posiva appears to have reduced the set of possible factors to one that is constituted by factors considered "reasonably likely to occur". Posiva's approach is reasonable, but the consequence from such a reduction of factors might be that a number of factors that have significant indirect effects on the system development may not have been considered.

Posiva's safety functions do not assume any particular time periods over which they are expected to be fulfilled. Posiva states that the safety functions are defined such that they are fulfilled all times to the extent that they are required to ensure post-closure safety. However, Posiva's performance targets are assumed to be maintained over the whole assessment period of 1 Ma, unless stated otherwise.

An assessment of whether the specification of the safety functions provides a disposal concept that is not sensitive to changes in the conditions of the bedrock and whether the characteristics of the engineered barriers will not change over time in a way that may have adverse effects on the safety functions, reduces to assessing the credibility of the specified performance targets, while considering a multitude of interactions between the barriers.

Posiva has considered a number of issues that have the potential adversely to influence the performance of the barriers, including canister overpack corrosion by pure de-oxygenated water, piping erosion of the buffer and backfill, chemical erosion of the buffer and interaction of alkaline groundwater with the buffer. Such issues acquire safety significance from their potential to contribute to the declined performance of the safety functions defined for the barriers. It is not clear for STUK how much the performance of a safety function may decline before performance of a barrier is compromised.

Posiva has assessed the fulfilment of the performance targets during different time periods in the performance assessment reported in Posiva 2012-04. Posiva uses the performance assessment to show that the system, designed and built according to the specified technical requirements, will be compliant with the performance targets initially and in the long term. Posiva's assessment is comprehensive enough at this licensing phase.

Posiva's safety case is based on the draft version of Guide YVL D.5 that was published after submittal of the licence application. The requirement regarding criteria for the performance targets was updated in the published version after Posiva's submission of the CL application. Due to ambiguities in argumentation and the lack of criteria for the performance targets, STUK had to devote effort to assessing the post-closure performance of the barriers to verify that the performance targets were based on high-quality scientific knowledge and expert judgement (YVL D.5, 409).

Conclusions

Although STUK has had some difficulties in reconciling Posiva's approach with the requirements and has identified significant differences in how the safety case is structured, the assessment that Posiva has described has been sufficient to justify the performance of the barriers adequately at this licensing phase. However, as Posiva moves towards an operating licence application it will need to address the development needs that STUK has identified. A safety case is a structured argument for the safety of a system. Specifically, STUK requires that Posiva shall construct an argument for the post-closure safety in which:

(1) Posiva shall reconsider its safety function and performance target approach in a critical way in order to clarify its safety argumentation and to remove internal inconsistencies in the targets before submission of the operating licence application,

(2) to understand better how, and to what extent, the performance of a safety function may decline before performance is compromised, before the operating licence phase Posiva shall redefine each performance target to include a quantitative criterion describing the characteristic which, when met, ensures the fulfilment of a safety function. Posiva shall also present a clear and unambiguous link between the safety functions, performance targets and design,

(3) the performance targets for the safety functions shall be supported more clearly by the performance analysis, especially given the substantial uncertainties involved during the early evolution of the disposal system; and

(4) uncertainties in the safety functions beyond the performance-target criteria shall be considered and managed systematically and comprehensively in variant and disturbance scenarios. The above considerations shall apply to the disposal system as a whole, including the low- and intermediate-level waste repository.

5.2 Scenarios

5.2.1 Formulation methodology

A04 of Guide YVL D.5 requires that the way scenarios are constructed should be systematic and take into consideration any events and factors that may be of relevance to post-closure safety and arise from:

a. external factors, such as climate changes, geological processes and events or human actions;
b. radiological, mechanical, thermal, hydrological, chemical, biological and radiation-related factors internal to the disposal system;
c. quality non-conformances in the barriers;

and the combined effects of all the aforementioned factors.

Posiva 2012-08 presents the methodology followed by Posiva to formulate the radionuclide release scenarios for the disposal system.

Formulation of scenarios describing the possible future developments of the disposal system is an integral and important part of a safety case. The postulated system evolutions are analysed taking into account the uncertainties that are inherent in such descriptions of future evolution, including the effects of possible declined performance of barriers on post-closure safety.

Posiva has defined scenarios as lines of evolution that may lead to failure of the canisters containing the spent nuclear fuel and to the release of radionuclides. A scenario should highlight the causal reasoning and present plausible cause and effect links that connect a future condition with the present. Posiva 2012-12 states that the scenarios are used to address uncertainties in the evolution of the disposal system. However, Posiva does not present a scenario as an evolution for the repository system. Posiva's scenarios and the descriptions of their derivation, appears as listings of the assumptions made for the safety analysis calculation.

According to Posiva 2012-08, scenarios need to be internally consistent and transparent. Posiva's safety case does not seem to clearlydemonstrate how internal consistency and transparency have been ensured in practice.

Formulation of Posiva's repository system scenarios and surface environment scenarios has been done in two separate processes. The reason for this is stated in Posiva 2012-08 to be the small number of factors (FEPs) simultaneously acting in the repository system and the surface environment, and the different assessment time windows involved.

Posiva's scenario process follows a systematic "top-down" approach to, first, identifying barrier safety functions and then considering the effect of a single factor (FEP) or a combination of factors on the identified safety functions, with due consideration of effects of uncertainties within the expected lines of evolution (Posiva 2012-08). It is rather unclear how this principle was implemented in practice. Posiva's overall purpose with scenarios is to represent the possible future evolution of the system by a finite set of discrete evolutionary lines and analyse them to demonstrate that the proposed repository system will perform safely up to one million years in the future. Because future system states cannot be predicted with any precision, a sufficient number of possible and reasonable lines of evolution needs to be defined to provide sufficient information to determine the overall safety of the repository system. Consideration of influences between FEPs in an interaction matrix (Posiva 2012-07) presents the linkages between the relevant FEPs. The link between the scenarios and some of the FEPs is visible, but not between the performance targets and the scenarios. Posiva has presented the relevant FEPs, but it is not obvious and easy to determine whether all the possible "failure modes" of the barriers have also been considered. This is mainly because Posiva has covered in one scenario a variety of factors in the evolution of the system. It is therefore not easy to estimate the effects of a single factor on the long-term safety. It is important to check that potential scenarios with a significant risk are not missing from the set of scenarios considered.

Due to the great number of performance targets that Posiva has specified, more systematic scenario building, by considering the possibility that the performance targets are either met or not, might result in a greater number of possible scenarios. The presentation of Posiva's scenario process is not as systematic and transparent as it could have been. While it is difficult to assess if Posiva's set of scenarios includes those most relevant to the safety analysis, it appears to provide reasonable enough assurance that a required level of post-closure safety can be maintained.

Posiva 2012-08 states that the formulation of scenarios for the surface environment has striven for consistency with the methodology used in the formulation of scenarios for the repository system. Posiva 2012-12 states that the approach for constructing the surface environment scenarios is somewhat different from that for the repository system, since the surface environment is assigned no safety functions. The presentation ofPosiva's scenario process for the surface environment appears to be a more consistent and transparent scenario process than for the repository system. The variant and disturbance scenarios for the surface environment are constructed mainly by considering reasonable deviations from the base scenario. The disturbance scenarios are constructed mainly by identifying unlikely FEPs or by considering unlikely deviations from the base scenario (Posiva 2012-08). However, Posiva's surface environment scenarios could have been constructed more systematically and comprehensively in terms of alternative assumptions about what are termed "scenario drivers".

Posiva ensures the consistency of repository system and surface environment scenarios by making radionuclide transport calculations compatible at the interface between the host rock and the surface environment. Ensuring that the assumptions made in the repository system and surface environment scenarios do not conflict with one another would have increased the consistency of repository system and surface environment scenarios. Posiva's safety case does not clearly present how uncertainties in the long-term development of the disposal system, many of which increase with time, were taken into consideration in the scenarios. In terms of total system evolution, uncertainties during the first 10 ka are generally smaller than for the remaining 990 ka of the assessment period of 1 Ma and the scenarios constructed to describe future possibilities should reflect this. Posiva has not separately presented repository system scenarios for the first 10 ka, which would have been made consistent with the scenarios for the surface environment. Consequently, it is unclear how Posiva's scenarios for the repository system reflect the increase of uncertainty with time. It is also unclear how this increasing uncertainty is considered in Posiva's post-closure safety analyses in relation to the decreasing radiological risk from the repository with time.

Posiva 2012-12 states the calculation cases to illustrate the impact of specific uncertainties, or combinations of uncertainties, related to the scenario definitions but does not present what these are. Scenarios themselves are intended to illustrate and capture uncertainties in the development of the disposal system by considering future possibilities that are either expected (base scenario) or deviate from the expected (variant and disturbance scenarios).

Posiva suggests that the performance assessment takes into consideration uncertainties in the initial state of the barriers and in the evolution of the repository system. As Posiva 2012-04 has the objective of presenting an assessment of the fulfilment of the performance targets during the expected evolution of the repository system (base scenario), the uncertainties considered therein should be contained in any performance-target criteria that Posiva has defined. Posiva identifies a number of "incidental deviations" that could result in the release of radionuclides but does not explain how the process for identifying the set of possible incidental deviations has been performed.

Preparedness for alternative future possibilities for system evolution should take place by considering also the possibility that the performance targets are not met. Posiva does not present a description of how the disposal system is perceived to evolve subsequent if one or several performance targets are not fulfilled, due to an "incidental deviation". Also, Posiva does not explain which performance targets are affected by any given incidental deviation, in what way and to what extent: for example, "buffer erosion in some deposition holes". In the base scenario, these deviations are assumed to be insignificant enough not to decline the performance of any barrier, i.e., all performance targets are assumed to be met. Variant and disturbance scenarios call for preparedness for the possibility of quality non-conformances significant enough to result in the declined performance of at least one barrier, i.e., at least one performance target is assumed not to be met. Such quality non-conformances could arise from, e.g., improper emplacement of a barrier, missing barrier components etc. In its scenarios, Posiva's safety case does not show preparedness for quality non-conformances significant enough to result in the declined performance of a safety function for any barrier other than the canister (initial penetrating defect).

Posiva has not presented any scenarios for the low- and intermediate-level waste repository in the report Posiva 2012-12 or included influences from this repository on scenarios constructed for the spent fuel repository.

Conclusions

STUK identifies several areas where Posiva's approach to constructing scenarios is difficult to follow or does not match our expectations of a comprehensive methodology. However, the scenarios selected and the analyses carried out are considered sufficient to test and illustrate the overall performance of the system, even though there are gaps to be filled and additional information that is needed before an operational licence stage. For the CLA, Posiva's presentation is considered adequate, but does not easily lend itself to concluding whether some key safety-significant evolutionary uncertainties have been accounted for in the analysed scenarios.

In future, Posiva's scenario process should be made more transparent, to include a definition of the purpose and scope of the scenario work and to have a clearer reporting practice. Posiva shall consider developing a more systematic and comprehensive approach that would enable an easier evaluation of scenarios for credibility, coverage and distinctness. This would help Posiva to be better prepared for future possibilities that deviate from the expected evolution of the disposal system, as well as for new knowledge and possible surprises that could unfold in the future. Posiva shall present each scenario as an evolution scheme, describing the potential future behaviour of the disposal system. The assumptions made in such scenarios are intended better to inform the choices made in radiological consequence analyses with regard to, e.g., model and input data selection.

The safety case shall cover the repositories for low- and intermediate level waste and for SNF in an integrated safety analysis of the disposal system.

5.2.2 Classification

According to para A05 of Guide YVL D.5, the base scenario shall assume that the performance targets defined for each safety function are met. The influence of declined performance of one or several safety functions shall be analysed by means of variant scenarios. Disturbance scenarios shall be constructed for the analysis of unlikely events impairing long-term safety referred to in requirement 316. The argumentation for the assumed extent of the declined performance of a safety function shall be presented.

Posiva 2012-12 suggests, based on GD 736/2008, that the base scenario needs to be defined with a high probability of causing radiation exposure, but with low consequences. This has led Posiva to define its base scenario to include a few canisters with an initial undetected penetrating defect. However, according to para A05 of Guide YVL D.5, the base scenario should, by definition, be based on the assumption that each of the performance targets is met whereby the canister overpack would remain unbreached. This means that quality non-conformances in the base scenario compliant with para A05 are assumed insignificant enough not to result in the declined performance of any of the safety functions, which clearly is not the case for Posiva's base scenario, as this assumes a few canisters with an initially penetrating defect. STUK notes, however, that Posiva's safety case is based on draft 4 of Guide YVL D.5, which was updated in draft version 5 after submittal of the licence application and that Posiva's approach is cautious and likely overestimates the impacts of the disposal facility especially during the first several thousands of years of the base scenario.

Posiva 2012-12 suggests that when the performance targets and target properties are met and future evolution follows reasonably likely lines (design basis scenarios), the safety functions are fulfilled. According to para A05 of Guide YVL D.5, fulfilment of all safety functions (or performance targets) defines the base scenario alone.

The base scenario that Posiva has defined assumes a quality non-conformance, resulting in the safety function for the canister being declined. Therefore, the base scenario shows characteristics of a variant scenario. Posiva 2012-12 suggests that, with more data becoming available in the future, it is likely that it will be possible to demonstrate that the probability of emplacing more than one canister with an initial undetected penetrating defect is less than 1% (less than 0.2% in Posiva 2012-08). In Posiva WR 2011-36, it is stated that the currently available data are insufficient, even when expert judgement is used, to make a reasonable estimate of the probability of emplacing a defective canister in the repository. In light of Posiva's argumentation, it appears possible that the probability might be greater than 1%, corresponding to more than 45 initially penetrated canisters. Since Posiva currently cannot show convincingly that the probability would be less than 1%, it should have considered a wider range of probabilities and a possibility that part of the initially defected canisters would have been emplaced successively in unfavourable canister positions, to reflect, e.g., a quality non-conformance due to an unforeseen systematic failure in QA/QC. Such considerations would contribute to increased robustness of the disposal system.

Posiva does not present explicitly which performance targets are assumed to be unfulfilled due to the assumptions made in the variant and disturbance scenarios (e.g., those in the variant scenario VS1, ”degradation of the outer part of the buffer”). The declined performance of one barrier may result in the declined performance of other barriers, not just via direct, but also via indirect influences between the barriers. In relation to variant scenario VS1, Posiva 2012-08 suggests that the declined performance of the buffer might result from several factors, or combinations of factors, that are likely to occur within the first tens of thousands of years after emplacement, such as piping erosion, mineralogical alteration and cementation, or from their combined effects. However, in Posiva 2012-09 it is assumed that a 3.5-cm thick zone in the outer rim of the buffer is affected by piping erosion alone, with Posiva 2012-45 cited for the justification of this assumption. However, Posiva 2012-45 does not provide such justification. Posiva does not explain how effects from such adverse factors as piping erosion translate into conceptualisation of a disturbed zone with a specific thickness, considering the assumed homogenization and self-sealing capability of the buffer. In order for the 3.5-cm disturbed zone to form, the self-sealing ability of the buffer should be adversely affected, which in turn means that a number of other performance targets might not be met.

Variant scenario VS2 assumes three episodes of glacial meltwater intrusion down to repository depth during the next 170 ka (Posiva 2012-04). Each episode is assumed to last for 333 and 1000 years for the reference and variant case, respectively. The first episode is assumed to start at 105 ka AP. The timings and durations of the meltwater episodes have not been justified in detail in Posiva's safety case. Alternative assumptions about, e.g., the onset of the first glacial period have been presented. Posiva 2012-12 suggests that, based on pessimistic assumptions, a few canisters might fail within 1 Ma, subsequent to chemical erosion of the buffer; a more pessimistic assumption would be that a few tens of canisters would fail.

A disturbance scenario is a special case of variant scenarios whereby the declined performance of one or several safety functions is assumed due to unlikely events referred to in para 316 of Guide YVL D.5. These events are intended to be induced by natural phenomena or caused by human actions. Accelerated corrosion of the canister insert is considered by Posiva's disturbance scenario AIC. Justifying corrosion to fall in either of the two above-mentioned categories is not considered reasonable and hence its influence on the declined performance of a safety function should be considered in variant scenarios.

The disturbance scenario RS assumes that a rock shear displacement sufficient to breach a canister occurs either at 40 ka or 155 ka after present (AP). Posiva says that the former time is selected arbitrarily and the latter is guided by assumptions made about climate evolution. As the arbitrariness of the former time is explicitly stated it would be important for Posiva to make alternative assumptions about it. Alternative assumptions about climate evolution should also be taken into account due to uncertainties in the long-term climate models. Posiva also says it has considered the effects of alternative assumptions about groundwater flow and composition, but does not identify which performance targets are assumed not to be met.

In addition to the assumptions made in scenario RS, variant RS-DIL assumes advective conditions to prevail once the buffer loss by chemical erosion exceeds 1200 kg. However, advective conditions may form much earlier than during the intrusion of melt water assuming, for example, that during the early evolution phase of the repository system piping erosion occurs. In Posiva 2012-04, it is suggested that a loss of 1200–1400 kg of buffer material would be possible without compromising the performance of the buffer. Following Posiva's reasoning, this would mean that, in case the material loss by piping erosion exceeds 1200 kg, advective conditions would form in the buffer without any chemical erosion being necessary. Significant piping erosion could have far reaching implications for the subsequent evolution of the repository system, as a number of performance targets may not be met as a consequence. The experimental results in Posiva WR 2012-100 for the complex interplay between piping erosion, saturation, material homogenization and build-up of swelling pressure suggest that continued research efforts are needed to bind the risk posed by piping erosion.

Posiva 2012-12 assumes that, during the ice-sheet retreat phase, the disposal system may become susceptible to dilute groundwater conditions and suggests that the estimate of the number of canister positions affected is strongly dependent on the duration of the melt water intrusion and, especially, on the model assumptions regarding the interaction between the fracture water and the rock matrix. As these factors include significant uncertainties, it is important that alternative assumptions are made about them and managed comprehensively in variant and disturbance scenarios if the assumptions are such that they result in the declined performance of the safety functions. If, on the other hand, the assumptions are such that they do not result in the declined performance of any safety function, they should be considered in the base scenario.

Based on model calculations, Posiva 2012-12 assumes that, for permafrost to reach repository depth, highly pessimistic climate conditions would be required. Consequently, Posiva's base scenario makes the assumption that permafrost does not reach repository depth. Posiva states that there are uncertainties in the timing and duration of periods of permafrost, but does not consider these uncertainties comprehensively in variant and disturbance scenarios. In Posiva 2012-04, it is suggested, that even if permafrost reached repository depth, it would not have significant effects on the material properties of the buffer and tunnel backfill. However, the safety significance of permafrost stems from consideration of its potential to contribute to the declined performance of safety functions, i.e., failure to fulfil performance targets. The basis for looking into the potential role of permafrost in impairing a safety function should be the conceptual model constructed to describe the safety function, which should address all the relevant (direct and indirect) influences within and between the barriers.

In relation to climate evolution, Posiva 2012-12 assumes the first permafrost period to start at 50 ka AP. Posiva assumes that while permafrost may develop after 50 ka AP, it is assumed to have no effects on the release rate of radionuclides, or on the release paths that could retard the transport of radionuclides to the surface. An alternative assumption would be that permafrost does have effects on the release rate of radionuclides, or on the release paths that could retard the transport of radionuclides to the surface. As an assumption is itself an expression of uncertainty, it is important that opposites of assumptions are also examined.

Conclusions

Posiva has followed Guide YVL D.5 to classify the scenarios. 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 Posiva uses to enhance the understanding of the system and are required to delineate the impacts of model and data uncertainties (Posiva 2012-08). While there is logic to all these categories, there is some arbitrariness in classifying the calculation cases. This makes tracking of scenario characteristics and their effect on performance somewhat difficult and, in some cases, this has led to misunderstanding in Posiva's way of classifying scenarios.

As management of disposal-system-wide uncertainty takes place by constructing a set of consistent scenarios that are distinct enough from one another and have a large coverage in terms of future possibilities, Posiva should have made alternative assumptions in the variant and disturbance scenarios as comprehensively as possible. This includes the assumptions made with regard to the timings of certain events. Such alternative assumptions would have contributed to improved robustness of the disposal system safety case.

Biosphere scenarios do not readily fit into the classification scheme used for the repository system; namely base, variant and disturbance. The methodology used to classify biosphere scenarios could be revised to improve transparency.

Nevertheless, Posiva has constructed and defined a set of scenarios and calculation cases that provides sufficient information on system evolution and response for the purposes of this licensing phase. For the future, a more systematic and transparent way of constructing consistent scenarios would produce additional safety-significant scenarios and calculation cases.

5.3 Post-closure safety assessment

5.3.1 Safety assessment

GD 736/2008 14§ requires that compliance with the requirements concerning long-term radiation safety, and the suitability of the disposal method and disposal site, shall be proven through a safety case that must analyse both expected evolution scenarios and unlikely events impairing long-term safety. The safety case comprises a numerical analysis based on experimental studies and complementary considerations insofar as quantitative analyses are not feasible or involve considerable uncertainties.

It is also required that compliance with the radiation exposure constraints for the most exposed people, as referred to in section 4 , shall be proven by considering a community that derives nutrition from the immediate surroundings of the disposal site and is most exposed to radiation. In addition to impacts on people, possible impacts on flora and fauna shall be analysed.

GD 736/2008 15§ requires that the input data and models utilised in the safety case 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.

The basis for selecting the computational methods used shall be that the actual radiation exposure and quantities of radioactive materials released remain below the results of safety analyses, with a high degree of certainty (in other words, the calculation method should produce results that are conservative). The uncertainties involved in the safety analysis, and their significance, shall be separately assessed.

Methodology

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;
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 fulfilment of performance targets. The impact of uncertainties in conceptual and numerical models is primarily analysed based on a discrete set of variant and disturbance scenarios and also by conducting sensitivity analysis. The performance assessment is discussed more in section 5.1.1 and performance of the barriers earlier in this report.

Deterministic sensitivity analyses are conducted through calculation cases, which are defined by varying assumptions pertaining to models and their parameters. Probabilistic sensitivity analyses (PSA) are conducted by assigning probability distributions to 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. Posiva 2012-09 presents an adequate representation of the models and information flow in post-closure safety assessment. The specific approach for groundwater modelling, a major component 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 and the LDF, and by using the stochastic DFN model.

The safety assessment requires many models and a large number of parameters. Posiva admits 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 in 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 limits the radionuclide discharge points for use in the biosphere modelling. A PSA on human dose should be conducted to determine the impact of uncertainty in discharge locations generated by the DFN model.

Safety analyses

Since the early analyses presented before the Decision-in-Principle phase, Posiva has devoted much attention to the data needed by the safety assessment model for a KBS-3-type deep repository. Significant progress has occurred in the formulation and analysis of scenarios, characterization and presentation of the site-specific data, along with the reasoning behind the assumptions in the performance analyses. These assumptions include the initial causes of the releases: i.e., failure of the canister due to an initial defect, corrosion or rock shear.

In contrast, the essential features of the modelling of the release and transport of radionuclides in the near and far field have not changed. Although the computational models have changed, the safety analysis is still based on the same conceptual models consisting of, e.g., degradation of the fuel matrix and the structural materials, behaviour of the instant release fraction, diffusion and sorption of the radionuclides in the near field and the advective transport of the radionuclides in the far field, accompanied by diffusion to and sorption on the host rock matrix. The mathematical models involved are well known and, with minor differences, used by other organizations dealing with similar safety assessments.

The approach that has been taken to defining mathematical models for radionuclide transport is described in some detail in the safety case reports and generally includes discussion of simplifications and assumptions. There is little discussion of alternatives to the overall approach, but this is to be expected, as the approach is mature and uncontroversial. Many of the conceptual models, calculation cases, mathematical models etc. have been developed iteratively and in parallel with SKB's safety case for the final disposal of spent nuclear fuel at the Forsmark site in Sweden. The use of GoldSim has allowed full coupling of decay chains (through solubility) and thus leads to a mathematical model that is more consistent with the conceptual model than has previously been the case. The methodology is either state-of-the-art, or at least compliant with best practice. This includes the codes selected for the assessment. Although the conceptual models relate to the safety functions, they have not been explicitly related to specific performance targets and corresponding criteria.

For the present safety case, Posiva has replaced the REPCOM code with the GoldSim code, and the FTRANS code with the MARFA code. GoldSim is widely used for radionuclide transport calculations. MARFA is also used by SKB for modelling transport through fractured rocks. Posiva has undertaken cross-comparison calculations against REPCOM and FTRANS (Posiva 2014-02), thereby maintaining the link with earlier assessments.

There is some confusion regarding the use of MARFA 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 in Appendix B of Posiva 2014-02. In its response to STUK's request for additional information, Posiva has confirmed that the version of MARFA is 3.2.3. Posiva also provided information of how the splitting algorithm was used.

The RS-DIL cases additionally include radionuclide transport in colloids. It was noted that, in a January 2014 newsletter, GoldSim identified an error in the calculation of colloids in pipes. STUK asked Posiva about the use of GoldSim, because it was not clear if Posiva has used the inbuilt functionality in GoldSim to calculate radionuclide transport in the RS-DIL cases. If Posiva has used this functionality, the calculation results might be affected by this error. Posiva responded that the inbuilt functionality in GoldSim was not used, but colloid-facilitated transport was calculated using D_e and K_d values. However, in the PSA for the RS-DIL scenario, the inbuilt functionality was used. Posiva updated the PSA for the RS-DIL scenario.

The transport path of radionuclides from a canister in an individual deposition hole to the biosphere (or to a major water conducting feature of bedrock) can be complex. Posiva has characterized the first parts of this pathway by three representative paths that dominate near field transport, namely: one directly from the buffer to a water conducting fracture intersecting the deposition hole (F), another through the excavation disturbed zone to the nearest fracture (DZ) and the third one through the tunnel backfill to the nearest fracture (TDZ). Each of these near field paths continues with an individual transport path in the far field rock. The total release from a single deposition hole is the sum of the releases of these three representative pathways. Each of the far field paths is characterized by transport resistance and four types of adjacent rock matrix. These characteristics change with the physical properties encountered along the path. Naturally, the pathways also depend on time. The characterization of each individual pathway is done by realizations of stochastic water flow models at a given time.

As the pathways are typically thousands of metres long, a large amount of spatially dependent data is needed to characterize even a single pathway for a given time. This affects the clarity of the presentation and makes the exact duplication of the analysis difficult. In fact, while Posiva has published lots of information on the approach, the exact and complete data for any single pathway cannot be found in the reports presented. However, there are many features of the modelling approach that reduce the importance of this problem. First, the transport resistance of a pathway is a cumulative characteristic, i.e., the total transport resistance of a pathway is the sum of the transport resistances of its parts. Second, the total release is typically dominated by one of the three representative pathways. Lastly, the variation of the rock type along the pathway does not seem to have a major influence on the retardation of the most important radionuclides. Consequently, similar results can be obtained by the much simpler approach of using a single pathway with single representative data, i.e., single value for (total) transport resistance and single values for (space independent) rock matrix and sorption.

The Reference Case considers one canister with a small initial penetrating defect. An important assumption is that the size of the defect does not increase with time, because the small size of the defect limits radionuclide migration out of the canister. Scenarios involving a gradually enlarging defect (VS1) and sudden loss of transport resistance through the defect (AIC and "growing-hole" cases in the PSA) are considered, so the impacts of a growing defect are explored. However, Posiva has not presented justifications for the assumption that the size of the defect is not increasing in the Reference Case, so it is unclear whether this is a non-cautious assumption.

As requested by STUK, Posiva has added statistical analyses of multiple canister failures to support the single canister deterministic analyses. It is worthwhile to note that the statistical approach for multiple canister failures gives smaller safety consequences than a corresponding single canister deterministic analysis. This result is due to the consideration of the probabilities and the fact that the deterministic reference case involves a conservative choice for the deposition hole.

The explanation of the mathematical model is not clear in the derivation of the equivalent flow rate (QF) 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 and it raises the question of 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 (in 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 a judgement of what actually happens at this interface.

Posiva has presented modelling and input data, which includes evidence from Onkalo, the results of tracer testing (undertaken by SKB and cited by 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 has used additional complementary cases to assess the influence of specific parameter values, alternative parameter correlations and alternative conceptual models that are not necessarily consistent with the scenarios. These complementary cases help to build further confidence in the assessment results, and also provide a useful indication of the degree of caution provided by assumptions in the 'main' calculation cases. In general, the performance or safety relevance of the complementary considerations presented in Posiva 2012-11 would have been more readily assessed had conceptual models been constructed for the safety functions. Without conceptual models, it is difficult to assess how the complementary considerations are intended to support the fulfilment of the safety functions. Also, it is difficult to assess if such considerations have the potential to contribute to the declined performance of a safety function if no conceptual model has been constructed to describe it.

Posiva has explored a large number of calculation cases, which are linked to conceptual and parameter uncertainties, such that the assessment is thorough. Posiva applies probabilities to unlikely events in order to calculate expectation values.

The analysis would benefit from further information on the significance of the following FEPs, which might lead to additional scenarios and, therefore, to additional calculation cases:

- melt water injection below a warm bottom glacier;
- upwelling of saline waters from depth;
- drift seal failure in transmissive zones.

Glacial melt-water injection is only assumed to occur during glacial retreat, as the melt front transgresses the site. According to Posiva, injection occurs for a period of 333 years. It is unclear how the length of this period is justified and how the length of the period has been derived. On the other hand, it could be that, under glacial conditions, the site would be overlain by a warm-based ice sheet and melt-water injection might be possible for many thousands of years.

Posiva states that in the future expected conditions the groundwater salinity (TDS) at repository level shall be less than 35 g/l. According to Posiva 2011-02, the TDS increases with depth and exceeds 35 g/l at a depth of approximately 600 m. It has been suggested that high salinity waters may have upwelled from depth since the preceding inter-glacial. Posiva 2012-04 describe how short-term 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 a scenario that addresses upwelling of waters with TDS >35 g/l.

A key process that has only been assessed to a limited extent is gas-mediated release and transport in the AIC disturbance scenario. 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 chemical form of C-14 and any subsequent reactions that alter the form, are important. Given the potential significance of transport of C-14 in gas, this is an area where the conceptual model and, consequently, the assessment calculations, could potentially be improved. For example, this might include replacing the cautious assumption that all C-14 gas rapidly migrates through the geosphere without significant dissolution, with a more realistic conceptual model that accounts for dissolution. Posiva is participating in the EU research project CAST, which is investigating these issues.

The assumption of instantaneous release of the 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. To help reduce this uncertainty, Posiva is participating in the EU project FIRST-NUCLIDES.

Also the assumptions regarding 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. STUK requested Posiva to submit additional information regarding a single canister shear failure at an early time (200 years after repository closure). Posiva´s analysis of an early earthquake is reasonable, although further work is required to decrease the uncertainty in the magnitude-frequency relationship that is used to estimate the frequency of occurrence of large earthquakes.

STUK requested additional information about probability-weighted multi-canister failure due to post-closure seismic hazard. The explanation given in Posiva’s response is still not clear. However, it seems that the approach for the probability-weighted multi-canister failure is closely similar to the probabilistic approach for an earthquake during the temperate period.

The geosphere fracture network and associated heterogeneity cannot be fully characterised. Sample data can be used to estimate parameter distributions and develop a Geo-DFN model, which in turn feeds into the Hydro-DFN. The scenarios, conceptual models and radionuclide transport calculations are underpinned by the Hydro-DFN model. Therefore there is strong reliance on the results of the DFN model and, in particular, the DFN model description of heterogeneity and random variation.

Posiva has explored 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 consequences of this have been considered when selecting which case to carry forward. The consequences of alternative DFN cases for the RNT results have also been considered, for example the BS-ALL case (Posiva 2014-02) considers an initially defective canister in each of the potential canister locations and Figure 7-10 in Posiva 2013-01 shows how the DFN case affects the number of failed canisters in the VS2 scenario.

A number of Posiva’s calculations have been reproduced independently for STUK, which provides a good test of the completeness of the data. However, these independent calculations brought up a number of minor errors, inconsistencies and uncertainties in the data and calculations. The AMBER code was used in the independent calculations to reproduce Posiva’s calculations. There are some differences between the AMBER and GoldSim results for the RS case, in terms of the responses to glacial events and also the radionuclides that contribute significantly to the radionuclide flux to the biosphere. Reproduction of Posiva’s results helps builds confidence in their calculations, despite the discrepancies they have identified.

Posiva has used probabilistic calculations to support sensitivity analysis and identification of the key parameters for performance. Posiva 2013-01 provides descriptions of key data underpinning the calculations and the confidence that can be placed in the models and data. The discussion highlights important uncertainties, areas of ongoing research where cautious assumptions have been made and the potential consequences of uncertainties, often supported by the results of the PSA. It is therefore important to have good confidence in the results of the PSA.

Despite this remaining uncertainty, overall additional sensitivity analyses help to build confidence in the results of the PSA. Confidence is further supported by the results of the PSA, which are sensible and can be explained. The PSA, however, is limited to just the "hole forever" and the "growing hole" cases. STUK requested Posiva to submit additional information regarding the PSA for the RS-DIL scenario. Posiva identified important parameters for the RS-DIL scenario and discussed how such information will be used in defining future work. In connection with the operating licence, the PSA should be made to cover an adequate set of scenarios, including the biosphere scenarios.

The PSA considers "hole forever" and "growing hole" cases. With the exception of C-14 in some extreme realisations in the growing hole case, radionuclide flux constraints are not exceeded. However, the significance of uncertainties associated with the IRF, fuel dissolution rate, and metal component corrosion rates are more important in the growing hole case than in the hole forever case, where the size and nature of the defect tend to limit releases. Posiva does not draw any conclusions about the relative likelihoods or significance of the two cases and, therefore, the significance of uncertainties in the IRF etc. The limited probabilistic sensitivity analysis uses up to 162 random parameters and provides useful information regarding important parameters. 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. While continuing to use calculation cases as part of the deterministic sensitivity analysis, Posiva should expand the PSA to cover adequate set of scenarios.

There is not a specific discussion in the safety case on how supporting methods should be used, or reference to an overarching process or procedure. However, Posiva makes use of supporting methods to support, e.g., the conceptual models, the calculation cases and the analysis of results. This includes useful quantitative discussions of the 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) and the time for water penetration into a canister with a pinhole defect (Posiva 2013-01).

Specific processes and procedures have been applied to data clearance and expert elicitation (Posiva 2013-01), which STUK considers as supporting methods. Data sources and quality aspects of the sources are documented according to specific guidelines. Individual data and databases are approved through a clearance procedure. Posiva 2013-01 describes the quality management measures applied to the models and data. It describes eight QA measures and where they have been applied in the safety assessment. The elicitation of expert opinion has been applied to specific cases when the understanding or data is conflicting and consensus is needed for the selection of key models and data (e.g. solubility and sorption data). Posiva's elicitation process should be improved by increasing transparency and traceability, and applying independent assessment of the elicitation outcomes. It would be improved also by using formal methods (e.g., Cooke methodology) aiming at quantifying the range of uncertainty in qualified expert opinion, rather than aiming for consensus (see previous comments).

Posiva (2013-01, Section 2.3) describes eight quality management measures applied to the models and data, and where they have been applied in the safety assessment. Posiva (2013-01, Section 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. This process resulted in some discrepancies in the data being identified by Posiva. These arose due to factors such as parallel working, miscommunications and the use of ad hoc data freezes for models. Additional calculations were undertaken by Posiva for those discrepancies that had a potential impact on the assessment results, and none of the discrepancies led to significant differences in the total radionuclide releases (Posiva, 2013-01 Appendix M).

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 (2013-01) and learning from experience will form important inputs into improved QA processes for updates to the safety assessment in support of the operating licence application; for example, to facilitate setting up a data freeze. Such a data freeze should greatly improve the QA of, and confidence in, the safety assessment calculations. If possible, there should be a single reference for the safety assessment data.

Low and Intermediate Level Waste Repository

The co-location of the spent nuclear fuel repository and a low and intermediate level waste (LILW) repository at the site is described in Posiva 2012-37. The LILW repository is planned to be located at –180 m along 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 in the LILW repository. As stated in Posiva 2012-37, the LILW repository 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 post-closure safety of the disposal of the spent fuel.”* The dose to a member of the most exposed group from the LILW repository is estimated to be less than 0,01 mSv/year. The major contributor to this dose is Sr-90.

Since the LILW repository is located directly above parts of the spent fuel repository and the both repositories are connected with the same access tunnel, STUK requested combined analysis of releases and doses from the disposal of the spent fuel and of the low and intermediate level waste (18/H42252/2014, 25.6.2014). Results presented in POS-0192880 are rough estimates of the releases and doses from the LILW and the spent fuel repositories combined. Posiva states that the combined radiological impacts from the LILW and the spent fuel repositories will remain, with high confidence, below the regulatory constraints. The contribution of the LILW repository to the combined dose (due to the releases of Ag-108m and Sr-90) decreases before the releases from the spent fuel repository would reach the surface. In general, the releases of I-129 and C-14 (especially) from the LILW repository keep the contribution of the LILW repository to the combined releases high, compared to the contribution of the spent fuel repository, up to 10,000 years after closure during the dose assessment time window. The difference between the contributions of the repositories decreases with time. After the dose assessment time window, the releases from the spent fuel repository dominate the release rates. The release from 10,000 to 50,000 years after closure is mainly due to the C-14 release from the spent fuel repository and, after that, at least up to 100,000 years after closure, due to the Cl-36 and I-129 releases from the spent fuel repository.

So far, Posiva has not carried out a detailed assessment of the interactions between the two repositories in terms of their HMC evolution and the consequent impacts on releases from each.

Conclusions

Posiva's approach to deterministic calculations is consistent with the YVL guidance. The calculation cases 'flow down' from the scenarios and are supported by a number of complementary calculation cases. A significant number of calculation cases is considered and the chosen calculation cases cover all the scenarios Posiva has defined and are consistent with the assessment period and disposal system. Overall, STUK considers that the calculations are cautiously realistic and, in general, the level of detail and manner of presentation of the radionuclide transport calculations is sufficient to provide an adequate understanding of the development of the technical arguments, the scientific and mathematical methods used and the results and conclusions reached.

The LILW repository is located directly above parts of the spent fuel repository and both repositories are connected with the same access tunnel. Therefore, Posiva shall include the LILW repository in the safety case for the spent fuel repository as an integral part. In other words, Posiva shall address the dose and release estimates from the spent fuel repository and LILW repository in a more consistent manner, so that combination of releases can be evaluated more reliably.

The calculation of probability-weighted multi-canister failure releases is difficult to follow and before the operational licence phase, Posiva shall provide a more extended description of how it is assembled. The description should include an assessment of the impact of an order of magnitude increased frequency over the deglaciation period. It would also be valuable for Posiva to compile the information to identify if, where and how it sees its analysis as being conservative. 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.

The synthesis of the assessment results could describe more clearly the key arguments that give confidence that the system will be safe. In connection with the operating licence, a PSA should be made to cover an adequate set of scenarios, including the biosphere scenarios.

5.3.2 Complementary considerations

Guide YVL D.5 A10 requires that, in the event that a scenario cannot be comprehensively and reasonably assessed by means of quantitative safety analyses, its significance shall be examined by means of complementary considerations, such as calculations by simplified methods, comparisons with natural analogues or observations of the geological history of the disposal site. The significance of such considerations grows as the assessment period increases and safety evaluations extending beyond the time horizon of one million years can mainly be based on complementary considerations. Complementary considerations shall also be made parallel to the actual safety assessment, to enhance the confidence in the results of the analysis, or certain parts of it.

Posiva describes the objective of the 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 the radiological hazard with naturally occurring radioactivity and radiation background over time, evidence for responses to climate and landscape change, analogues for relevant processes and the impacts of discrete events, such as earthquakes. Appendix C in Posiva 2012-11 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 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 performance targets. 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 safety functions and key processes.

There are no 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. It is apparent that the toxicity of spent fuel decreases significantly with time and, at 100,000 years, the radiotoxicity index of 9,000 tonnes of spent fuel is similar to that of the Cigar Lake Uranium ore body. Because the canisters are assumed to stay intact (except for the possibility of an initial defect) for several hundred thousand years, this kind of complementary information provides high confidence in the safety of the repository.

Posiva uses appropriate caution in interpreting such information. For example, Posiva 2012-11 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 archaeological analogue study is discussed in Posiva 2012-11 to support the low corrosion rate of copper. In that study, a corrosion rate of 0.15 µm/a was calculated, under oxidizing conditions. This provides confidence regarding the even lower corrosion rate under the reducing conditions of the repository.

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: for example, under rock shear conditions. While many examples are given 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 that are 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), 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.

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 it also does not exactly match repository conditions. However, complementary considerations reduce uncertainties by enhancing understanding of the phenomena that are factored into the models used for safety assessment.

Regarding earthquake probability, the statement that the density and magnitude of earthquakes in Finland is generally much lower than in other areas is justified. However, a special feature in Scandinavia is the enhanced probability immediately after retreat of the ice sheet. A large number of events have been dated in Sweden based on observations in Quaternary clay sediments. The focus in Posiva's complementary considerations is 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 5 cm. Data attached to Posiva WR 2007-05 show that displacements of about 10–20 cm have been observed near Olkiluoto (only some were postglacial, related to the last glacial advance). Further south, near Kustavi, displacements of almost 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 observed by Hutri et al. (2004, 2007) should be included in the argumentation, to justify Posiva conclusion of "limited impact of earthquakes."

Calculations of radionuclide transport in the geosphere make only 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). An example is the potential significance of release of C-14 labelled gases. In Posiva 2012-11, Posiva provides a 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.

Conclusions

Posiva's objective in presenting complementary considerations is to enhance confidence in the quantitative analyses developed in performance assessment. Complementary considerations provide a measure of confidence, but are not suited to a quantitative reduction of uncertainties in performance assessment. In general, Posiva uses the complementary considerations effectively to enhance confidence in the safety case and the information presented can be considered adequate for this licensing phase.

However, complementary considerations are not explicitly mapped to safety functions and performance targets; Posiva should improve mapping to safety functions, relative importance of barriers and key processes.

5.3.3 Compliance with the regulatory criteria

GD 736/2008 14§ requires that compliance with the requirements concerning long-term radiation safety and the suitability of the disposal method and disposal site, shall be proven through a safety case that must analyse both expected evolution scenarios and unlikely events impairing long-term safety. The safety case comprises a numerical analysis based on experimental studies and complementary considerations, insofar as quantitative analyses are not feasible, or involve considerable uncertainties.

It is also required that compliance with the radiation exposure constraints for the most exposed people, as referred to in section 4 , shall be proven by considering a community that derives nutrition from the immediate surroundings of the disposal site and is most exposed to radiation. In addition to impacts on people, possible impacts on flora and fauna shall be analysed.

GD 736/2008 4§ requires that disposal of nuclear waste shall be planned so that radiation impacts arising as a consequence of expected evolution scenarios will not exceed the constraints given in subsections 2 and 3. In any 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:

1. the annual dose to the most exposed people shall remain below the value of 0.1 mSv; and
2. the average annual doses to other people shall remain insignificantly low.

During assessment periods after the period referred to above in subsection 2, average quantities of radioactive materials released over long time periods into the living environment, shall remain below the maximum values specified separately for each radionuclide by STUK. These constraints shall be specified so that:

1. at a maximum, radiation impacts caused by disposal can be equivalent to those caused by natural radioactive materials in earth's crust; and
2. on a large scale, the radiation impacts remain insignificantly low.

GD 736/2008 5§ says that the significance of unlikely events impairing long-term safety shall be assessed by evaluating the reality, probability and possible consequences of each event. Whenever possible, the acceptability of the expectancies of radiation impacts caused by such events shall be evaluated in relation to the annual dose and release rate constraints of radioactive materials, as referred to in section 4.

YVL D. 5 gives more specific requirements in paras 307–318.

Posiva has developed an advanced and elaborate biosphere model that is state-of-the-art; however its documentation is not transparent. For example, it is not possible to reproduce the dose calculations presented in the biosphere safety assessment (Posiva 2012-10) and supporting reports. The main reason for this appears to be the extent and the complexity of the biosphere model.

Posiva should identify the important parameters for the biosphere; probabilistic sensitivity analyses should be done also for the biosphere scenarios. However, because of the very low source term during the dose window, Posiva estimates a very high safety margin; therefore the uncertainties in the biosphere models will not change the basic conclusions.

Based on Posiva's assessment, the variant scenarios with two different release locations cause the highest dose estimates for the most exposed group among the variant scenarios. The effect of uncertainty in DFN predicted discharge locations should be examined more closely in the future.

The safety assessment calculations (Posiva 2012-09) give the radionuclide release rates to the biosphere normalised by the flux constraints given by STUK. The flux constraints listed only cover a subset of radionuclides that are included in the calculation. It is not clear what flux constraint values Posiva used for the remaining radionuclides. Posiva's demonstration of its compliance with the normalized release rate regulatory constraints is acceptable.

The base scenario releases are more than three orders of magnitude smaller than the regulatory release constraints. The disruptive scenarios are the only ones that challenge the capabilities of the engineered barriers and, in these scenarios; the estimated releases are higher, being only one order of magnitude below the regulatory constraint in the rock shear case.

1000 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) show the consequences of 1000 year averaging on the normalised releases, which are significant for the RS2-DIL scenario.

Posiva applies the 1000-year averaging and also applies probability weighting only in the RS scenario. The 1000 year averaging seems to smooth (i.e., reduce) the peak by a factor less than five. The probability weighting is much more significant as the annual probability of an earthquake per square kilometer per capable fault is taken as 10–7. In the RS scenario, multiple canisters fail, resulting in a high source term. The other scenario with higher normalized release is the AIC, or accelerated insert corrosion scenario. In this scenario, one container fails completely as a result of the corrosion products from 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 two to three orders of magnitudes. It must be noted that the releases in the AIC scenario are not probability weighted, which is in line with the fact that the process of accelerated corrosion of the canister insert is not an event compliant with para 316 of Guide YVL D.5.

Posiva has considered the effects of unlikely events, including rock shear and human intrusion. Human intrusion scenarios are considered in the biosphere assessment. The probabilities of unlikely events have been considered and expectation values of effective doses and normalised release rates are below regulatory constraints, for the cases presented in Posiva 2012-12.

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 depth water well are assessed, but the results are not presented in that report. Posiva assumes that human intrusion will not occur before 1000 years.

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. Due to the fact that such chronic effects have not been assessed, it must be noted that the biggest exposure is to the drill crew and geologists, resulting from abstracted core materials.

STUK requested Posiva to submit additional information regarding the rationale for not considering human intrusion before 1000 years (at, say, 200 years) after repository closure. In its response, Posiva states that there is a low likelihood of intrusion and the highest dose is due to inhalation, and that long-lived actinides are the most significant nuclides contributing to the dose.

Conclusions

Posiva has presented the annual doses and releases resulted from the calculation cases that fall under the base and variant scenarios. The doses and releases are below the constraints set in the Section 4 of the GD 736/2008. Posiva has identified unlikely events and estimated their likelihoods. Posiva has analyzed the annual doses and releases and assessed their expectation values where appropriate. The results are below the regulatory constraints.

5.4 Reliability of the post-closure safety case

5.4.1 Models and data

GD 736/2008 15§ states: *"The input data and models utilised in the safety case 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.*

The basis for selecting the computational methods used shall be that the actual radiation exposure and quantities of radioactive materials released remain below the results of safety analyses, with a high degree of certainty. The uncertainties involved in the safety analysis, and their significance, shall be separately assessed."

Instead of compiling the information available and describing how the level of knowledge about a specific research topic has grown and improved over the past 30 years of KBS-3's existence, Posiva is often content to support its claims with arguments derived from a single investigation. The results of some of these investigations post-date the conclusions about post-closure safety in the safety case reports. The fact that a number of Posiva's topical reports were unavailable upon receiving Posiva's safety case raises concerns about the transparency of its preparation. Also, many of the literature references used to support specific claims are in the form of a Posiva report which, in terms of an impact factor, do not compare with journal articles that have undergone a recognised peer-review process. On some occasions, Posiva has also used results from an unpublished report to support a claim.

Posiva's documentation contains references to SKB's documentation, but Posiva does not draw any conclusions on the quality and reliability of this information.

For some parameters, Posiva 2013-01 is found to report more than one numerical value, depending on the context in which the parameter is used, but no reason for this is given. The use of multiple values to describe one and the same parameter reveals the lack of a data freeze for the safety case.

The methodology used by Posiva includes identification of the key safety functions and it brings out the key issues and uncertainties. Posiva states that the roles of the barriers constitute the safety functions of the barriers.

The conceptual models, mathematical models and data are adequate and appropriate for the construction licence phase. A set of scenarios has been assessed through a number of calculation cases, which are supported by complementary calculations and a probabilistic sensitivity analysis.

Posiva has used data management and QA procedures to make the safety case more reliable. Discrepancies in source data can be identified, but these have been evaluated and found to be insignificant by Posiva.

Therefore overall the reliability of the data and models can be considered adequate for this licensing phase.

Although the safety analysis can be considered reliable, there is scope for improved the 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; and
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 RTD programme.

In addition to the potential enhanced quality assurance procedures identified by Posiva, improvements that would enhance reliability of the safety case as it continues to be developed further include:

1. the safety case should be restructured to meet the needs of the authority;
2. the reports should be more transparent and the information presented more easily traceable;
3. to the extent possible, the large amount of duplication that is currently present should be avoided;
4. 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 reviewed in order to get a good understanding of the safety assessment.

Posiva asserts that the input data are adequately verified and confirmed. However, it is not easy to 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 in Posiva's documentation. This kind of information would provide confidence in the overall quality of the safety case.

Posiva has developed models by incorporating applicable FEPs in models. The models are executed to determine whether the safety functions are fulfilled during various periods of time.

The fulfilment of individual targets for the host rock and the EBS are summarized in considerable detail.

As mentioned by Posiva, models are based on incorporating all relevant FEPs that are expected to be operative during the one million year assessment period. When possible, Posiva has used data and models that are said to represent conditions that are expected to prevail, including potential deviations.

Probabilistic sensitivity analysis provides some idea of the importance of parameters, but Posiva's safety case lacks a description of the most safety significant parameters. However, Posiva submitted such a description for the base scenario, the growing hole scenario and the RS-DIL scenario. Posiva should include such a list for all scenarios in the next phase of the analysis in order to identify issues to be considered important for post-closure safety. According to Posiva's base scenario (BS-RC), the small hole diameter of the initial defect and the fuel alteration parameter can be identified as the two most important parameters that contribute to release rate. Similarly, the mass of buffer in the cavity and sorption coefficient of the buffer and backfill are the two most important parameters that lower the release rate. It can also be seen that geosphere flow parameters are not so important. This is mainly because the migration barrier properties of the overall rock are not playing a significant role in the scenarios analysed. This example is from the base scenario and other scenarios may give different results in this sense. The base scenario hides the importance of other barriers and, because of that, Posiva should develop scenarios and analyses that establish the importance of individual barriers, including the near-field rock that meets the RSC requirements for use.

To further enhance confidence in the reliability of the safety case, Posiva should provide (1) a list of the 10 most significant parameters affecting post-closure safety – this should include all scenarios, (2) a description 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.

Conclusions

Considering the reliability of the safety case the most important reports are Synthesis, Models and Data, Formulation of Radionuclide Release Scenarios, Assessment of Radionuclide Release Scenarios, Design Basis and Performance Assessment reports. Posiva's analyses and models and data are mostly of high enough scientific quality.

Posiva has presented safety funtions in the safety case and presents open safety significant issues and uncertainties related to those. Posiva justifies the safety of disposal by means of the safety functions. However, Posiva does not present explicitly a link between open safety significant issues and performance targets.

Posiva does not present conceptual models for each safety function. It is concluded that mathematical models and source data are adequate at this phase. Posiva has formulated a set of scenarios and calculation cases based on them. Calculation cases are supported by complementary considerations and probabilistic sensitivity analysis.

Generally, it can be concluded that the reliability of models and data is adequate at this phase.

Even though it is concluded that the safety case is reliable it needs further development. More understandable and unambiguous description of the evolution of the barriers and identification of the most important barriers and conclusion from the uncertainty analysis and its comparison to RD&D plan would help the evaluation of the reliability.

In addition, methodologies related to constructing a safety case need more development before operating licence application. Scenario formulation shall be more systematic and comprehensive and should be more easily traceable in the safety case. Safety functions and performance targets shall be defined in a way that enables a more unambiguous assessment of the linkage between the undeclined/declined performance of the barrier(s) and the scenarios constructed to describe the potential future behaviour of the disposal system.

The structure and manner of representation of the safety case needs development so that the compliance of the regulatory requirements can be evaluated more easily.

Posiva should indicate more clearly its own position in safety significant matters and justify the choices made in the safety case. The references in the safety case must be clear and referred documents shall be available when operating licence application is submitted.

The safety case must cover the entire disposal system, which also means that the low- and intermediate-level radioactive waste safety analysis must be combined with the safety case of disposal of spent fuel.

The reliability of the safety case is adequate at this phase. However, performance and safety analysis needs development to increase the reliability of the safety case.

5.4.2 Uncertainty assessment

Guide YVL D.5 requires that the significance of the uncertainties involved with the safety case shall be assessed by means of appropriate methods. 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 has described its approach to developing the safety case, including uncertainty assessment, and the uncertainties are documented in Posiva 2013-01. Posiva's approach consists of adequately characterizing the site, appropriately designing the engineered barrier components to meet the intended safety functions and performance targets, conducting operations that would meet the RSC and the LDF, identifying and characterizing uncertainties, conducting analyses to demonstrate compliance with regulations and providing other supporting arguments to enhance confidence.

The regulatory requirements and Posiva's approach to treating uncertainty are described in Posiva 2012-12, which also 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., aleatoric, epistemic, irreducible etc.), overall, a large number of uncertainties have been identified and explored adequately for this licensing phase.

Description of the uncertainties of each FEP is commensurate with the description of the FEP. The inventory of uncertainties appears to be complete and it is a question of how these are used, first to determine the calculation cases and, second, to inform the model descriptions (with associated data bases) that will determine the adequacy of the utilisation of the FEP descriptions.

Posiva is participating in many ongoing RD&D programmes further to reduce uncertainties and build confidence to the safety case. Posiva 2012-09 describes how the outputs of the safety assessment feed into Posiva's Research, Development and Design (RD&D) programme.

Posiva 2013-01 describes the activities that are being undertaken during 2013-2015 to improve confidence in the models and data. Posiva has identified a broad range of activities in this field.

The results of the safety assessment and uncertainty analyses have been fed into the RD&D programme. Collation and integration of the results of all the different uncertainty analyses is not presented within the main safety case document. An integration process of uncertainty analyses could collate and describe the relative significance of all the uncertainties and could also describe which uncertainties cannot be reduced and which uncertainties should be the subject of further research. An integration process would also 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.

Posiva also manages some uncertainties by defining rules for the system, such as: *"The deposition holes with inflow above 0.1 l/min will not be accepted for canister emplacement (Posiva, 2012-04, p. 113)."* Posiva realizes that these rules cannot be guaranteed in every case and, therefore, Posiva considers in a sensitivity analysis that a certain percentage of deposition holes will not meet this rule.

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 amounts of aleatoric variability/uncertainty (natural randomness) in the description of both climate change and seismic activity, which will perhaps require expert elicitation to quantify. Aleatoric 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 for selecting other features of the site. Because of the rather short observational period or small datasets on which to base climate and seismic evaluations, there is also a large amount of epistemic uncertainty, 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 of setting 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 aleatory randomness. Posiva demonstrates that it meets the regulatory criteria (normalized release or dose) with a margin spanning several degrees of magnitude and, because of that, it can be concluded with a high degree of certainty that uncertainties will not change the overall conclusion regarding post-closure safety.

Posiva's safety case would have benefited from a list and an assessment of different kind of uncertainties involved in the disposal system. Such an assessment would have been useful in guiding the selection of devoted techniques to manage the various uncertainties. Often, no justification is given by Posiva for selecting certain data or preferring them over some other data published in the open literature. This would have shed light on the span of uncertainty in the data used.

The licensee does not provide any explicit relationship between time and uncertainty. 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.

The far future is generally more uncertain than the nearer future: that is, many uncertainties increase with time. The repository system is a passive system that evolves slowly in response to external stresses (primarily climate change and tectonic/seismic activity) and internal stresses (primarily thermal, water flow, and rock-water interactions). There are no events involved with the development of the disposal system that can cause sudden damage. A large earthquake at the site is the only event 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 to characterize, reduce, and manage these uncertainties.

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 2012-09.

Posiva ignores the possibility of common cause failures of EBS components, due either to undetected malfunctioning of machines/processes, or due to human errors in detection, or both. Thus, the creation of initial defects and their detection may not be entirely random. However, independent calculations show that the likelihood of exceeding the regulatory constraints, even if all the canisters are assumed to have a defect, is small. After rejecting the importance of multiple canister failures, as explained above, Posiva then conducts Monte Carlo simulation of the base case, with one container having an initial defect.

Posiva 2012-09 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.

Posiva 2012-09 states that: *"The probability density functions (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 merge uncertainty and variability together, when these are two distinct characteristics of data. Variability usually describes changes with time or location in space, while uncertainty is the lack of knowledge about the value at any given time and location.

There is a risk in assigning probability density function to parameters such as the sorption coefficient based on measured values using crushed rock samples and insufficient knowledge of the time dependence of the processes involved.

In the 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 terrain and ecosystems development modelling, so that there is, effectively, a screening level of uncertainty analysis. In the surface and near-surface hydrological modelling report, there is also an attempt to propagate some estimates of uncertainty to the dose assessment modelling. This appears to be less successful.

Conclusions

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 programme. Posiva should consider more uncertainties due to potential human errors. Posiva does not differentiate between aleatoric and epistemic uncertainties; this is reasonable in this phase of licensing, but greater attention should be paid to uncertainties arising from lack of knowledge or epistemic uncertainties. 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. Posiva should consider using a traditional reference biosphere calculation, using local data, to enhance confidence in the dose calculations.

6 Conclusions

General principles

Posiva has followed a stepwise approach to implementation of nuclear waste disposal. Posiva has also taken advantage of spent nuclear fuel activity decrease through interim storage. Posiva has developed a safety concept that is in line with regulatory requirements. Posiva has not defined spent nuclear fuel as a disposal barrier, but has otherwise considered the role of spent fuel matrix in post closure safety.

Posiva has submitted a safety case portfolio that in general fulfils the regulatory requirements. An integrated safety case, that takes into account both SNF and LILW disposal, should be presented in the operating licence application documentation.

Monitoring

The monitoring programme presented in Posiva report 2012-01, is adequate at this licencing phase and gives the monitoring plans and programmes for 2012–2018. For the operational phase, the report gives a short generic description of each monitoring field.

The monitoring plan for the EBS is at a very early stage, and needs further work starting from an overall strategy for EBS monitoring. The technical problems related to detection equipment need to be solved.

Posiva has not included rock stresses as part of monitoring programme and this matter is discussed in Section 4.2 of this report. In the other geoscientific fields, hydrogeology and hydrogeochemistry monitoring plans are considered to put emphasis on the most critical matters, considering post-closure safety.

Spent nuclear fuel

Posiva has adequately characterized spent nuclear fuel and the source term and the requirements are fulfilled at this phase of licensing process.

Posiva has not defined post-closure safety related criteria for SNF other than for heat production and criticality safety. Posiva should consider the WAC regarding inventory of the most significant nuclides and fuel alteration rate which are consistent with the analysis made in the safety case.

According to Posiva's probabilistic sensitivity analysis of the safety case, the fuel alteration process is one of the most safety significant parameters. In its ongoing RD&D work, Posiva should provide a stronger basis for the assumed 10-7/year dissolution rate value and reduce uncertainties related to the IRF inventory, especially in Cl-36, I-129 and C-14.

Posiva applied burn-up credit to reach the conclusion of post-closure subcriticality. In STUK's opinion, this approach is adequately justified and STUK's requirements are fulfilled at this stage, although long-term canister evolution, especially possible changes in geometry, needs further analysis. Future analysis before an operating licence application should consist of considerations of possible changes in geometry causing criticality and evaluation of the consequences of canister criticality as a bounding analysis.

Canister

Posiva has characterized properties of canister materials and the majority of the critical properties are well-undestood at the present. However, there are some topics (especially copper creep and corrosion) that need further clarification.

Posiva's general description of the manufacturing methods for the canister components fulfils the STUK's requirement at this stage as does its general description of the inspections methods for the canister components.

Posiva has presented manufacturing methods for the canister components and qualification plans for the methods and STUK's requirements are fulfilled at this stage. However, Posiva should perform further development of the casting process for the cast iron insert.

Posiva has presented non-destructive testing methods for the canister components and qualification plans for the NDT-methods that fulfil STUK's requirements at this stage.

STUK will follow-up Posiva's manufacturing and welding development work as part of the STUK's inspection programme for the construction phase (RTO).

Posiva has described and justified the performance of the canister adequately at this phase. However, there will remain uncertainties regarding performance of the canister that shall need further RD&D work before an operating licence application. The most safety significant uncertainties are related to copper corrosion and creep ductility. Posiva has submitted a development plan of the disposal concept where it has recognized the following subjects for further research: copper corrosion in oxygen-free water; enhancement of CSM; copper corrosion in high chloride concentrations; effect of explosive residues on SCC; microbially induced corrosion of copper and creep ductility. STUK will follow the progress of Posiva's RD&D work on these issues.

Buffer, backfill and sealing structures

For this licensing phase, Posiva's characterization approach does not need to be fully developed as long as Posiva is aware of the shortcomings involved and is carrying out dedicated research work to improve the understanding of the properties affecting on the behaviour of the clay/bentonite materials. STUK considers it sufficient to identify a programme of work to ensure that a scheme is in place at the appropriate time. Clearly, this programme will need to take account of the issues identified above and Posiva will need to carry out more work to ensure that the scheme is comprehensive. The currently documented understanding of material properties affecting the performance of the clay/bentonite barriers is mainly empirical and fairly limited. Posiva has acknowledged this situation and has plans (Development programme, project ECCA) to improve understanding and to study the relationships between the material properties and the performance further. While STUK considers that the understanding is sufficient at this licensing phase it requires more work to be completed before an operating licence application.

It is likely that any future decision to replace MX-80 or, for example, Friedland clay by another type of bentonite may require significant additional, material-specific data and associated modelling of behaviour to confirm the suitability of such a substitution.

Given the long time before closure systems are likely to be deployed, STUK considers that the understanding is sufficient for this licensing phase but requires more work in the period before an operating licence application. There is time to develop the characterization approach, based on the experience gathered from buffer and backfill materials.

The modular approach developed provides a procedure to select the correct materials and components for various closure parts in the repository, depending on the performance requirements of the closure at each location.

STUK considers that the route to a sound QC system is understood by Posiva and the eventual QC programme is likely to utilize well-developed quality system methodologies. Because QC activities for the buffer will not come into play for some time (allowing adequate time to prepare them), Posiva's description of QC activities in connection with producing systems like the buffer and backfill are considered sufficient at this phase of licensing. There is clearly work to be done in producing both the technology and the necessary documentation for various parts of the process.

Although there are several areas identified above where Posiva will need to provide further argumentation in future work, STUK considers that Posiva has described and justified the performance of the buffer, backfill and closure adequately at this licensing phase. In particular, in moving towards an operating licence application, there are requirements for further developments with respect to the performance of the buffer, backfill, especially as many of the performance targets lack a criterion. Before submission of an operating licence application, Posiva should reconsider the safety functions and performance targets critically in order to improve and clarify their argumentation and to remove internal inconsistencies in the target specifications. Examples of performance issues that call for further argumentation include long-term chemical stability of montmorillonite and microbial activity in the buffer and backfill, owing to their potentially significant influence on the performance of these and other barriers. At present, it is difficult to assess if some of the performance targets are based on sufficient, high-quality scientific knowledge and expert judgement. A clearer connection of the performance targets to the functionality expected of the backfill is called for in the operating licence phase. Posiva should form a more coherent view of the expectations of the performance of the closure at the operating licence phase.

There is also a need to develop FEP descriptions further, to address all the relevant interactions within and between barriers more clearly and comprehensively, and to construct a conceptual model for each safety function of the barriers and the factors affecting them. This would contribute to a more robust specification of the performance-target criteria. Posiva's progress in its RD&D work regarding these issues will be followed by STUK.

Site characterization

Posiva adequately describes ductile and brittle deformation, and lithology in the Olkiluoto central areas. However, Posiva also recognises that better understanding of ductile evolution, lithology, and brittle deformation history is required for the detailed-scale modelling work that it needs for the planned repository volume. The understanding of ductile deformation (history and kinetics) is important in understanding and predicting three-dimensional lithological continuity and brittle deformation. The critical primary data and justifications for the ductile deformation model should be presented more clearly. Posiva considers its alteration modelling results relatively uncertain. However, because of the mineralisation potential of hydrothermal alteration, there is an evident need to constrain and conclude the significance of alteration better. Posiva does not assign any levels of uncertainties for its geo-DFN modelling, but significant uncertainties should be expected. In general terms, Posiva has progressed significantly in assigning uncertainties for its hard rock models, but there is still further work to be done. Increasing the consistency between hard rock sub-models and uncertainty handling will increase confidence in the safety case.

Posiva's groundwater flow modelling is among the leading-edge approaches in site-scale, crystalline hard rock research and is able to include critical factors and concepts that need to be accounted for. Given its state-of-the-art nature, STUK considers that the current framework is reasonable and the results calculated should be qualitatively acceptable. However, the modelling develops a complicated line of reasoning on the depth relations of fracture sizes, frequencies, specific capacities, and transmissivities. The input of the hydro-DFN is pre-processed in several ways and the conceptual correctness and its predictive power can be further upgraded and extended to include alternative assumptions on topics such as flow channelling and connectivity. There should be a better justification why the boundary between DZ3 and DZ4 lies at 400 metres. The repository is located directly below this boundary and on the lower hydraulic conductivity side of this zone division. The measurement results of the PFL tool are vital in setting up a hydrogeological flow model. However, there are concerns about what the PFL actually measures underground. Posiva should improve the evidence that the PFL tool works correctly in all the conditions it is used for, because the whole of the hydrogeological modelling starts from these measurements. The deterministic hydrogeological zone model needs a definite amount of connectivity to be capable to conduct water. There is a persistent difference in how Posiva justifies zone dimensions in brittle deformation and in hydrogeological zone modelling, although the disciplines share common discontinuity information on the bedrock. There should be more consistency between crystalline hard rock models and hydrogeological models, because these studies estimate the potential release pathways from the repository. Both consistency and strengthening the source data reliability will increase the confidence of the safety case.

STUK agrees that the justification for the interpreted hydrogeochemical evolution and the establishment of reference water types is mostly credible. The main results of the interpretations are adequate and are among Posiva's most firmly based findings regarding what can be expected with respect to Olkiluoto's future hydrogeochemical evolution. The characterisation of hydrogeochemical buffers regarding redox, pH, and against dilute waters are logical and well justified. However, Posiva omits discussion about the significance of abrupt seawater intrusion (density inversion) into the Olkiluoto bedrock and its effects on bedrock redox conditions. Moreover, certain characterisation results are in significant disagreement with Posiva's considerations of future hydrogeological evolution (to be discussed below). Although geochemical work indicates robust natural geochemical barrier conditions, there is a need to conceptualise and quantify the safety-critical hydrogeochemical processes. There are considerable uncertainties regarding the rate and history of interaction of SFR pore waters and waters in fractures. Clarification of pore water – fracture water discrepancy remains a significant open issue to be answered, because of its potential consequences for effective surface area assumptions and thereby its effects on radionuclide transport modelling results. The discrepancy also questions the sufficiency of current hydro-DFN models.

Although there are continuing difficulties associated with the in-situ stress measurements, the data gathered are considered to be adequate for qualitative stress estimations in Olkiluoto. However, further confirmation is needed. There is a need, in the near future, to supplement rock stress measurements with reliable data and improve the current rock stress models. The rock stress model is among the principal sources of information that Posiva uses to plan and justify the orientations of deposition tunnels. There is also a longer-term need to characterise rock and fracture zone strength and stability properties. The stability predictions for tunnels to be excavated need further improvements. Currently, models predict the tunnel stability rather qualitatively. The discrepancies are caused by the well-developed schistosity, the changes in tunnel profile, local fracturing, the variation of the rock types and possibly other factors. In the view of thermal properties, the shallow depth generalisation raises the question of robustness. Average values for veined gneiss should be shown to be conservative. Uncertainties of thermal property measurements exhibit relatively high variability, as a result of, e.g., heterogeneity and anisotropy within samples. Apparently this variability could be diminished by increasing the sample size. Adequate understanding of baseline rock stress and stability conditions are of primary importance, because they are among the key factors guiding the design and construction of the repository.

Posiva provides a credible argument and support for the significance of the repository near-field rock in providing the long-term performance and isolation capacity of the natural barrier. Although the role of the natural barrier has been shown adequately for the construction license, the flow-related transport is strongly dependent on the modelling concept utilised. Consequently, potential uncertainties related to the hydro-DFN are inherited by the transport calculations. For example, the connectivity of the hydro-model can be overestimated and bedrock retardation underestimated if the bedrock being modelled is not correctly parameterised. The bedrock could behave more as a SCN than in the way that it is conceptualised in the current DFN-model. The hydrogeological conceptualisation and parameterisation of the repository near-field is important and needs to be confirmed with further P-O work and model comparisons. The understanding of detailed scale migration and retention properties for the rock matrix and the heterogeneities of fracture planes remain as key issues for future research.

There is a continuous need to look for consistency, especially between the most safety critical modelling disciplines, and Posiva has recognised this as an important way to increase the credibility of the safety case. Integrating hydrogeological and hydrogeochemical modelling in a consistent palaeohydrogeological model has a central role. Further confidence building also requires consideration of independent integrated model conceptualisations. At a smaller scale, the internal consistency between, e.g., crystalline hard rock submodels, will inevitably increase robustness of the performance assessment. Similarly, showing consistency between the brittle deformation and the deterministic hydrogeological zone models will increase confidence. Further characterisation of the Olkiluoto eastern areas is needed for consistency building in the models used in the central area, but also because of the future disposal plans for the area. The GPS measurements monitored at and around Olkiluoto represent a rather unintegrated area of Posiva's studies. Evidently, the movements detected provoke questions that will need to be answered. There is possibly an important connection between the Olkiluoto tectonic stresses and the observed movements.

Posiva's approaches to evaluation of future climate give an insight into the future evolution of the site but raise questions, which is unsurprising in this complex and developing area of science. One issue is how robust the climate scenarios need to be in order to provide a convincing safety case. Analyses relating the full range of potential variations of glacial conditions to the response of the release barrier system are needed. There is much geoscientific information available from the Quaternary that Posiva could apply in estimating future lines of evolution, because this is the most valuable argumentation for site stability. Posiva should analyse the possibility of a more varied, abruptly changing, and prolonged global temperate period and compare these analyses with available palaeosea-level records. There is also a need to evaluate further the various possibilities related to onset and extent of future permafrost conditions. Posiva's present estimate of future hydrogeological conditions is overly pessimistic, since there is no coupling to the TDS regulating hydrogeochemical reactions. In hydrogeochemical considerations, Posiva assumes future boundary water conditions that do not get much support, either from the site characterisation work, or from geochemical modelling work. In hydrogeochemical modelling, Posiva also uses porosity assumptions that are in contradiction, e.g. with the transport modelling work. Posiva should complement its seismicity analyses with alternate assessment methods, such as PHSA and PFDHA methodologies. Posiva has studied potential consequences of postglacial EQ shear with deterministic analyses that are bound to the BFZ model concept (uniform continuous structures). To gain more realism, Posiva should consider also more heterogeneous conceptualisations and alternative techniques (e.g. PFC) to analyse the potential movements.

The practices of QC are not as transparent as Posiva presents them to be. The site characterisation and reporting mostly avoids assigning any safety significance to the results found, although some characterisation results should certainly be put at the primary QC level. Similarly, uncertainty handling of characterisation results calls for handling with a graded approach. Posiva needs to specify more clearly how data, models, analyses and uncertainties are classified into safety importance grades that designate their significance to the safety case conclusions. In certain fields of science, the use of formal expert elicitation should be explored further. The elicitation work should be targeted on defining uncertainties around estimates, rather than trying to reach precise results from controversial and frequently deficient data.

Site suitability

The performance assessment conducted by Posiva shows that according to expected evolution, the favourable properties of the rock surrounding the disposal facilities will continue to evolve in a stable and predictable manner, and the requirements imposed by Posiva on the bedrock are likely to be fulfilled by a large margin. According to results presented in safety case this basis is credible.

At present the connection between the performance targets and design specifications remains unclear. Consequently, it is difficult for Posiva to construct the facility and demonstrate its acceptability so that the requirements by para. 508 of YVL D.5 will be fulfilled.The EBS related performance targets are conservative bounds that need to be fulfilled for EBS at all times. Before the start of the underground construction activities, Posiva needs to introduce the essential, site performance assessment based properties to be preserved for the bedrock, in addition to the EBS based performance targets that are already available and their relationship to design requirements. There also remain further needs for development towards the operating licence application regarding both performance targets and requirements of the bedrock. Before submission of the operating licence application, Posiva needs to reconsider its safety functions and performance targets on the whole and to all barriers.This means improving and clarifying argumentation and removing internal inconsistencies from the performance in the target specifications.

Based primarily on Posiva's practical experiences during excavations, it can reasonably be assumed that the bedrock around the disposal tunnels and holes will be adequately stable. However, taking into account rock heterogeneity and the current level of understanding of in-situ stresses especially, it is clear that rock mechanical conditions require more work. From the viewpoint of understanding and optimising long-term safety, Posiva's bedrock stability argumentation, concentrated on the possibility of abnormally high stresses, is not adequate (POSIVA 2012-24). This is also acknowledged by Posiva and further work is suggested, e.g., in POSIVA 2013-01.

It is evident that the FENCAT database is a valuable source of seismic information for Northern Europe. The main drawback of all seismic databases is their short history and, to compensate for this, a global approach to seismic records of cratonized compressional areas would increase confidence. With respect to long-term safety, Posiva's seismic stability justifications should be based more on geological observations, models and records than on historic event databases. Geologically, most information available in Northern Europe is related to the Weichselian glaciation. The potential consequences of more extreme conditions should be evaluated, to confirm the robustness of the chosen conceptualisations.

In general terms, Posiva's arguments on low hydraulic conductivity at the disposal depth in Olkiluoto are justified. The suitability of bedrock for disposal is predicted and detected with Posiva's RSC. The hydrogeological design requirements are in a central role in this classification and the success of the RSC is a cornerstone of hydrogeological favourability justifications. Posiva also supports hydraulic favourability with hydrogeological measurements and observations, and implementation of these in its modelling work. Some boundary conditions used in the modelling work have been questioned by hydrogeological experts and need to be better justified in future.

Currently, the hydrogeochemical stability indications at the planned disposal depth are convincing. Results of the palaeohydrogeological baseline characterisation at Olkiluoto are Posiva's strongest evidence for stability. However, the explanation of historical salinity evolution, as well as potential future evolution of salinity, needs to be improved and justified because of the lack of water-rock interactions and its relationship to the hydrogeological modelling concept chosen. Furthermore, Posiva still needs to improve its geochemical process understanding, in order to improve the confidence in the hydrogeochemical buffer capacities of the bedrock that ensure the general geochemical site favourability. There is a specific need to understand in detail how the species concentrations that are defined as critical for release barriers (EBS and near-field bedrock) behave in the various geochemical environments considered possible in the future.

Olkiluoto is unlikely to have resource interest for future human populations. However, Posiva should continue to evaluate the economic mineralogy of Olkiluoto and its surroundings as construction continues. Regarding all respects of natural resources, Posiva should justify more rigorously that Olkiluoto is comparable to any other supracrustal gneiss area in Southern Finland.

Posiva's explanations on the chosen disposal depth are adequate. Posiva also describes qualitatively how various properties of the bedrock vary as functions of depth, and it concludes that the chosen depth is favourable for high level waste disposal. Posiva's original treatment gave the impression that the disposal depth was selected by the Government in its 2000 decision. In future, Posiva should describe more clearly how the site properties affecting disposal safety vary at the disposal depth. Also, the gradients towards unfavourable conditions should be described more clearly.

Rock classification

In the near future, Posiva needs to develop the RSC further and verify the pragmatic applicability of the methodology. Posiva applies a 'deterministic' approach to define LDFs, FPIs and respect volumes, and much of this determinism is based on expert judgements or point-wise observations. Posiva relies on an individual plane conceptualisation in describing bedrock discontinuity features. Difficulties in discontinuity mapping at many scales prove this to be a significant simplification. The plane conceptualisation can also be an oversimplification and alternative approaches should be scoped, because unexpected results and relationships may arise. Many of the RSC criteria need further development and there should be consistency between overall design requirements and the monitoring work to be implemented in the repository. Also, the extent of the methodology should be re-considered. Rock classification methodology is meant to take into account all the aspects that can affect long-term performance of the bedrock (YVL D.5 507). At present, Posiva does not present any criteria for how the probable suitability of unexcavated bedrock is deduced from pilot hole studies. The effective criteria for each RSC scale and for each step of RSC application need to be identified more clearly.

Posiva presents summary flow charts on the

RSC decision process for three different scales. Some improvements to these should be considered. The summary flow charts should be updated to match the general outline chart of construction. Posiva has also drafted detailed decision sheets showing how it intends to assure the design specifications and requirements. Updates will be needed to the criteria in the detailed decision sheets as Posiva revises its VAHA system. The RSC work and the hydrogeological P-O, measurement, testing and monitoring work are intimately related and a routine programme to implement both should be presented. Modifications to hydraulic connections as a result of construction actions should be monitored more carefully (e.g. with hydraulic head measurements) and included into RSC decisions. Continuous development of both RSC and DFN models are necessary for building confidence on chosen conceptual models and site performance.

Long-term effects of construction activities

Owing to the small amount of data available, the consequences of the EDZ that will result in D&B excavations continue to be questionable, although STUK agrees that induced fracturing does not question the viability of the disposal concept. Posiva is still considering various possibilities of mitigating, e.g., the deposition tunnel floor EDZ. Posiva has not thoroughly justified its arguments on the hydraulic conductivity of the EDZ, especially if further mechanical damage is developed in the tunnel perimeter EDZ during the thermal phase of the repository. Therefore, it is still necessary for Posiva to continue both EDZ and thermally induced fracturing investigations.

The mitigation of hydrogeological and hydrogeochemical disturbance has been considered by Posiva. However, these considerations do not cover the complete extent indicated in YVL D.5 508. In addition to salinity evolution, Posiva should show more quantitatively how extensive the hydrogeological and hydrogeochemical perturbations are expected to be during the years of repository operation and how the disturbed system will find its way back to, or close to, its baseline equilibrium state after closure of the repository. Posiva also needs to evaluate how the repository near-field responds hydrogeologically and hydrogeochemically to the thermal pulse caused by the SNF.

Demonstrations, manufacturing and installation tests

STUK considers that the most important, near-term priority for Posiva must be early demonstration of its ability to reproducibly emplace its engineering barrier system at their intended initial state, preferably in underground conditions. According to the PSAR decision (1/H42241/2012) this has to be done before the starting of the construction of the preparatoty phase (panel 1).

STUK sees that the emplacement of barriers will need almost real-time quality control and an instantaneous decision-making procedure. The information received so far from the demonstration machines and related software does not confirm readiness for this.

Posiva is late with the demonstration programme and is not able to demonstrate the feasibility of the concept even at the system level. If the demonstrations with canister and buffer can be carried out successfully then it can be expected that the whole concept will be feasible. However, there remain uncertainties due to the fact that the feasibility of some other barriers (backfill, including plug, deposition hole (bottom) and nearby rock) remains to be shown.

There also remains work to be done for the commissioning phase of the facility (commissioning plan, tests both non-nuclear tests and nuclear tests after getting the OL).

Despite these specific issues, Posiva's overall intentions and approach to demonstration activities are reasonable and credible from the CLA point of view. However, STUK has concerns about clarity and precise timing, which will affect the feasibility and schedule of the project. The plans presented in Posiva's “Development programme” would, however, be sufficient in proving the feasibility of the concept, if successfully carried through.

Safety functions and performance targets

Posiva has presented the safety functions for the barriers and it is concluded that Posiva's and STUK's interpretations of a safety function differ from one another. In future Posiva should redefine safety functions so that it is easier for STUK to evaluate the performance of the barriers in relation to the fulfilment of the safety functions. Despite the different interpretations of a safety function, the current formulation of the safety case can be used satisfactorily to demonstrate an adequate level of post-closure safety. Therefore, it can be concluded that Posiva has adequately described and defined the safety functions at this licensing phase.

Posiva has also presented performance targets for the safety functions and presented a criterion for such performance targets it considers a criterion to be definable for. Although STUK has had some difficulties in reconciling Posiva's approach with the requirements and has identified significant differences in how the safety case is structured, the assessment that Posiva has described has been sufficient to justify the performance of the barriers adequately at this licensing phase. However, as Posiva moves towards an operating licence application it will need to address the problems that STUK has identified and there thus remain further needs for development regarding performance, especially as many of the performance targets of the barriers lack criteria. A safety case is a structured argument for the safety of a system. Specifically, STUK requires that Posiva shall construct an argument for the post-closure safety in which: (1) Posiva shall reconsider its safety function and performance target approach in a critical way in order to clarify its safety argumentation and to remove internal inconsistencies in the targets before submission of the operating licence application, (2) to understand better how, and to what extent, the performance of a safety function may decline, before the operating licence phase Posiva shall redefine each performance target to include a quantitative criterion describing the characteristic which, when met, ensures the fulfilment of a safety function. Posiva shall also present a clear and unambiguous link between the safety functions, performance targets and design, (3) the performance targets for the safety functions shall be supported more clearly by the performance analysis, especially given the substantial uncertainties involved during the early evolution of the disposal system; and (4) uncertainties in the safety functions beyond the performance-target criteria shall be considered and managed systematically and comprehensively in variant and disturbance scenarios. The above considerations shall apply to the disposal system as a whole, including the low- and intermediate-level waste repository.

Scenarios

STUK identifies several areas where Posiva's approach to constructing scenarios is difficult to follow or does not match our expectations of a comprehensive methodology. However, the scenarios selected and the analyses carried out are considered sufficient to test and illustrate the overall performance of the system, even though there are gaps to be filled and additional information that is needed before an operational licence stage. For the CLA, Posiva's presentation is considered adequate, but does not easily lend itself to concluding whether some key safety-significant evolutionary uncertainties have been accounted for in the analysed scenarios.

In future, Posiva's scenario process should be made more transparent, to include a definition of the purpose and scope of the scenario work and to have a clearer reporting practice. Posiva shall consider developing a more systematic and comprehensive approach that would enable an easier evaluation of scenarios for credibility, coverage and distinctness.

The safety case shall cover the repositories for low- and intermediate level waste and for SNF in an integrated safety analysis of the disposal system.

Posiva has followed Guide YVL D.5 to classify the scenarios. 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 Posiva uses to enhance the understanding of the system and are required to delineate the impacts of model and data uncertainties.

Nevertheless, Posiva has constructed and defined a set of scenarios and calculation cases that provides sufficient information on system evolution and response for the purposes of this licensing phase. For the future, a more systematic and transparent way of constructing consistent scenarios would produce additional safety-significant scenarios and calculation cases.

Safety assessment

Posiva's approach to deterministic calculations is consistent with the YVL guidance. The calculation cases 'flow down' from the scenarios and are supported by a number of complementary calculation cases. A significant number of calculation cases is considered and the chosen calculation cases cover all the scenarios Posiva has defined and are consistent with the assessment period and disposal system. Overall, STUK considers that the calculations are cautiously realistic and, in general, the level of detail and manner of presentation of the radionuclide transport calculations is sufficient to provide an adequate understanding of the development of the technical arguments, the scientific and mathematical methods used and the results and conclusions reached.

The LILW repository is located directly above parts of the spent fuel repository and both repositories are connected with the same access tunnel. Therefore, Posiva shall include the LILW repository in the safety case for the spent fuel repository as an integral part. In other words, Posiva shall address the dose and release estimates from the spent fuel repository and LILW repository in a more consistent manner, so that combination of releases can be evaluated more reliably.

The calculation of probability-weighted multi-canister failure releases is difficult to follow and before the operational licence phase, Posiva shall provide a more extended description of how it is assembled. The description should include an assessment of the impact of an order of magnitude increased frequency over the deglaciation period. It would also be valuable for Posiva to compile the information to identify if, where and how it sees its analysis as being conservative. 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.

The synthesis of the assessment results could describe more clearly the key arguments that give confidence that the system will be safe. In connection with the operating licence, a PSA should be made to cover an adequate set of scenarios, including the biosphere scenarios.

Complementary considerations

Posiva's objective in presenting complementary considerations is to enhance confidence in the quantitative analyses developed in performance assessment. Complementary considerations provide a measure of confidence, but are not suited to a quantitative reduction of uncertainties in performance assessment. In general, Posiva uses the complementary considerations effectively to enhance confidence in the safety case and the information presented can be considered adequate for this licensing phase.

Compliance with the regulatory criteria

Posiva has presented the annual doses and releases resulted from the calculation cases that fall under the base and variant scenarios. The doses and releases are below the constraints set in the Section 4 of the GD 736/2008. Posiva has identified unlikely events and estimated their likelihoods. Posiva has analyzed the annual doses and releases and assessed their expectation values where appropriate. The results are below the regulatory constraints.

Reliability of the post-closure safety case

Posiva's analyses and models and data are mostly of high enough scientific quality.

Posiva has presented safety funtions in the safety case and presents open safety significant issues and uncertainties related to those. Posiva justifies the safety of disposal by means of the safety functions. However, Posiva does not present explicitly a link between open safety significant issues and performance targets.

Posiva does not present conceptual models for each safety function. It is concluded that mathematical models and source data are adequate at this phase. Posiva has formulated a set of scenarios and calculation cases based on them. Calculation cases are supported by complementary considerations and probabilistic sensitivity analysis.

Generally, it can be concluded that the reliability of models and data is adequate at this phase.

Even though it is concluded that the safety case is reliable it needs further development. More understandable and unambiguous description of the evolution of the barriers and identification of the most important barriers and conclusion from the uncertainty analysis and its comparison to RD&D plan would help the evaluation of the reliability.

In addition, methodologies related to constructing a safety case need more development before operating licence application. Scenario formulation shall be more systematic and comprehensive and should be more easily traceable in the safety case. Safety functions and performance targets shall be defined in a way that enables a more unambiguous assessment of the linkage between the undeclined/declined performance of the barrier(s) and the scenarios constructed to describe the potential future behaviour of the disposal system.

The structure and manner of representation of the safety case needs development so that the compliance of the regulatory requirements can be evaluated more easily.

Posiva should indicate more clearly its own position in safety significant matters and justify the choices made in the safety case. The references in the safety case must be clear and referred documents shall be available when operating licence application is submitted.

The safety case must cover the entire disposal system, which also means that the low- and intermediate-level radioactive waste safety analysis must be combined with the safety case of disposal of spent fuel.

Posiva's approach for handling uncertainties is based on identifying, avoiding, reducing and assessing. 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.

The reliability of the safety case is adequate at this phase. However, performance and safety analysis needs development to increase the reliability of the safety case.

Turvallisuusperustelu käytetyn ydinpolttoaineen loppusijoitukselle Olkiluodossa

Posiva Oy (Posiva) on toimittanut Olkiluodon käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitoksen rakentamislupahakemuksen yhteydessä valtioneuvoston asetuksen 736/2008 edellyttämän loppusijoituksen pitkäaikaisturvallisuutta käsittelevän turvallisuusperustelun Säteilyturvakeskukselle (STUK) hyväksyttäväksi.

Valtioneuvoston asetus ydinjätteiden loppusijoituksen turvallisuudesta (VNA 736/2008) edellyttää, että loppusijoituslaitoksen pitkäaikaisturvallisuutta koskevien säteilyturvallisuusvaatimusten täyttyminen sekä loppusijoitusmenetelmän ja -paikan soveltuvuus osoitetaan turvallisuusperustelulla.

STUKin tarkastaman turvallisuusperusteluaineiston perusteella laitoksen pitkäaikaisturvallisuus on analysoitu rakentamislupavaiheeseen riittävällä tavalla. Tulosten perusteella on osoitettu, että laitos on turvallinen ympäristön ihmiselle ja muulle elolliselle luonnolle laitoksen sulkemisen jälkeen kuten valtioneuvoston asetus edellyttää. Lisäksi Posiva on osoittanut loppusijoitusmenetelmän ja -paikan soveltuvuus rakentamislupavaiheeseen riittävällä tavalla. STUK hyväksyy turvallisuusperustelun ja esittää seuraavat vaatimukset. Liitteenä oleva esittelymuistio sekä turvallisuusperustelun tarkastusraportti, *Review report – post-closure safety case*, sisältävät vaatimusten perusteet.

Luonnollisen vapautumisesteen ominaisuudet ja toimintakyky

1. Turvallisuusperustelun luotettavuuden parantamiseksi STUK edellyttää, että Posiva vaiheittain kehittää luonnollisen vapautumisesteen karakterisointiin sekä toimintakyvyn osoittamiseen liittyvien eri tutkimusalojen tulosten ja mallikuvausten yhteen sovittamista käyttölupahakemukseen mennessä.
2. Posivan on käyttölupahakemukseen mennessä tarkasteltava nykyistä laajemmin ilmaston kehittymisen vaihtoehtoja ja yksityiskohtaisemmin niiden vaikutuksia loppusijoitusjärjestelmään.

Loppusijoituspaikan soveltuvuus

3. Posivan on esitettävä ennen loppusijoitustunnelien ja -reikien rakentamisen aloittamista kallion, toimintakykyanalyysiin perustuvat, säilytettävien lähikallion ominaisuuksien ja suunnitteluvaatimusten väliset yhteydet siten, että niistä käy ilmi, miten rakentamisen kallioperälle aiheuttamat häiriöt (mekaaniset, geokemialliset ja hydrogeologiset) pysyvät hallittuina ja asetettuja suunnitteluvaatimusten mukaisina ja kuinka vaatimuksia noudattamalla voidaan olettaa edullisten ominaisuuksien säilyvän pitkällä aikavälillä.
4. Posivan on laajennettava kallioperän jännitystilojen mittausaineistoja nykyisestä sekä tarkennettava kallion perustilan jännitystilatulkintoja ennen loppusijoitustilojen rakentamisen aloittamista. Lisäksi kallion jännitystila- ja stabiiliustutkimuksia ja niihin liittyviä kehitystoimenpiteitä on jatkettava rakentamisen aikana.
5. Posivan on laajennettava seismisiä tarkasteluja ja liitettävä jatkotarkastelujen tulokset viimeistään loppusijoituslaitoksen käyttölupahakemukseen. Lisäksi aineiston laajuutta on kasvatettava myös käytön aikana. Maanjäristysten vaikutuksia on tarkasteltava myös vaihtuvissa isostaattisissa kuormitustilanteissa (esim. jääkaudet).
6. Posivan on esitettävä suunnitelma rakoverkkomallinnustavan luotettavuuden varmentamisesta ennen loppusijoitustilojen rakennustöiden aloittamista. Louhinnan aiheuttamien hydro-

geologisten häiriöiden ja mittausmenetelmien arviointi ja lähtötietojen raportoinnin valmistelu on aloitettava rakentamisluvan myöntämisen jälkeen. Valitun mallinnustavan jatkoperustelu ja luotettavuuden arviointi on esitettävä viimeistään laitoksen käyttölupahakemukseen mennessä.

7. Posivan on osoitettava hydrogeokemian ja hydrogeologian tulkintojen riittävä yhdenmukaisuus viimeistään laitoksen käyttölupahakemukseen mennessä.
8. Posivan on tarkennettava Olkiluodon luonnonvaroihin liittyvien tarkasteluiden perusteluja viimeistään laitoksen käyttölupahakemuksen yhteydessä.

Sijoitustilojen asemointi

9. Posivan on ennen loppusijoitustilojen rakentamisen aloittamista päivitettävä kallioluokituksen ohjeistusta tarvittavin osin vaatimus 3 huomioiden. Lisäksi Posivan on esitettävä ennen loppusijoitustilojen rakentamisen aloittamista suunnitelma luokituksen luotettavuuden arviointimenettelyistä ja suunnitelmat luokituksen jatkokehityksestä.
10. Posivan on ennen loppusijoitustilojen rakentamisen aloittamista tarkennettava kallioluokitukseen liittyviä hyväksymismenettelyjä kattamaan rakentamisen eri vaiheet, mukaan lukien pilottireikätutkimukset.
11. Posivan on ensimmäisten loppusijoitustunnelien rakentamisen aikana arvioitava kallioluokitukseen liittyvien kriteerien kattavuutta ja menettelyn toimivuutta ja liitettävä niistä selvitys käyttölupahakemukseen.

Loppusijoituskapseli

12. Posivan on jatkettava loppusijoituskapselin valmistustekniikoiden kehitystyötä siten, että sekä BWR- että VVER–tyyppisen kapselin vaatimusten mukaisia komponentteja kyetään valmistamaan ennen käyttölupahakemuksen jättämistä.
13. Posivan on arvioitava tarkemmin kapselin toimintakykyä heikentävien tekijöiden ja siihen liittyvien kehitystarpeiden(kuparin korroosion puhtaassa hapettomassa vedessä, kuparin korroosion sulfidi-mallin (CSM) kehitystyön, kuparin korroosion korkeissa kloridipitoisuuksissa, räjähdysaineista jäävien typpiyhdisteiden vaikutuksen kuparin jännityskorroosioon sekä mikrobien vaikutukset kapselin toimintakykyyn) turvallisuusmerkitystä tarkastelemalla näiden tekijöiden ja kehitystarpeiden sekä niihin sisältyvien epävarmuuksien vaikutuksia toimintakykytavoitteiden toteutumiseen rakentamislupahakemuksessa esitettyä selkeämmin käyttölupahakemukseen mennessä.
14. Posivan on jatkettava kuparin virumisen tutkimuksia ja erityisesti selvitettävä virumismekanismin, seosaineiden ja epäpuhtauksien (fosfori, rikki) sekä lämpötilan ja kuormitustasojen vaikutusta.

Puskuri, tunnelitäyttö ja sulkeminen

15. Posivan on selkiytettävä puskurin ja tunnelitäytön toimintakyvyn saavuttamisen ajalliseen kestoon liittyvien epävarmuuksien vaikutusta loppusijoitusjärjestelmän toimintaan käyttölupahakemukseen mennessä.
16. Posivan on esitettävä selkeämmin loppusijoituslaitoksen sulkemisrakenteiden ennakoitu toiminta käyttölupahakemukseen mennessä.
17. Posivan on tarkennettava puskurin, tunnelitäytön ja sulkemisen toimintakykyä heikentävien tekijöiden turvallisuusmerkitystä tarkastelemalla näiden tekijöiden ja niihin sisältyvien epävarmuuksien vaikutuksia toimintakykytavoitteiden toteutumiseen rakentamislupahakemuksessa esitettyä selkeämmin käyttölupahakemukseen mennessä.

Käytetty ydinpolttoaine

18. Posivan on jatkettava turvallisuusperustelun luottavuuden parantamista siten, että Posiva pienentää epävarmuuksia, jotka koskevat radionuklidien vapautumisnopeutta polttoainematriisista, IRF:n ja C-14:n inventaaria sekä IRF:n ja C-14:n vapautumista.
19. Posivan on jatkettava loppusijoituskapselin geometrian pitkäaikaiskehittymisen tarkasteluja ja tarkasteltava kriittisyyden seurauksia ennen käyttölupahakemuksen jättämistä.

Matala- ja keskiaktiivisen jätteen loppusijoitustila

20. Posivan on esitettävä tarkennetut yksityiskohtaisemmat suunnitelmat loppusijoituslaitokseen tulevasta matala- ja keskiaktiivisen jätteen loppusijoitustilasta ja tarkennettu arvio

loppusijoituslaitokseen sijoitettavien erilaisten ydinjätelajien yhteisvaikutuksista ennen matala- ja keskiaktiivisen jätteen loppusijoitustilan rakentamisen aloittamista.

21. Posivan on yhdistettävä matala- ja keskiaktiivisen jätteen loppusijoittamisen vaikutukset koko loppusijoituslaitoksen kattavaan skenaario- ja turvallisuusanalyysiin sekä esitettävä turvallisuusperustelussa tarkennettu arvio loppusijoituslaitokseen sijoitettavien erilaisten ydinjätelajien yhteisvaikutuksista ja esitettävä tältä osin päivitetty turvallisuusperustelu käyttölupahakemuksen yhteydessä.

Turvallisuustoiminnot ja toimintakykytavoitteet

Posivan on käyttölupahakemukseen mennessä:

22. tarkasteltava uudelleen lähestymistapaansa turvallisuustoimintojen ja toimintakykytavoitteiden määrittämiseksi selkiyttääkseen turvallisuusperustelua ja poistaakseen epäjohdonmukaisuuksia toimintakykytavoitteiden määrittelyistä;
23. määritettävä kukin toimintakykytavoite vapautumisesteen mitattavissa tai arvioitavissa olevan ominaisuuden avulla ja sisällytettävä kuhunkin niistä tätä ominaisuutta kuvaavan kriteerin, jotta toimintakykytavoitteen täyttyminen ja heikkeneminen voidaan arvioida yksiselitteisemmin ja selkeämmin;
24. esitettävä selkeä ja yksiselitteinen yhteys vapautumisesteiden turvallisuustoimintojen, toimintakykytavoitteiden ja suunnitteluvaatimusten välillä;
25. kehitettävä konseptuaalisia malleja, joilla kuvataan turvallisuustoimintoja ja niihin vaikuttavia tekijöitä, toimintakykytavoitteiden toteutumisen yksikäsitteisemmäksi arvioimiseksi;
26. tuettava vapautumisesteiden toimintakyvyn analyysillään yksiselitteisemmin toimintakykytavoitteiden toteutumista ottamalla erityisesti huomioon loppusijoitusjärjestelmän varhaiseen kehitysvaiheeseen sisältyvän epävarmuuden.

Skenaarioanalyysi

Posivan on käyttölupahakemuksen yhteydessä:

27. esitettävä skenaariot loppusijoitusjärjestelmän mahdollista tulevaa käyttäytymistä kuvaavina kehityskulkuina;
28. selkiytettävä skenaarioiden muodostamisen tapaa, jotta voidaan helpommin varmistua skenaarioiden kattavuudesta loppusijoitusjärjestelmän mahdollisten kehityskulkujen suhteen;
29. perusteltava selkeämmin turvallisuusperustelussa esitettävien skenaarioiden valinta;
30. osoitettava skenaarioanalyysissä systemaattisempaa ja laaja-alaisempaa varautumista vapautumisesteiden turvallisuustoimintojen heikkenemisiin, ml. vapautumisesteiden laatupoikkeamien (esimerkiksi valmistus- ja asennusvirheet) vaikutuksesta.

Turvallisuusperustelun kehittäminen ja luotettavuus

Posivan on:

31. tehtävä käyttölupahakemuksen yhteydessä herkkyystarkasteluja kattavammin eri skenaarioiden mukaisille laskentatapauksille sekä radionuklidien kulkeutumiselle biosfäärissä;
32. toimitettava käyttölupahakemuksen yhteydessä selkeämpi kuvaus maanjäristyksen todennäköisyydellä painotetusta usean loppusijoituskapselin hajoamisen vaikutusten tarkastelusta ja siitä, miten laskenta kytkeytyy siihen liittyvään loppusijoitusjärjestelmän tulevaisuuskehitykseen. Kuvauksessa tulee selvittää tarkemmin, miten mannerjäätikön sulamisen aikana muuttuvat olosuhteet huomioidaan laskennassa konservatiivisesti;
33. kehitettävä turvallisuusperustelun rakennetta ja esitystapaa (selkeys, läpinäkyvyys, jäljitettävyys, käytettyjen lähtötietojen yhdenmukaisuus) sekä esitettävä turvallisuusperustelussa tehtävät johtopäätökset ja niiden perustelut selkeämmin, jotta turvallisuusvaatimusten täyttyminen on helpommin todennettavissa käyttölupahakemuksen yhteydessä;
34. toimitettava STUKille kaikki turvallisuusperustelun raportit käyttölupahakemuksen yhteydessä.

Johtaja	Risto Paltemaa
Toimistopäällikkö	Jaakko Leino

Turvallisuusperustelu käytetyn ydinpolttoaineen loppusijoitukselle Olkiluodossa, esittelymuistio

Yleistä

Posiva Oy (Posiva) on toimittanut 28.12.2012 valtioneuvostolle hakemuksen käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitoksen rakentamiseksi Eurajoen Olkiluotoon.

Posiva on toimittanut Olkiluodon käytetyn ydinpolttoaineen kapselointi- ja loppusijoituslaitoksen rakentamislupahakemuksen yhteydessä valtioneuvoston asetuksen ydinjätteiden loppusijoituksen turvallisuudesta 736/2008 edellyttämän loppusijoituksen pitkäaikaisturvallisuutta käsittelevän turvallisuusperustelun Säteilyturvakeskukselle (STUK) hyväksyttäväksi. Valtioneuvoston asetus edellyttää, että loppusijoituslaitoksen pitkäaikaisturvallisuutta koskevien säteilyturvallisuusvaatimusten täyttyminen ja loppusijoitusmenetelmän ja -paikan soveltuvuus osoitetaan turvallisuusperustelulla. Turvallisuusperustelussa on koottu todisteita, analyysejä ja perusteluja siitä, että loppusijoitus voidaan toteuttaa turvallisuusvaatimusten mukaisesti.

STUKilla on ollut turvallisuusperustelun tarkastuksen tukena useita ulkopuolisia asiantuntijoita tieteen ja tekniikan eri aloilta.

Posiva on edelläkävijä turvallisuusperustelun laatimisessa, esittämisessä sekä käytetyn ydinpolttoaineen loppusijoituksen pitkäaikaisturvallisuuden perustelemisessa. Posiva on esittänyt laajan turvallisuusperustelun ja suuren määrän pitkäaikaisturvallisuuden osoittamista tukevia tutkimusaineistoja ja analyysejä. Posivan turvallisuusperustelu noudattaa IAEA:n ja NEA:n esittämiä hyviä käytäntöjä. Turvallisuusperustelun dokumentoimiseksi tai rakenteeksi ei ole yleistä ohjetta, mutta turvallisuusperustelun pääkohdista on muodostettu kansainvälinen yhteisymmärrys. Turvallisuusperustelun on sisällettävä selkeästi esitetty turvallisuuskonsepti ja kattava kooste lähtötiedoista ja analyyseistä. Posiva esittää turvallisuuskonseptin selvästi ja lähtötiedot sekä analyysit ovat yleisesti ottaen tämänhetkistä kansainvälistä tasoa edustavia.

Pitkäaikaisturvallisuutta koskevan turvallisuusperustelun tarkastus

STUKin tarkastaman turvallisuusperusteluaineiston perusteella laitoksen pitkäaikaisturvallisuus on analysoitu rakentamislupavaiheeseen riittävällä tavalla. Tulosten perusteella on osoitettu, että laitos on turvallinen ympäristön ihmiselle ja muulle elolliselle luonnolle laitoksen sulkemisen jälkeen kuten valtioneuvoston asetus edellyttää. Lisäksi Posiva on osoittanut loppusijoitusmenetelmän ja -paikan soveltuvuus rakentamislupavaiheeseen riittävällä tavalla. Tarkastus osoittaa kuitenkin, että turvallisuusperustelua on edelleen tarpeen kehittää selkeyttämällä turvallisuuden argumentointia ja siihen liittyviä menetelmiä, sekä pienentämällä vapautumisesteiden toimintakykyyn liittyviä epävarmuuksia.

Tämä esittelymuistio perustuu Posivan rakentamislupahakemuksen esittämän turvallisuusperustelun ja STUKille toimitettujen siihen liittyvien asiakirjojen tarkastukseen. Esittelymuistion lisäksi turvallisuusperustelusta tehtävän päätöksen liitteenä on englanninkielinen turvallisuusperustelun tarkastusraportti, *Review report – post-closure safety case*. Turvallisuusperustelun tarkastusraportissa on esitetty esittelymuistiossa esitettyjen vaatimusten taustat ja yksityiskohdat sekä runsaasti tarkastushavaintoja. Tässä esittelymuistiossa on esitetty vaatimuksina turvallisuuden kannalta tärkeimmät asiat.

Oikeudelliset perusteet

YEA 35 §, YEA 108 §, YEA 109 §, VNA 736/2008, YVL D.5

Päätösesitys

Esitän, että STUK hyväksyy Olkiluodon kapselointi- ja loppusijoituslaitoksen pitkäaikaisturvallisuutta koskevan turvallisuusperustelun seuraavin vaatimuksin:

Luonnollisen vapautumisesteen ominaisuudet ja toimintakyky

Olkiluoto on yli 25 vuoden työn tuloksena monessa suhteessa monimuotoisimmin tutkittu osa suomalaista kallioperää. Loppusijoituspaikan rakentamisen aloittamiseksi tehty karakterisointityö on riittävää. Karakterisointityötä on jatkettava edelleen rakentamisen edetessä loppusijoituspaikan vähemmän tutkittuihin osiin. Posivan loppusijoituspaikan kuvaus perustuu useiden tutkimusalojen ja -menetelmien tuloksiin, joista saadun tiedon yhdistämisessä kokonaiskäsitykseksi on vielä kehitettävää. Eri tutkimusalojen tulosten ja mallikuvausten yhteen sovittamista on jatkettava ja syvennettävä turvallisuusperustelun luotettavuuden parantamiseksi.

1. Turvallisuusperustelun luotettavuuden parantamiseksi STUK edellyttää, että Posiva vaiheittain kehittää luonnollisen vapautumisesteen karakterisointiin sekä toimintakyvyn osoittamiseen liittyvien eri tutkimusalojen tulosten ja mallikuvausten yhteen sovittamista käyttölupahakemukseen mennessä.

Loppusijoituspaikan toimintakykyanalyysin keskeinen osa on tulevaisuuden ilmaston loppusijoitusjärjestelmään kohdistamien vaikutusten arviointi. Turvallisuusperustelun tärkeänä ja perusteltuna lähtökohtana ovat tiedot Veikseljäätiköitymisestä ja tulkinnat sitä edeltäneistä jäätiköitymisvaiheista. Eri havaintoihin ja mallilaskelmiin perustuva ilmaston kehittymisen kuvaus on rakentamislupavaiheeseen riittävä. Muuntelemalla laajemmin ilmastonkehitysmallin lähtötietoina käytettäviä lämpimien ja kylmien ilmastojaksojen ajoituksia, kestoja ja olosuhteita, mallin kattavuutta voidaan kehittää mahdollisten tulevaisuuden kehityskulkujen osalta. Vastaavasti toimintakykyanalyyseissä on huomioitava, kuinka loppusijoitusjärjestelmä kokonaisuutena toimii erilaisissa mekaanisissa, hydrostaattisissa, termisissä ja kemiallisissa kuormitustilanteissa sekä vaihtoehtoisten kehityskulkujen muuttuvissa olosuhteissa.

2. Posivan on käyttölupahakemukseen mennessä tarkasteltava nykyistä laajemmin ilmaston kehittymisen vaihtoehtoja ja yksityiskohtaisemmin niiden vaikutuksia loppusijoitusjärjestelmään.

Loppusijoituspaikan soveltuvuus

Keskeinen osa turvallisuusperustelussa esitettyä loppusijoituspaikan kuvausta perustuu paikan toimintakykyanalyyseistä tehtyihin tulkintoihin paikan soveltuvuudesta ja toimintakyvystä. Analyysit perustuvat havaintoihin ja tulkintoihin loppusijoituspaikan ominaisuuksista ja paleohydrogeologiasta sekä arvioihin paikan tulevasta pitkäaikaisesta kehittymisestä.

Posiva on esittänyt jo KBS-3-konseptin kehityksen varhaisessa vaiheessa kallion pitkäaikaiselle toimintakyvylle tavoitteita, jotka perustuvat teknisten vapautumisesteiden toimintakyvyn varmistamiseen. Posivan kallioperän toimintakykyanalyysi osoittaa rakentamislupavaiheeseen riittävällä tavalla, että odotettavissa olevissa tulevaisuuden pitkäaikaisissa kehityskuluissa loppusijoitustiloja ympäröivässä lähikalliossa edullisiksi katsottujen ominaisuuksien kehitys on vakaata ja ennakoitavaa, ja että Posivan kallioperälle asettamat, teknisistä vapautumisesteistä johdetut, toimintakykytavoitteet toteutuvat suurella varmuudella.

Loppusijoitustilat on rakennettava ja suljettava siten, että tavoitteena on kallioperän ominaisuuksien säilyttäminen pitkäaikaisturvallisuuden kannalta suotuisina. Tavoitteena on, että rakentamisen kallioperälle aiheuttama häiriö pysyy hallittuna ja asetettuja suunnitteluvaatimusten mukaisina, jotta teknisille vapautumisesteille suotuisat ja ennakoidut mekaaniset, geokemialliset ja hydrogeologiset olosuhteet säilyvät rakentamisen ajan ja alkavat sulkemisen jälkeen palautua kohti ennen rakentamisen aloittamista vallinnutta perustilaa kohtuullisen ajan sisällä. Posiva tuo tavoitteen esille yleisellä tasolla KBS-3-menetelmän turvallisuuskonseptissa, mutta ei käsittele yksiselitteisesti loppusijoitustilojen lähikallion roolia ja sen ominaisuuksien säilymistä loppusijoitustiloja ympäröivän kallion turvallisuustoiminnoissa tai toimintakykytavoitteissa. Lähikallion säilytettävillä ominaisuuksilla ja suunnitteluvaatimuksilla on oltava riippuvuudet siten, että niillä perustellaan hyväksyttäviä rajoja rakentamisen ja käytön aikana aiheutuvalle häiriölle. Posivan on myös osoitettava, että teknisille vapautumisesteille suotuisat ja ennakoidut mekaaniset, geokemialliset ja hydrogeologiset olosuhteet säilyvät niille asetetuissa rajoissa rakentamisen ajan ja alkavat sulkemisen jälkeen palautua kohti ennen rakentamisen aloittamista vallinnutta perustilaa.

3. Posivan on esitettävä ennen loppusijoitustunnelien ja -reikien rakentamisen aloittamista kallion, toimintakykyanalyysiin perustuvat, säilytettävien lähikallion ominaisuuksien ja suunnitteluvaatimusten väliset yhteydet siten, että niistä käy ilmi, miten rakentamisen kallioperälle aiheuttamat häiriöt (mekaaniset, geokemialliset ja hydrogeologiset) pysyvät hallittuina ja asetettuja suunnitteluvaatimusten mukaisina ja kuinka vaatimuksia noudattamalla voidaan olettaa edullisten ominaisuuksien säilyvän pitkällä aikavälillä.

Maanalaisten tutkimustilojen louhinnan aikana Posiva on kerännyt tietoa Olkiluodon kallioperän vakaudesta. Tiedon perusteella Posiva olettaa kallioperän riittävän stabiiliksi loppusijoitustunnelien ja -reikien ympärillä. Kallioperän perustilan jännitystilojen ymmärrykseen ja mittausaineistojen tuloksiin sisältyy kuitenkin epävarmuuksia, joita Posivan on vähennettävä ennen loppusijoitustilojen (keskustunnelit, loppusijoitustunnelit) rakentamisen aloittamista, sillä kallion jännitystilat ja stabiilius ovat keskeisiä suunnittelua ja rakentamista ohjaavia tekijöitä. Lisäksi jatkossa tarvitaan lisäselvitystä kallion heterogeenisuuden vaikutuksista kallion stabiiliuteen ja parempaa rikkonaisuusvyöhykkeiden kalliomekaanisten ominaisuuksien ymmärrystä eri mittakaavoissa.

4. Posivan on laajennettava kallioperän jännitystilojen mittausaineistoja nykyisestä sekä tarkennettava kallion perustilan jännitystilatulkintoja ennen loppusijoitustilojen rakentamisen aloittamista. Lisäksi kallion jännitystila- ja stabiiliustutkimuksia ja niihin liittyviä kehitystoimenpiteitä on jatkettava rakentamisen aikana.

Posiva perustelee Fennoskandian kilpialueen kallioperän vähäistä seismistä aktiivisuutta historiallisilla tiedoilla ja mittausaineistoilla. Aineistot tukevat olettamusta, että Olkiluodon kallioperä on seismisesti vakaa myös tulevaisuudessa, ja että loppusijoituskapselin rikkovan maanjäristyksen todennäköisyys on hyvin pieni. Posivan seismiset tarkastelut ovat rakentamislupavaiheeseen riittäviä, mutta niitä on laajennettava turvallisuusperustelun luotettavuuden parantamiseksi. Seismisen riskin selvittämistä on jatkettava ottamalla monipuolisemmin huomioon Olkiluodon kallioperän rakenteet ja niiden ominaisuudet sekä arvioimalla laajemmin maanjäristysvoimakkuuksia ja esiintymistiheyksiä eri geologisissa olosuhteissa. Loppusijoitusjärjestelmään kohdistuvan seismisen riskin tarkastelua on laajennettava tekemällä todennäköisyysperusteisia seurausanalyysejä, joissa huomioidaan kattavammin maanjäristysten syntymisen ja etenemisen mekanismeja sekä siirrosten leviäminen ympäröiviin rikkonaisuusrakenteisiin.

Posiva yleistää suuret ja pienet rikkonaiset vyöhykkeet yksittäisiksi muotopinnoiksi. Posivan on tarkasteltava myös mallinnustapoja, jotka kuvaavat kalliorikkonaisuutta epäyhtenäisemmin ja empiirisemmin. Tarkastelutavan muutos voi vaikuttaa esimerkiksi järistysvoimakkuuksien tulkintoihin, rikkonaisuusvyöhykkeisiin liitettäviin varoetäisyyksiin ja yksittäisten kriittisten rakojen koosta tehtäviin oletuksiin. Posivan on myös analysoitava tarkemmin lämpötilan nousun vaikutukset kallioperän vakauteen loppusijoituslaitoksen käytön aikana ja sulkemisen jälkeen. Loppusijoitetusta käytetystä ydinpolttoaineesta syntyvä lämpökuorma voi aiheuttaa muutoksia kallion stabiiliuteen ja vedenjohtavuuteen.

5. Posivan on laajennettava seismisiä tarkasteluja ja liitettävä jatkotarkastelujen tulokset viimeistään loppusijoituslaitoksen käyttölupahakemukseen. Lisäksi aineiston laajuutta on kasvatettava myös käytön aikana. Maanjäristysten vaikutuksia on tarkasteltava myös vaihtuvissa isostaattisissa kuormitustilanteissa (esim. jääkaudet).

Posiva perustelee vähäistä kalliopohjavesien virtausta loppusijoitustilojen ympärillä Olkiluodon kallion eheydellä ja kallion luokitusjärjestelmällä, jonka avulla Posiva esittää kykenevänsä valitsemaan loppusijoitukseen sopivat tiiviit kallio-osat. Esitetyt perustelut kallion tiiveydestä ja pohjaveden vähäisestä virtauksesta ovat riittävät, mutta jatkossa Posivan on koottava selkeä yhteenveto kalliopohjaveden virtausmallista, sen yhteensopivuudesta geologisiin malleihin ja malleissa käytetyistä lähtötiedoista. Loppusijoituspaikan kallioperän hydraulisten ominaisuuksien ja louhinnan aiheuttamien hydrogeologisten häiriöiden karakterisointitekniikoihin sisältyy epävarmuuksia, minkä vuoksi käytettävien mittaustekniikoiden luotettavuutta on varmennettava. Loppusijoitustilojen eri tutkimus- ja toteutusvaiheissa on varmistettava suunnitelmallisesti, että louhittavaksi aiottu ja valmis loppusijoitustunneli täyttää sille asetetut vaatimukset.

Rakoverkkomallinnustavan luotettavuus on varmennettava rakentamisen aikana vertaamalla loppusijoitustilojen hydrogeologian mallinnustuloksia toteutetuista tunneleista saataviin tietoihin. Vettä johtavan rikkonaisuuden mallinnukseen on käytettävissä vaihtoehtoisia kallion heterogeenisuuden huomioivia menetelmiä, joita tulisi tarkastella ainakin valitun mallinnustavan luotettavuuden toteamiseksi. Eri mallinnustavat voivat johtaa esimerkiksi nykyisiä oletuksia kuivempiin loppusijoitustiloihin ja toisaalta yksittäisiin vettä johtaviin rakopinta-alaltaan pienempiin virtauskanaviin, joissa suuret virtaukset ovat mahdollisia.

6. Posivan on esitettävä suunnitelma rakoverkkomallinnustavan luotettavuuden varmentamisesta ennen loppusijoitustilojen rakennustöiden aloittamista. Louhinnan aiheuttamien hydrogeologisten häiriöiden ja mittausmenetelmien arviointi ja lähtötietojen raportoinnin valmistelu on aloitettava rakentamisluvan myöntämisen jälkeen. Valitun mallinnustavan jatkoperustelu ja luotettavuuden arviointi on esitettävä viimeistään laitoksen käyttölupahakemukseen mennessä.

Posivan esittämät perustelut kallion pohjavesikemian suotuisuudesta loppusijoitussyvyydellä ovat uskottavia. Olkiluodon kallion perustilan hydrogeokemiallinen karakterisointi ja paleohydrogeokemian kehittymisen tulkinta ovat Posivan vahvinta perusteluaineistoa sijoitustilojen lähikallion stabiiliudesta. Posiva esittää turvallisuusperustelussaan muun muassa arvioita suolaisuuden kehittymisestä seuraavan 50 000 vuoden aikana. Nämä kehityskulut vaikuttavat loppusijoitustiloja ympäröivän lähikallion pohjavesien laimenemisen suhteen ylipessimistisiltä, sillä ne eivät huomioi pintavesien suotautumisen yhteydessä tapahtuvia vesi-kalliovuorovaikutuksia. Posivan on edelleen tarkennettava ja parannettava hydrogeokemian kehittymisen kuvausta. Lisäksi Posivan on parannettava käsitystä rakentamisesta aiheutuvien häiriöiden palautumisesta laitoksen osien sulkemisen jälkeen. Tärkeä pohjavesikemian stabiiliuden selvityskohde liittyy kalliohuokosvesien ja rikkonaisuusvyöhykkeiden kalliopohjavesien kemiallisen koostumuksen erojen syihin.

7. Posivan on osoitettava hydrogeokemian ja hydrogeologian tulkintojen riittävä yhdenmukaisuus viimeistään laitoksen käyttölupahakemukseen mennessä.

Posivan käsityksen mukaan Olkiluoto ei luonnonvarojen suhteen ole kiinnostava tulevaisuudessa. Posivan esittämä perustelu on riittävä rakentamislupavaiheeseen. Käyttölupahakemusaineistossa luonnonvaroihin liittyvää tarkastelua on selkeytettävä ja päivitettävä alueen geologiasta saadun tiedon lisääntyessä.

8. Posivan on tarkennettava Olkiluodon luonnonvaroihin liittyvien tarkasteluiden perusteluja viimeistään laitoksen käyttölupahakemuksen yhteydessä.

Sijoitustilojen asemointi

Posiva käyttää sopivien kalliolohkojen valintaan ja loppusijoitustiloja ympäröivän kallion riittävän laadun varmistamiseen kallioluokitusjärjestelmää, jossa on esitetty kriteerit ja niiden todentaminen loppusijoituslaitoksen, paneelialueen, sijoitustunnelin ja sijoitusreiän mittakaavassa. Vaatimuksenmukaisuuden toteaminen ja hyväksyntä tapahtuu vaiheittain. Posiva on laatinut luokitusjärjestelmälle ohjeistuksen, jonka mukaisesti tehdään ensimmäisten loppusijoitustunnelien ja -reikien soveltuvuusarviointi. Kallioluokitusjärjestelmän luotettavuutta on erittäin tärkeä arvioida loppusijoitustilan ensimmäisen vaiheen rakentamisen aikana ja sen jälkeen sekä ottaa huomioon järjestelmän käyttökokemukset sen jatkokehityksessä. Esimerkiksi luokituksen kriteerejä eri mittakaavoissa ja rakentamisen eri vaiheissa sekä ennuste-toteumamenettelyä on edelleen kehitettävä. Posivan on viimeisteltävä arviointiprosessin menettelyt sekä esitettävä tarkemmat suunnitelmat kallioluokituksen jatkokehityksestä ennen rakentamisen aloittamista. Kallioluokitusjärjestelmä arvioidaan kokonaisuudessaan uudelleen käyttölupahakemuksen käsittelyn yhteydessä.

Nykyinen luokitus korostaa erityisesti loppusijoitukseen valittavien kalliolohkojen mekaanista stabiiliutta ja vähäistä pohjaveden virtausta rakentamisesta huolimatta. Posivan on arvioitava loppusijoitustilan ensimmäisen rakentamisvaiheen aikana, kattaako luokitusjärjestelmä pitkäaikaisturvallisuuden kannalta merkittävät ja loppusijoitustunnelista havainnoitavat ominaisuudet. Posivan on myös esitettävä selkeämmin kallioluokituksen kriteerien yhteys loppusijoitustiloja ympäröivän kallion osalta säilytettäviin ominaisuuksiin. Posivan on myös perusteltava tarkemmin loppusijoituslaitoksen asemointia rajaavien rakenteiden ja yksittäisten laajojen rakojen suojaetäisyyksien määrittäminen.

9. Posivan on ennen loppusijoitustilojen rakentamisen aloittamista päivitettävä kallioluokituksen ohjeistusta tarvittavin osin vaatimus 3 huomioiden. Lisäksi Posivan on esitettävä ennen loppusijoitustilojen rakentamisen aloittamista suunnitelma luokituksen luotettavuuden arviointimenettelyistä ja suunnitelmat luokituksen jatkokehityksestä.
10. Posivan on ennen loppusijoitustilojen rakentamisen aloittamista tarkennettava kallioluokitukseen liittyviä hyväksymismenettelyjä kattamaan rakentamisen eri vaiheet, mukaan lukien pilottireikätutkimukset.
11. Posivan on ensimmäisten loppusijoitustunnelien rakentamisen aikana arvioitava kallioluokitukseen liittyvien kriteerien kattavuutta ja menettelyn toimivuutta ja liitettävä niistä selvitys käyttölupahakemukseen.

Loppusijoituskapseli

Posiva on kehittänyt loppusijoituskapselin valmistustekniikoita 1990-luvulta asti. Posiva on keskittynyt pääasiassa referenssikapselityypin (BWR) valmistustekniikoiden kehittämiseen, ja on rakentamislupavaiheeseen mennessä valmistanut alustavat laatuvaatimukset ja mekaaniset ominaisuudet täyttäviä kapselin osia (sekä kuparivaippa että valurautainen BWR-sisäosa).

12. Posivan on jatkettava loppusijoituskapselin valmistustekniikoiden kehitystyötä siten, että sekä BWR- että VVER-tyyppisen kapselin vaatimusten mukaisia komponentteja kyetään valmistamaan ennen käyttölupahakemuksen jättämistä.

Turvallisuusperustelussa esitetty loppusijoituskapselin turvallisuustoiminto perustuu kapselin sisäosan mekaaniseen ja kuparivaipan kemialliseen kestävyyteen. Posiva on esittänyt kapselin toimintaa heikentäviä olosuhteita ja tapahtumia sekä selvitystöitä, joiden se esittää olevan kehitystarpeita loppusijoituskapselin eheyden kannalta. Tällaisina kehitystarpeina Posiva esittää:

- kuparin korroosion puhtaassa hapettomassa vedessä;
- kuparin korroosion sulfidi-mallin (CSM) kehitystyön;
- kuparin korroosion korkeissa kloridipitoisuuksissa;
- Onkaloon räjähdysaineista jäävien typpiyhdisteiden vaikutuksen kuparin jännityskorroosioon; sekä
- mikrobien vaikutukset kapselin toimintakykyyn.

Posivan tunnistamista tekijöistä erityisen merkittäviä kapselin toimintakyvyn, ja siten myös pitkäaikaisturvallisuuden, kannalta ovat kuparin sulfidi-mallin kehitystyö sekä räjähdysaineista jäävien typpiyhdisteiden ja mikrobitoiminnan vaikutus kapselin turvallisuustoiminnon heikentymiseen. Edellä mainitut tekijät voivat kohdistua jokaiseen loppusijoituskapseliin ja siten myös vaarantaa jokaisen loppusijoituskapselin eheyden.

Loppusijoituskapselin eheyttä voi uhata myös kuparivaipan vaurioituminen plastisen deformaation ja/tai virumisen seurauksena. Posiva on tutkinut kuparin virumista kokein ja mallinnuksin. Kapselin kuparin virumismekanismia loppusijoituslaitoksessa vallitsevissa vaihtelevissa lämpötiloissa ja kuormitustasoissa sekä fosforiseostuksen vaikutusta kuparin virumiseen ei tunneta riittävän hyvin.

Vapautumisesteiden toimintakykyyn vaikuttavien tekijöiden turvallisuusmerkitystä on tarkennettava tarkastelemalla näiden tekijöiden ja niihin sisältyvien epävarmuuksien vaikutuksia toimintakykytavoitteiden toteutumiseen rakentamislupahakemuksessa esitettyä selkeämmin.

13. Posivan on arvioitava tarkemmin kapselin toimintakykyä heikentävien tekijöiden ja siihen liittyvien kehitystarpeiden(kuparin korroosion puhtaassa hapettomassa vedessä, kuparin korroosion sulfidi-mallin (CSM) kehitystyön, kuparin korroosion korkeissa kloridipitoisuuksis-

sa, räjähdysaineista jäävien typpiyhdisteiden vaikutuksen kuparin jännityskorroosioon sekä mikrobien vaikutukset kapselin toimintakykyyn) turvallisuusmerkitystä tarkastelemalla näiden tekijöiden ja kehitystarpeiden sekä niihin sisältyvien epävarmuuksien vaikutuksia toimintakykytavoitteiden toteutumiseen rakentamislupahakemuksessa esitettyä selkeämmin käyttölupahakemukseen mennessä.

14. Posivan on jatkettava kuparin virumisen tutkimuksia ja erityisesti selvitettävä virumismekanismin, seosaineiden ja epäpuhtauksien (fosfori, rikki) sekä lämpötilan ja kuormitustasojen vaikutusta.

Puskuri, tunnelitäyttö ja sulkeminen

Posiva on tunnistanut puskurin ja tunnelitäytön toimintaa heikentäviä olosuhteita ja tapahtumia (satunnaiset poikkeamat), joilla voi olla vaikutusta pitkäaikaisturvallisuuteen. Tällaisina satunnaisina poikkeamina esitetään mm. sulfaatin pelkistyminen kapselin ulkovaipan korroosiota aiheuttavaksi sulfidiksi tunnelitäytön vaillinaisesta homogenisoitumisesta aiheutuvissa alhaisen tiheyden alueissa ja suotautuvan meteorisen veden tai jään sulamisveden aiheuttama puskurin kemiallinen eroosio, mikä voi johtaa puskurin tiheyden pienenemiseen joissakin sijoitusrei'issä.

Posivan tunnistamien satunnaisten poikkeamien lisäksi mahdollisia puskurin ja tunnelitäytön toimintakykyä heikentäviä tekijöitä voivat olla esimerkiksi:

- montmorilloniittisaven mineraloginen muuntuminen loppusijoituksen pohjavesiolosuhteissa;
- mikrobitoiminta, joka voi aiheuttaa kapselin korroosiota aiheuttavan sulfidin muodostumista ja montmorilloniitin liukenemista;
- sisäinen eroosio (engl. piping erosion) sijoitusreiästä loppusijoitustunneliin virtaavan pohjaveden vaikutuksesta; sekä
- puskurin sementoituminen, joka voi aiheuttaa mm. sen plastisuuden ja paisumisominaisuuden heikkenemisen.

Em. tekijöistä erityisen merkittäviä puskurin ja tunnelitäytön toimintakyvyn, ja siten myös pitkäaikaisturvallisuuden, kannalta ovat montmorilloniitin mineraloginen muuntuminen ja mikrobitoiminta niiden jokaiseen loppusijoitustunneliin ja -reikään mahdollisesti kohdistamien vapautumisesteiden turvallisuustoimintoja heikentävien vaikutusten vuoksi. Edellä mainittujen tekijöiden vaikutus voi kohdistua jokaiseen loppusijoituskapseliin ja siten myös aikaistaa niiden tiiveyden menetystä. Vain osaa loppusijoitusrei'istä koskeva sisäinen eroosio voi tapahtuessaan olla merkittävä puskurin ja kapselin toimintakykyä heikentävä tekijä johtuen sen ajoittumisesta loppusijoituksen alkuvaiheeseen jolloin se voi vaikuttaa voimakkaasti loppusijoitusreiän lähialueen myöhempään kehittymiseen. Puskurin sementoituminen on keskeinen tekijä arvioitaessa seismiseen aktiivisuuteen liittyvän kalliosiirroksen mahdollisia vaikutuksia loppusijoituskapselien mekaaniselle kestävyydelle. Puskurin ja tunnelitäytön toimintakyvyn saavuttamisen ajalliseen kestoon liittyy merkittäviä epävarmuuksia, joiden vaikutuksia toimintakykytavoitteiden toteutumiseen on tarkasteltava nykyistä laajemmin ja selkeämmin.

Vaikka sulkemisen toteutus ei ole ajankohtainen useaan vuosikymmeneen, on Posivan muodostettava nykyistä selkeämpi käsitys sulkemisen ennakoidusta toiminnasta osana loppusijoitusjärjestelmää.

Vapautumisesteiden toimintakykyyn vaikuttavien tekijöiden turvallisuusmerkitystä on tarkennettava tarkastelemalla näiden tekijöiden ja niihin sisältyvien epävarmuuksien vaikutuksia toimintakykytavoitteiden toteutumiseen rakentamislupahakemuksessa esitettyä selkeämmin.

15. Posivan on selkiytettävä puskurin ja tunnelitäytön toimintakyvyn saavuttamisen ajalliseen kestoon liittyvien epävarmuuksien vaikutusta loppusijoitusjärjestelmän toimintaan käyttölupahakemukseen mennessä.
16. Posivan on esitettävä selkeämmin loppusijoituslaitoksen sulkemisrakenteiden ennakoitu toiminta käyttölupahakemukseen mennessä.
17. Posivan on tarkennettava puskurin, tunnelitäytön ja sulkemisen toimintakykyä heikentävien tekijöiden turvallisuusmerkitystä tarkastelemalla näiden tekijöiden ja niihin sisältyvien epävarmuuksien vaikutuksia toimintakykytavoitteiden toteutumiseen rakentamislupahakemuksessa esitettyä selkeämmin käyttölupahakemukseen mennessä.

Käytetty ydinpolttoaine

Radionuklidien vapautuminen polttoaine-elementistä on turvallisuuden arvioinnin kannalta merkittävä parametri. Siihen sekä nopeasti vapautuvan osuuden (IRF) inventaariin ja C-14-inventaariin ja radionuklidien vapautumiseen liittyy epävarmuuksia, joilla on merkitystä turvallisuuden arvioimisen luotettavuuteen.

18. Posivan on jatkettava turvallisuusperustelun luottavuuden parantamista siten, että Posiva pienentää epävarmuuksia, jotka koskevat radionuklidien vapautumisnopeutta polttoainematriisista, IRF:n ja C-14:n inventaaria sekä IRF:n ja C-14:n vapautumista.

Loppusijoituskapselin suunnittelussa on huomioitu käytetyn ydinpolttoaineen kriittisyysturvallisuuden asettamat vaatimukset. Loppusijoitetun polttoaineen pitkäaikainen kriittisyysturvallisuus on osoitettu konservatiivisin kriittisyysanalyysein rakentamislupaa varten riittävällä tavalla. Posivan esittämien kriittisyysturvallisuusanalyysien perusteella ei voida täysin sulkea pois loppusijoituskapselin kriittisyyttä pitkällä aikavälillä. Analyyseissä on tehty tältä osin hyvin konservatiivisia oletuksia loppusijoituskapselin geometrian pitkäaikaiskehittymisestä, joten loppusijoitetun polttoaineen uudelleenkriittisyys vaikuttaa hyvin epätodennäköiseltä.

19. Posivan on jatkettava loppusijoituskapselin geometrian pitkäaikaiskehittymisen tarkasteluja ja tarkasteltava kriittisyyden seurauksia ennen käyttölupahakemuksen jättämistä.

Matala- ja keskiaktiivisen jätteen loppusijoitus

Loppusijoituslaitos sisältää tilat käytetylle ydinpolttoaineelle sekä kapselointilaitoksen käytöstä ja käytöstäpoistosta kertyvälle matala- ja keskiaktiiviselle jätteelle. Posivan STUKille toimittamassa aineistossa käsitellään matala- ja keskiaktiivisen jätteen käsittelyä, loppusijoitusta ja loppusijoituksen pitkäaikaisturvallisuutta kolmessa eri raportissa. Raporteissa esitettyjä seikkoja ei ole yhdistetty varsinaiseen käytetyn ydinpolttoaineen loppusijoituksen turvallisuusperusteluun.

Posivan rakentamislupahakemusaineistosta ei käy ilmi yhdistettyinä koko loppusijoituslaitoksen sulkemisen jälkeiset lasketut vuotuiset säteilyannokset ja aktiivisuuspäästöt. Posivan loppusijoituspaikan toimintakykyanalyysi ei sisällä ajotunnelin varrelle rakennettavaa matala- ja keskiaktiivisen jätteen loppusijoitustilaa. Valtioneuvoston asetuksen 736/2008 annos- ja päästörajat koskevat kaikkea yhteen loppusijoituslaitokseen sijoitettavaa ydinjätettä. Käytetyn ydinpolttoaineen ja matala- ja keskiaktiivisen jätteen loppusijoitustiloja on käsiteltävä yhtenä kokonaisuutena, sillä tilat voivat vuorovaikuttaa esimerkiksi pohjaveden kemiallisten muutosten tai käytetyn ydinpolttoaineen aiheuttaman termisen muutoksen kautta. Siten samassa laitoksessa sijaitsevilla erityyppisillä loppusijoitustiloilla ei ole omia annos- ja päästörajoja, vaan viranomaisvaatimusten täyttyminen on osoitettava koko loppusijoituslaitokselle ja tilojen mahdolliset keskinäiset vuorovaikutukset sekä niihin liittyvät epävarmuudet on arvioitava koko loppusijoituslaitoksen yhdistävässä skenaario- ja turvallisuusanalyysissa. Posiva on täydentänyt rakentamislupahakemusta selvityksellä POSIVA-STUK-10290, 27.8.2014 esittämällä alustavia tarkasteluja matala- ja keskiaktiivisen jätteen loppusijoituksesta ja pitkäaikaisturvallisuudesta.

20. Posivan on esitettävä tarkennetut yksityiskohtaisemmat suunnitelmat loppusijoituslaitokseen tulevasta matala- ja keskiaktiivisen jätteen loppusijoitustilasta ja tarkennettu arvio loppusijoituslaitokseen sijoitettavien erilaisten ydinjätelajien yhteisvaikutuksista ennen matala- ja keskiaktiivisen jätteen loppusijoitustilan rakentamisen aloittamista.
21. Posivan on yhdistettävä matala- ja keskiaktiivisen jätteen loppusijoittamisen vaikutukset koko loppusijoituslaitoksen kattavaan skenaario- ja turvallisuusanalyysiin sekä esitettävä turvallisuusperustelussa tarkennettu arvio loppusijoituslaitokseen sijoitettavien erilaisten ydinjätelajien yhteisvaikutuksista ja esitettävä tältä osin päivitetty turvallisuusperustelu käyttölupahakemuksen yhteydessä.

Turvallisuustoiminnot ja toimintakykytavoitteet

VNA 736/2008:n mukaisesti loppusijoituksen pitkäaikaisturvallisuuden tulee perustua toisiaan täydentävien vapautumisesteiden turvallisuustoimintoihin, joiden on estettävä tehokkaasti loppusijoitettujen radioaktiivisten aineiden vapautumista kallioperään. Turvallisuustoiminnolla tarkoitetaan loppusijoitettujen radioaktiivisten aineiden vapautumista ja kulkeutumista estävää ja rajoittavaa tekijää.

Posiva on esittänyt rakentamislupahakemusaineistossa vapautumisesteiden tehtävät ja määritellyt niille turvallisuustoiminnot. Posivan esittämät turvallisuustoiminnot kuvaavat yleisluontoisesti vapautumisesteiden tehtävät, ja eristämiseen ja radionuklidien vapautumisen ja kulkeutumisen rajoittamiseen kohdistuvat toiminnot.

Kullekin turvallisuustoiminnolle edellytetään korkeatasoiseen tutkimustietoon ja asiantuntijaharkintaan perustuvat toimintakykytavoitteet, joilla tarkoitetaan vapautumisesteen mitattavaa tai arvioitavissa olevaa ominaisuutta ja joihin sisältyvän kriteerin täyttymisen katsotaan varmistavan turvallisuustoiminnon toteutumisen. Posiva on asettanut toimintakykytavoitteet turvallisuustoiminnoille, mutta ei esitä selkeästi toimintakykytavoitteiden määrittämisen tapaa. Kaikkia Posivan toimintakykytavoitteita ei ole määritelty vapautumisesteen mitattavan tai arvioitavissa olevan ominaisuuden avulla. Useimmista toimintakykytavoitteista puuttuu tätä ominaisuutta kuvaava kriteeri.

Posivan esittämän vapautumisesteiden toimintakykyanalyysin on tuettava yksiselitteisemmin asetettuja toimintakykytavoitteita selkeiden perustelujen ja erityisesti kriteerien avulla. Yksikäsitteisempien toimintakykytavoitteiden avulla voidaan myös perustella ja arvioida loppusijoitusjärjestelmän kehittymiseen sisältyviä epävarmuuksia.

Systemaattinen ja laaja-alainen varautuminen odotettavissa olevasta kehittymisestä poikkeaviin kehityskulkuihin edellyttää selkeän näkemyksen muodostamista turvallisuustoimintojen mahdollisesta heikentymisestä ja sen laajuudesta. Posivan aineistosta ei käy selkeästi ilmi varautuminen eri turvallisuustoimintojen heikentymisiin.

Toimintakykytavoitteiden toteutumisen arvioimiseksi yksikäsitteisemmin on turvallisuustoimintojen määrittelyjä ja niihin vaikuttavia tekijöitä kuvaavia konseptuaalisia malleja kehitettävä. Konseptuaaliset mallit ovat keskeisessä asemassa myös muodostettaessa selkeämpi käsitys turvallisuustoimintojen heikkenemisen laajuudesta toimintakykytavoitteiden kriteerien osoittaman toiminta-alueen ulkopuolella.

Teknisille vapautumisesteille on asetettu suunnitteluvaatimukset, jotka on Posivan mukaan johdettu turvallisuustoiminnoille asetetuista toimintakykytavoitteista. Suunnitteluvaatimusten ja vapautumisesteiden toimintakyvyn välistä yhteyttä ei kuitenkaan ole esitetty riittävän yksiselitteisesti.

Posivan on käyttölupahakemukseen mennessä:

22. tarkasteltava uudelleen lähestymistapaansa turvallisuustoimintojen ja toimintakykytavoitteiden määrittämiseksi selkiyttääkseen turvallisuusperustelua ja poistaakseen epäjohdonmukaisuuksia toimintakykytavoitteiden määrittelyistä;
23. määritettävä kukin toimintakykytavoite vapautumisesteen mitattavissa tai arvioitavissa olevan ominaisuuden avulla ja sisällytettävä kuhunkin niistä tätä ominaisuutta kuvaavan kriteerin, jotta toimintakykytavoitteen täyttyminen ja heikkeneminen voidaan arvioida yksiselitteisemmin ja selkeämmin;
24. esitettävä selkeä ja yksiselitteinen yhteys vapautumisesteiden turvallisuustoimintojen, toimintakykytavoitteiden ja suunnitteluvaatimusten välillä;
25. kehitettävä konseptuaalisia malleja, joilla kuvataan turvallisuustoimintoja ja niihin vaikuttavia tekijöitä, toimintakykytavoitteiden toteutumisen yksikäsitteisemmäksi arvioimiseksi;
26. tuettava vapautumisesteiden toimintakyvyn analyysillään yksiselitteisemmin toimintakykytavoitteiden toteutumista ottamalla erityisesti huomioon loppusijoitusjärjestelmän varhaiseen kehitysvaiheeseen sisältyvän epävarmuuden.

Skenaarioanalyysi

Posiva on määritellyt skenaariot kehityskulkuina, jotka voivat johtaa loppusijoituskapselien vioittumiseen ja radionuklidien vapautumiseen.

Posiva on muodostanut loppusijoitustilan perusskenaarion olettamalla yhden tai muutaman alkuvioittuneen loppusijoituskapselin muiden vapautumisesteiden toimiessa ennakoidusti täyttäen niiden turvallisuustoiminnoille asetetut toimintakykytavoitteet. Muunnelmaskenaariot on muodostettu Posivan tunnistamien satunnaisten, radionuklidien vapautumiseen johtavien poikkeamien avulla ja häiriöskenaariot ottamalla huomioon YVL D.5:n edellyttämät pitkäaikaisturvallisuutta heikentävät epätodennäköiset tapahtumat. Pintaympäristön skenaariot ensimmäiselle 10 000 vuodelle Posiva on muodostanut loppusijoitustilan skenaarioista riippumattomasti.

Posiva ei STUKin näkemyksen mukaan ole varautunut yksiselitteisesti muiden vapautumisesteiden kuin loppusijoituskapselin (ulkovaipan lävistävä alkureikä) turvallisuustoimintoja heikentäviin laatupoikkeamiin skenaarioissaan.

Posiva ei tarkastele muunnelma- ja häiriöskenaarioissa riittävän systemaattisesti ja kattavasti mahdollisuutta, että yksi tai useampi toimintakykytavoite ei täyty. Posivan skenaarioiden muodostamisen tavan perusteella ei voida myöskään varmistua, että kaikkiin turvallisuuden arvioimisen kannalta merkityksellisiin loppusijoitusjärjestelmän kehityskulkuihin olisi varauduttu riittävästi.

Posivan on käyttölupahakemuksen yhteydessä:

27. esitettävä skenaariot loppusijoitusjärjestelmän mahdollista tulevaa käyttäytymistä kuvaavina kehityskulkuina;
28. selkiytettävä skenaarioiden muodostamisen tapaa, jotta voidaan helpommin varmistua skenaarioiden kattavuudesta loppusijoitusjärjestelmän mahdollisten kehityskulkujen suhteen;
29. perusteltava selkeämmin turvallisuusperustelussa esitettävien skenaarioiden valinta;
30. osoitettava skenaarioanalyysissä systemaattisempaa ja laaja-alaisempaa varautumista vapautumisesteiden turvallisuustoimintojen heikkenemisiin, ml. vapautumisesteiden laatupoikkeamien (esimerkiksi valmistus- ja asennusvirheet) vaikutuksesta.

Turvallisuusperustelun kehittäminen ja luotettavuus

Posivan turvallisuusanalyysi perustuu deterministiseen laskentaan, mutta sitä on täydennetty todennäköisyysperusteisella herkkyystarkastelulla. Herkkyystarkastelu on tehty valitulle joukolle laskentatapauksia, joissa tarkastellaan radionuklidien vapautumista ja kulkeutumista kallioperässä. Herkkyystarkastelussa on tunnistettu turvallisuusanalyysin merkittävimmät parametrit ja tarkastelu on riittävä rakentamislupavaiheessa. Herkkyystarkasteluja on tehtävä kattavammin eri skenaarioiden mukaisille laskentatapauksille sekä radionuklidien kulkeutumiselle biosfäärissä.

Posiva on STUKin pyynnöstä täydentänyt rakentamislupahakemusta selvityksellä POSIVA-STUK-10270, 3.7.2014. STUK pyysi tarkennuksia maanjäristyksen todennäköisyydellä painotetusta usean loppusijoituskapselin hajoamisen vaikutusten tarkastelusta. Posiva liittää tarkastelunsa todennäköisyyksiin pohjautuvaan maanjäristystarkasteluun, mutta esitetyt todennäköisyydet eivät ole riittävän perusteltuja. Posivan toimittamaa selvitystä ei voida pitää tältä osin riittävänä. Posivan on esitettävä selkeämmin usean kapselin hajoamisen tarkastelu huomioiden mannerjäätikön sulamisen aikana nopeasti muuttuvat geologiset olosuhteet.

Posiva on tiedonhallinta- ja laadunhallintamenettelyjen avulla lisännyt turvallisuus-perustelun luotettavuutta. Kuitenkin eri vaiheissa laadituissa aineistoissa esitetyissä lähtötiedoissa on havaittu ristiriitaisuuksia. Tästä syystä analyysien lähtötietojen yhden-mukaisuutta on parannettava esimerkiksi ”jäädyttämällä” käytettävät lähtötiedot riittävän ajoissa, jotta ne ovat yhtenäiset käyttölupahakemukseen yhteydessä toimitettavaa turvallisuusperustelua varten. Yleisesti ottaen lähtötietojen ja mallien luotettavuus voidaan todeta riittäväksi rakentamislupavaiheessa.

Vaikka turvallisuusperustelun voidaan todeta olevan riittävän luotettava, Posivan esittämä turvallisuusperustelu vaatii kehittämistä. Turvallisuusperustelun yhteenvedossa on esitettävä ymmärrettävämpi ja yksikäsitteisempi kuvaus vapautumisesteiden kehittymisestä, turvallisuusmerkityksellisimpien parametrien ja turvallisuuden laskennalliseen arviointiin merkittävimmin vaikuttavien vapautumisesteiden tunnistaminen sekä yhteenveto epävarmuusanalyysistä. Lisäksi näiden vertaaminen konseptin kehitysohjelmaan helpottaa turvallisuusperustelun luotettavuuden arviointia.

Turvallisuusperustelun rakenne ja esitystapa vaativat kehittämistä, jotta turvallisuus-vaatimusten täyttyminen on helpommin todennettavissa.

Turvallisuusperustelussa Posiva ei ilmaise aina selvästi omaa kantaansa turvallisuuteen liittyvissä kysymyksissä tai perustele tehtyjä valintoja. Posivan on esitettävä selkeämmin johtopäätöksensä ja niiden perustelut. Turvallisuusperustelussa tehtyjen viittausten on oltava selkeitä ja viitattujen aineistojen on oltava saatavissa käyttölupahakemusta jätettäessä.

Turvallisuusperustelun luotettavuus on tarkastuksen perusteella riittävä rakentamislupavaiheessa. Toimintakyky- ja turvallisuusanalyysi vaativat kuitenkin kehittämistä turvallisuusperustelun luotettavuuden lisäämiseksi. Posivan on:

31. tehtävä käyttölupahakemuksen yhteydessä herkkyystarkasteluja kattavammin eri skenaa-

rioiden mukaisille laskentatapauksille sekä radionuklidien kulkeutumiselle biosfäärissä;

32. toimitettava käyttölupahakemuksen yhteydessä selkeämpi kuvaus maanjäristyksen todennäköisyydellä painotetusta usean loppusijoituskapselin hajoamisen vaikutusten tarkastelusta ja siitä, miten laskenta kytkeytyy siihen liittyvään loppusijoitusjärjestelmän tulevaisuuskehitykseen. Kuvauksessa tulee selvittää tarkemmin, miten mannerjäätikön sulamisen aikana muuttuvat olosuhteet huomioidaan laskennassa konservatiivisesti;
33. kehitettävä turvallisuusperustelun rakennetta ja esitystapaa (selkeys, läpinäkyvyys, jäljitettävyys, käytettyjen lähtötietojen yhdenmukaisuus) sekä esitettävä turvallisuusperustelussa tehtävät johtopäätökset ja niiden perustelut selkeämmin, jotta turvallisuusvaatimusten täyttyminen on helpommin todennettavissa käyttölupahakemuksen yhteydessä;
34. toimitettava STUKille kaikki turvallisuusperustelun raportit käyttölupahakemuksen yhteydessä.

Kuuleminen

Päätöksen sisällöstä ja asetetusta aikarajasta on kuultu 30.1.2015 lähetetyllä sähköpostilla Posivan Samu Myllymaata, Vesa Ruuskaa ja Tiina Jalosta. Kuulemisvastauksen perusteella Posiva toivoo, että vaatimukset käydään STUKin kanssa läpi ja sovitaan yhteinen näkemys millä perusteella kukin vaatimus katsotaan täytetyksi, koska jotkin turvallisuusperustelun päätöksen vaatimukset ovat hyvin yleisiä. Lisäksi Posiva esitti muutosehdotuksia (yliviivattuna ja lihavoituna) seuraaviin vaatimuksiin:

Loppusijoituspaikan soveltuvuus

3\. Ennen ~~loppusijoitustilojen~~ **loppusijoitustunnelien ja -reikien**, rakentamisen aloittamista Posivan tulee esittää kallion toimintakykyanalyysiin perustuvat säilytettävien lähikallio-ominaisuuksien ja suunnitteluvaatimusten väliset yhteydet siten, että niistä käy ilmi, miten rakentamisen kallioperälle aiheuttamat häiriöt (mekaaniset, geokemialliset ja hydrogeologiset) pysyvät hallittuina ja asetettuja suunnitteluvaatimuksia vähäisempinä ja kuinka vaatimuksia noudattamalla voidaan olettaa edullisten ominaisuuksien säilyvän pitkällä aikavälillä.

Posiva esittää että otetaan huomioon 5.2.2015 puhelinpalaverissa keskusteltu asia, että keskustunnelien rakentamisen jälkeen Posivan tulee esittää vaatimuksen mukaiset selvitykset. Posiva ymmärtää että vaatimuksella tarkoitetaan sitä, että miten loppusijoitustilat rakennetaan mahdollisimman pienillä häiriöillä ja palautuvat perustilaa kohti.

Muutosehdotus on hyväksytty.

4\. Posivan on laajennettava kallioperän jännitystilojen mittausaineistoja nykyisestä sekä tarkennettava kallion perustilan jännitystilatulkintoja ennen ~~loppusijoitustilojen~~ **loppusijoitustunnelien ja -reikien rakentamisen aloittamista**. Kallion jännitystila- ja stabiiliustutkimuksien tulee lisäksi olla jatkuva tutkimus- ja kehitysaihe rakentamisen aikana.

Posiva esittää että rajataan kuten vaatimuksessa 3. ”ennen loppusijoitustunnelien ja -reikien rakentamisen aloittamista, jotta saadaan keskustunneleista lisää tutkimustietoa.”

Posivan on tehtävä lisää jännitystilamittuaksia myös ennen keskustunnelien rakentamisen aloittamista. Keskustunnelien louhinta rajaa paneelin sijoittumista, joten on tärkeää saada riittävä ymmärrys alueen jännitystilasta jo ennen keskustunnelien louhimista.

6\. Posivan on esitettävä suunnitelma, **tilojen soveltuvuuden osoittamiseksi mahdollisesti käytettävän** rakoverkkomallinnustavan luotettavuuden varmentamisesta ennen **loppusijoitustilojen** rakennustöiden aloittamista. Louhinnan vaikutusten ja hydrogeologisten mittausmenetelmien arviointi sekä lähtötietojen raportoinnin valmistelu on aloitettava välittömästi rakentamisluvan myöntämisen jälkeen. Valitun mallinnustavan jatkoperustelu ja luotettavuuden arviointi on tehtävä viimeistään laitoksen käyttölupahakemukseen mennessä.

Posiva esittää, että alleviivatusta lauseesta tehdään selvyyden vuoksi oma vaatimus siten, että siinä ilmaistaan vaatimuksen liittyvän louhintavauriovyöhykkeeseen (EDZ). Jäljelle jääneet kaksi lausetta yhdistetään ja lisätään tummennetut osat, sillä ei ole päätetty tullaanko rakoverkkomallinnustapaa käyttämään loppusijoitustilojen soveltuvuuden osoittamisessa.

Vaatimusta on selvennetty.

8. STUK edellyttää päivitystä Olkiluodon luonnonvaroihin liittyviin ~~stä tarkasteluista~~ **tarkasteluihin ja niiden perusteluihin** viimeistään laitoksen käyttölupahakemuksen yhteydessä.

Posiva ehdottaa sanamuodoksi yllä olevaa, jotta täsmennetään että erityisesti perusteluihin pitäisi kiinnittää huomiota.

Vaatimusta on täsmennetty tältä osin.

Sijoitustilojen asemointi

9. Ennen **loppusijoitustilojen** rakentamisen aloittamista Posivan on päivitettävä kallioluokituksen ohjeistusta tarvittavin osin vaatimus 3 huomioiden. Lisäksi Posivan on esitettävä ennen **loppusijoitustilojen** rakentamisen aloittamista suunnitelma luokituksen luotettavuuden arviointimenettelyistä ja suunnitelmat luokituksen jatkokehityksestä.

Posiva esittää yllä olevat sanalisäykset vaatimuksen täsmentämiseksi. Kallioluokitusmenettelyn vaiheistus kattaa myös rakentamisen alkuvaiheet, ml. esim. keskustunneleiden pilottireikätutkimukset (= paneelin rakentamisen 1. vaihe), kuten STUKille toimitetussa RSC-menettelyohjeessa on kuvattu.

10. Kallioluokitukseen liittyviä hyväksymismenettelyjä on vaiheistettava kattamaan myös rakentamisen alkuvaiheet, mukaan lukien pilottireikätutkimukset, ja luokitukseen liittyviä kriteerejä on edelleen tarkennettava sekä osoitettava niiden yhteys pitkäaikaisturvallisuuden kannalta edullisiin kallioperän säilytettäviin ominaisuuksiin. Täydennettyä kallioluokittelujärjestelmää arvioidaan kokonaisuudessaan uudelleen käyttölupahakemukseen mennessä.

Vaatimuksessa on hyvä viitata vaatimukseen 9.

Vaatimukset 9 ja 10 on kirjoitettu uudelleen. Korvaavat vaatimukset ovat 9, 10 ja 11.

Kapseli

11. Posivan on jatkettava loppusijoituskapselin valmistustekniikoiden kehitystyötä siten, että **sekä** BWR- **että** VVER–tyyppisen kapselin vaatimusten mukaisia komponentteja kyetään valmistamaan ennen käyttölupahakemuksen jättämistä.

Posivalla ei ole tähän vaatimukseen muutosehdotuksia. Lauserakenne voi selventää yllä olevan mukaisesti.

Vaatimusta on selvennetty tältä osin.

13. Posivan on edelleen tutkittava kuparin virumista; mekanismin, seosaineiden, lämpötilan ja kuormitustasojen vaikutusta kuparin virumiseen.

Posiva ehdottaa tarkennettavaksi seosaine fosforiksi ja epäpuhtaus rikiksi.

Vaatimusta on muokattu tältä osin.

Puskuri, tunnelitäyttö ja sulkeminen

Käyttölupahakemukseen mennessä Posivan on:

14. selkiytettävä puskurin ja tunnelitäytön toimintakyvyn saavuttamisen ajallisen keston epävarmuuden vaikutusta toimintakykytavoitteiden toteutumiseen;

Posiva käsittää että tällä tarkoitetaan puskurin ja täytön vettymistä (saturoimista), ja toivoo vaatimuksen täsmentämistä siltä osin.

Vaatimusta on täsmennetty tältä osin.

Matala- ja keskiaktiivisen jätteen loppusijoituslaitos

Posivan on:

19. esitettävä tarkennetut yksityiskohtaisemmat suunnitelmat loppusijoituslaitokseen tulevasta matala- ja keskiaktiivisen jätteen loppusijoitustilasta ja tarkennettu arvio Posivan loppusijoituslaitokseen sijoitettavien erilaisten ydinjätelajien yhteisvaikutuksista ennen **matala- ja keskiaktiivisen jätteen loppusijoitustilan** rakentamisen aloittamista;

Posiva esittää yllä olevan tekstin lisäämistä.

Vaatimusta on täsmennetty tältä osin.

Turvallisuustoiminnot ja toimintakykytavoitteet

21. tarkasteltava uudelleen lähestymistapaansa turvallisuustoimintojen ja toimintakykytavoitteiden määrittämiseksi selkiyttääkseen turvallisuusperustelua ja poistaakseen epäjohdonmukaisuuksia toimintakykytavoitteiden määrittelyistä;

Posivalla ei ole tähän vaatimukseen kommentoitavaa. Posiva toivoo kuitenkin aktiivista vuoropuhelua vaatimusten 21-25 osalta. Mahdollisen YVL-ohjeuudistuksen YVL-ohje vaatimuksia näiltä osin voisi selkeyttää.

Posivan kanssa käydään vuoropuhelua kyseisten vaatimuksien osalta.

Skenaarioanalyysi

26. esitettävä skenaariot loppusijoitusjärjestelmän mahdollista tulevaa käyttäytymistä kuvaavina kehityskulkuina;

Posivalla ei ole tähän vaatimukseen muutosehdotuksia. Posiva toivoo kuitenkin aktiivista vuoropuhelua vaatimusten 26–29 osalta erityisesti TURVA-2020 projektin suunnittelun aikana.

Posivan kanssa käydään vuoropuhelua kyseisten vaatimuksien osalta.

29. osoitettava skenaarioanalyysissä systemaattisempaa ja laaja-alaisempaa varautumista vapautumisesteiden turvallisuustoimintojen heikkenemisiin, ml. vapautumisesteiden laatupoikkeamien vaikutuksesta.

Posivalla ei ole tähän vaatimukseen muutosehdotuksia. Tässä asiassa Posiva toivoo aktiivista vuoropuhelua siitä että mitä "systemaattisempi ja laaja-alaisempi varautuminen" tarkoittaa. Posiva ymmärtää tämän myös siten että on esitettävä paremmin, mitkä tapaukset ollaan sisällytetty mihinkin skenaarioon ts. millaiset laatupoikkeamat on otettava huomioon skenaarioanalyyseissä.

Turvallisuusperustelun kehittäminen ja luotettavuus

30. tehtävä käyttölupahakemuksen yhteydessä herkkyystarkasteluja kattavammin eri skenaarioiden mukaisille laskentatapauksille sekä radionuklidien kulkeutumiselle biosfäärissä;

Posivalla ei ole tähän vaatimukseen muutosehdotuksia. Posiva toivoo kuitenkin aktiivista vuoropuhelua vaatimusten 30–36 osalta erityisesti TURVA-2020 projektin suunnittelun aikana.

Posivan kanssa käydään vuoropuhelua kyseisten vaatimuksien osalta.

32. kehitettävä turvallisuusperustelun rakennetta ja esitystapaa, jotta turvallisuusvaatimusten täyttyminen on helpommin todennettavissa käyttölupahakemukseen mennessä;

Posiva toivoo täsmennettävän mitä turvallisuusvaatimuksilla tässä yhteydessä tarkoitetaan.

Vaatimusta on selvennetty ja yhdistetty vaatimukset 32, 33, 34 sekä 36.

35. ~~saatettava~~ toimitettava kaikki turvallisuusperustelun raportit hyväksyttäväksi ~~valmiiksi ennen~~ viimeistään käyttölupahakemuksen toimittamisen yhteydessä toimittamista; sekä

Posiva esittää yllä olevat tekstimuutokset selkeyden vuoksi.

Vaatimusta on selvennetty tältä osin.

Päätös- ja esittelymuistioluonnokset on lähetetty kuultavaksi 9.2.2015 tehtyjen muutosten (vaatimukset 6, 9, 10 ja 11) osalta. Toisessa kuulemisessa Posivalla ei ollut huomautettavaa päätöksen sisältöön.

Jaakko Leino