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The disposal site and underground construction

Part I: The disposal site and the natural barrier

Part II: Preserving the favourable properties of the bedrock during construction

Neil Chapman, Adrian Bath, Joel Geier, Ove Stephansson

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Preface

This report is a summary compilation of the findings of STUK's expert reviewers in the area of geosciences and the natural barrier to support STUK's evaluation of Posiva's Construction License Application (CLA) for the planned spent nuclear fuel repository at Olkiluoto.

The Core Group of reviewers has advised STUK over the period since the Decision in Principle to proceed with geological disposal of spent fuel at Olkiluoto. Members of the team have reviewed numerous documents developed by Posiva over the last decade or more, have made frequent visits to the ONKALO facility with STUK's inspectors and have attended topical workshops at which issues have been discussed in detail with Posiva staff and expert contractors.

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

This report consolidates and summarises the separate template reports. In the process, material has been significantly condensed and edited to provide a more readable Consolidated Review Report. Discussions between the Core Group members in May 2014 allowed identification of the key issues arising, enabled common positions to be reached and facilitated the subsequent consolidation of comments and conclusions. The consolidation was carried out by the Key Consultant for the Natural Barrier area (Professor Neil Chapman) and the resulting report was approved by the other members of the Core Group. It thus represents a consensus view of this group.

The review work was supported by specialist evaluations in the fields of fractured rock hydrogeology, seismology, structural geology, hard rock construction and climate and glaciology. These expert reviewers assessed specific reports and subsequent workshops were held with Posiva on some of these topics to clarify issues. The findings and suggestions of these workshops, which were agreed between the specialist reviewers present, have been incorporated into this report.

CHAPMAN Neil, BATH Adrian, GEIER Joel, STEPHANSSON Ove. Loppusijoituspaikka ja maanalainen rakennelma. STUK-TR 17. Helsinki 2015. 14 s + 100 s + 20 s.

Avainsanat: radioaktiivinen jäte, käytetyn ydinpolttoaineen loppusijoitus, KBS-3-konsepti, kallioperägeologia, hydrogeologia, hydrogeokemia, paleohydrologia, kalliomekaniikka, kiteinen rakoillut kallio

Tiivistelmä

Tämä raportti on yhteenveto Säteilyturvakeskuksen (STUK) käyttämien ulkopuolisten geotieteiden asiantuntijoiden arvioinneista, jotka teetettiin Posivan rakentamislupahakemuksen tarkastuksen yhteydessä STUKin oman arvioinnin tueksi.

Työhön osallistunut arviointiryhmä on toiminut STUKin tukena Posivan käytetyn ydinpolttoaineen loppusijoituksen ensimmäisestä periaatepäätöksestä lähtien. Ryhmän jäsenet ovat arvioineet useita Posivan raportteja viimeisen kymmenen vuoden aikana, he ovat vierailleet Onkalossa useita kertoja STUKin tarkastajien kanssa ja he ovat osallistuneet useisiin STUK järjestämiin aiheeseen liittyviin työpajoihin, joissa arviointihavainnoista on keskusteltu Posivan ja Posivan konsulttien kanssa.

Viimeisimmällä arviointikierroksella ryhmä on keskittynyt Posivan TURVA-raporttikokonaisuuteen (pitkäaikaisturvallisuus), joka on keskeinen osa vuonna 2012 toimitettua rakentamislupahakemusta. Jokainen ryhmän jäsen on keskittynyt arviossaan omaan erikoisalueeseensa. Arviointihavainnot ja kommentit on kirjattu STUKin valmistelemaan arviointiraporttipohjaan.

Tämä raportti tiivistää ja vetää yhteen erillisten arviointiraporttien havainnot. Alkuperäisiä yksittäisten konsulttien arviointiraporttien tekstejä on tiivistetty ja editoitu, jotta yhteenvetoraportista on luettava kokonaisuus. Toukokuussa 2014 järjestetyn työpajan keskusteluissa arviointiin osallistuneet asiantuntijat tunnistivat ja keskustelivat tärkeimmistä arviointihavainnoista. Yhteenvetoraportin on koonnut professori Neil Chapman, joka toimi STUKin avainkonsulttina paikkatutkimuksiin liittyvissä asioissa. Kaikki arviointiryhmän jäsenet ovat hyväksyneet raportin, joten se edustaa arviointiryhmän jäsenten näkemystä.

Arviointityöhön osallistui vakiojäsenten lisäksi erikoisosaajia seuraavilta aloilta: rakoilleen kallioperän hyrdogeologia, seismologia, rakenteellinen geologia, kalliorakentaminen, ilmasto ja jääkaudet. Nämä erikoisasiantuntijat arvioivat oman erityisalansa raportteja ja osallistuivat niiden aihealueista järjestettyihin työpajoihin, joissa tutkimushavainnoista keskusteltiin Posivan kanssa. Työpajoissa kirjatut havainnot ja ehdotukset on sisällytetty tähän yhteenvetoraporttiin.

Acronyms used in this report

This report uses many acronyms that are common in the field of geological disposal of radioactive wastes and several that are specific to Posiva's license application or to this review programme.

ACM
Alternative conceptual model

BFZ
Brittle fracture zone

BP
(years) before present (time)

CC/CCR
Complementary consideration (report: Posiva 2012-11)

CLA
Construction License Application

CPM
Continuous porous medium

DBR
Design Basis Report: Posiva 2012-03

DEM
Digital elevation model

DFN
Discrete fracture network (model)

DH
Deposition hole (for a spent fuel canister)

DOC
Dissolved organic carbon

DSM
Detailed-scale model (of geological structures)

DT
Demonstration tunnel

EBS
Engineered barrier system

ECPM
Equivalent continuous porous medium

EDZ
Excavation disturbed zone

EFPC
Extended full perimeter criterion (see FPI)

EPR
European pressurised reactor

EQ
Earthquake

FDB
Posiva fracture database

FEP
Features, events and processes

FPI
Full perimeter intersection (of a fracture, around the walls, floor and roof of a tunnel)

GCM
Global climate model

GPR
Ground penetrating radar

GSI
Geological strength index

HTU
Hydraulic testing unit

HZ
Hydrogeological (or hydraulic) zone (a major fracture zone hosting groundwater flow)

IZ
Influence zone (around a fault or fracture)

LDF/LDZ
Layout determining feature/zone

LILW
Low and intermediate level radioactive waste

LVDT
Linear Variable Differential Transducer (cell, to measure rock stress)

MDR
Models and Data Report (Posiva 2013-01)

MDZ
Minor deformation zone (equivalent radius >75 m and <564.2 m)

MIS
Marine Isotope Stage

OLA
Operating License Application

OSD
Olkiluoto Site Description (Posiva 2011-02)

P-O
Prediction-Outcome tests in pilot boreholes and subsequent tunnel excavations

PA
Performance assessment

PAR
Performance Assessment Report: Posiva 2012-04

PAVE
Pressurised water sampling equipment, used in boreholes

PDF
Probability density function

PFDHA
Probabilistic fault displacement hazard analysis

PFL
Posiva Flow Log (tool)

PGF
Post-glacial faulting

PH
Pilot hole (drilled before excavation of an opening)

PSA
Probabilistic safety assessment

PSHA
Probabilistic seismic hazard analysis

QA / QC
Quality assurance / quality control

RAI
Request (to Posiva) for additional information

RMD
Rock matrix diffusion

RMM
Rock mechanics model

RSC
Rock suitability classification (and RSC 2012 report: Posiva 2012-24)

RQD
Rock quality designation

SCN
Sparse channel network

SCR
Stable continental regions

SDR
(Disposal) System Description report (Posiva 2012-05)

SEM
Scanning electron microscopy (as used for characterisation of colloids)

SF
Spent fuel

SFR
Sparsely fractured rock (rock mass between large, conductive fractures)

SIS
Scandinavian ice sheet

SKB
Swedish Nuclear Fuel and Waste Management Company

SSM
Swedish Radiation Safety Authority

TBM
Tunnel boring machine

TCF
Tunnel crossing feature

TCM
Tectonic continuum model

TERO
Termiset ominaisuudet (thermal properties) probe

tHM
Tonnes of heavy metal (as a measure of the mass of spent fuel)

THMC
Thermal, hydrogeological, mechanical, chemical (properties, behaviour, parameters)

UCS
Uniaxial compressive strength

UOPL
Underground Openings Production Line report (Posiva 2012-22)

VAHA
Posiva requirements management system

WR
(Posiva) Working Report

Summary of the key issues affecting the construction license

Posiva has carried out a thorough and comprehensive programme of work to characterise the Olkiluoto site, both from the surface, using boreholes and drillcores, and in the ONKALO underground facility. The quality of the investigation work and the modelling and interpretation of its results is generally of a very high standard and, in many areas, represents the state-of-the-art in methodology and technology. The expert reviewers have been impressed by the totality of the work carried out by Posiva's expert staff and contractors, and by their commitment to continue and improve both understanding and application during the construction phase. Our overall finding is that, if continued and completed as intended, the planned programme of work should deliver a high-quality facility to host the EBS and spent fuel, and all the geoscientific data necessary to support a successful safety case at the time of submission of an operating license application.

In a programme of this size and complexity it is inevitable that some areas require further work, that several are in a development stage that will require acquisition of more construction experience and that some still involve significant uncertainties that will need resolution. Identifying the areas and topics that have direct impact on STUK's response to the Construction License Application (CLA) has been the main focus of this review.

The expert review group considers that none of the topics it has identified has such significance for the current safety case or for Posiva's construction plans that it would prevent STUK from giving a positive safety appraisal. Nevertheless, these topics will need to be addressed by Posiva over the coming years – some of them before construction in the disposal rock volume should commence. The background to these topics and the detailed considerations on how to address them can be found in the main Sections of this report. This introductory Section brings them forwards within three Groups of suggested requirements and commitments for Posiva:

1. **Before construction:** Requirements to be met before underground construction (meaning excavation of disposal tunnels/panels/boreholes or drilling into the proposed disposal rock volume) or component fabrication (meaning manufacture of EBS components that will be used for spent fuel disposal) begins. The necessary tasks should be completed to an agreed schedule, with regular reporting to STUK.
2. **Before operating licence application:** Requirements for work that should be completed, or have sufficient progress made, with the outputs included in the Safety Case, Design, Operational and other materials in the OLA. There should be regular reporting to STUK in the period prior to the OLA.
3. **Commitments to longer term RD&D.** Programmes of work should be initiated/continued to enhance and improve data and understanding about topics in the areas of Safety Case, Design and Operation, with progress reported regularly to STUK.

Whilst some matters in Group 2 need to be resolved before the OLA, the requirement of 'sufficient progress' can only be judged properly at the time of the OLA and it is consequently difficult to draw a clear line between Groups 2 and 3 for some topics. There are certainly many areas where continued developments in the wider fields of science and engineering will improve our understanding and affect considerations of how best to manage a geological repository. It thus seems inevitable that R&D will continue well beyond the start of the operational stage. For the current evaluation, we have thus not distinguished between Groups 2 and 3, except to identify any specific tasks that should be completed before the OLA.

Group 1: Requirements before construction in the disposal volume begins

1. **Target properties and VAHA:** The current VAHA needs to be clarified and improved to the point that it can be used routinely to support design and site characterisation decisions. This will involve better definition of some of the design requirements and specifications at Levels 4 and 5 (including ensuring that parameters leading to fulfilment of long-term target properties can be measured reliably and routinely) and the development of change-control procedures. The traceability of some specifications is poor. Vague definitions need to be improved. Use of the words 'low' and 'limited' is unaccountable and not acceptable for regulatory purposes.
2. **RSC utilisation:** The RSC development and demonstration work is well-conceived but at an early and consequently immature stage. It should continue with high priority and be linked to the VAHA improvement work. Several specific issues require particular attention:
   a. the tunnel and DH inflow criteria and the methodology to measure them: there are uncertainties surrounding the derivation and proposed measurement approaches and some clarification is needed before the CLA can be approved, even though it is recognised that it may be further updated in the early stages of construction;
   b. whether there is a need to have RSC for the thermal properties of the rock, either at the deposition tunnel scale, or for individual DHs (lithological mapping, conductivity, anisotropy etc) and, if so, how and when these would be measured;
   c. RSC measurement approach to qualifying the panel or tunnel-scale natural hydrochemical properties of the disposal volume in a disturbed environment;
   d. systematic and integrated testing of tunnel floor EDZ characterisation methods so that a routine deployment procedure is ready for use in all deposition tunnels. Development of the procedure should include integration of GPR, geo-electrical and hydraulic tests so that a single measurement system/procedure can be selected for use as part of routine tunnel construction work. This development should be integrated with planning for routine tunnel floor scaling procedures. Posiva should consider including an EDZ factor in its RSC.
   e. improvement of the value of data from the prediction-outcome technique;
   f. an RSC deployment handbook for users. This should encompass the use and documentation of alternative layout options to be tested by the Panel Calculator. To avoid too much complexity with a multiplicity of parameters, the parameters to be varied in tests should be clearly stated.

Posiva should present a clear plan and procedures for the construction and operational management **decision-making steps and hold-points**, to which the RSC will provide one of the key inputs. STUK will then be able to match its inspection programme to these decision-points and will be clear about which information they need to assimilate. Particular attention needs to be placed onto the procedures that will be applied when significant uncertainties or marginal conditions are encountered in system properties, or where alternative construction or operational options are possible. The documentation should address:

a. issues such as how many deposition tunnels are to be constructed at one time and whether such decisions will affect the quality of RSC interpretations;

b. how ‘hold points’ will be incorporated into the management system;
c. a time schedule for further ‘demonstration activities’ aimed at developing, testing and updating of the RSC Manual in the early stages of construction and to ensure that the activities described are at a sufficiently detailed level to capture the routine decisions that will have to be taken when characterising the rock and gathering RSC data;
d. management of situations where tests fail or are inconclusive, or require support by new or additional work;
e. a routine programme of hydrogeological testing and monitoring work that will be used once panel construction begins that will have the objective of validating and continuously improving and making more precise the models of groundwater flow at the scale of each panel and deposition tunnel, utilising state-of-the-art testing techniques and instrumentation;
f. a documented version of the Panel Calculator that can be evaluated and used as a basis for inspection.

It seems inevitable that an RSC toolkit that can be used routinely and with confidence should not be expected to be in place until a lot of ‘in-panel’ experience has been acquired. However, there are many loose ends and gaps at the present, and a complete and comprehensive RSC system does need to have been developed and tested repeatedly for reliability in the first deposition tunnels that are available in the period between the CL and the OLA.

3. **Design adaptation and the construction process:** Presentation of a strategy, plan and allocation of responsibilities for the design and construction decision-making procedures (possibly in the forthcoming ‘Management of the Disposal Concept’ document). Criteria and assessment procedures are needed for making decisions such as:
   a. thermal dimensioning (currently based on average values for generalised rock-type groupings);
   b. appropriate respect volumes (influence zones, IZ) around LDFs;
   c. panel locations and deposition tunnel orientations;
   d. choice of rock support systems in deposition areas, required stand-up times in each area of the repository and removal of the support system before backfilling;
   e. use of the eastern site area;
   f. whether to use a 2-storey design and, if so, how and when to decide on feasible depth, design and construction staging for the whole facility;
   g. optimising disposal panel depths taking account of all critical safety, environmental and economic factors;
   h. if/how Posiva intends to use the EUROCODE methodology to guide and control construction.

In addition, Posiva should present its plans for extending and retaining the pool of skilled geoscientists that will be required for the construction period, especially for the characterisation work and RSC application. Highly skilled and motivated geoscientists and engineers are working in this area today, but Posiva needs to consider the long-term availability of resources and the assurance of strength-in-depth over the next decades.

4. **Rock stress regime:** Posiva should present its plans for improving its current rock stress model and stress measurement database to a point that it is adequate to support the design decisions that will be used during construction and for the boundary conditions of the rock mechanics models. These plans, including campaigns of stress measurements, should be implemented as soon as further work begins at ONKALO.

5. **Enhanced hydrogeological characterisation and modelling of the deposition volume:** The hydrogeological characterisation programme for further demonstration excavations and for the main construction phase needs significant work. An improved and state-of-the-art hydrogeological testing programme for all deposition areas (panel to DH scale) that includes routine head measurements and interpretation, and the extended testing and use of pilot holes is required. This programme should be demonstrated and tested in further work in the DTs and in the first few deposition tunnels, and should be integrated with the RSC development and design planning and decision-making strategy. Factors to be addressed are:
   a. Resolving uncertainties about what the PFL tool is actually measuring (e.g. possible double counting of inflows; the meaning of the measurements in terms of the volume of rock or extent of the hydraulic network that is actually tested by the PFL along a given 20 m length of pilot hole). This work should include a scientific and engineering description of the design basis, operational protocols, testing and validation of the tool. The PFL is still a relatively novel measurement instrument that has only seen a limited scope of application – mainly by just two organizations, Posiva and SKB – with limited theoretical evaluation, laboratory testing and in situ validation, compared with more mature hydrogeological testing methods. Hence, it cannot yet be regarded as a robust, fully qualified measurement instrument. These uncertainties need to be explored and clarified by continued testing and verification of PFL results against other observations, as well as modelling of the measurement procedures and well-documented laboratory testing under controlled conditions. The output of this work should clearly identify and quantify the uncertainties in data measurement and interpretation: these should be related specifically to each of the individual measurement campaigns in critical surface and pilot boreholes that have been used as the principal sources of data to calibrate the Hydro-DFN model. In the short-term, POSIVA could quantify the uncertainties in interpretation of the PFL and HTU tests.
   b. The Hydro-DFN development is complex and hard to trace through the documentation, with many analysis procedures and implementation techniques that have been developed ad hoc in the course of the site descriptive model development and subsequent application. A concise and systematic summary description of the whole DFN conceptual framework and its implementation, plus its applications, is required.
   c. A planned programme of measurements is needed that will (i) lead to better validation of the limited DFN 'predictive' capability for spatial utilisation, (ii) gather the most appropriate data necessary to qualify DHs and tunnels, (iii) test alternative conceptual frameworks for flow in the rock mass and (iv) continuously improve confidence in the DFN model and its results, as applied to PA and the qualification of near-field rock. For example, the area density (intensity) of inflows to the tunnels, when compared to the pilot borehole inflows for the same rock, is a key measurement for reducing the uncertainty in any discrete network model. Although Posiva has recently demonstrated an approach for obtaining water leakage mapping data that could be useful, the link between field observations and model validation has yet to be made.
   d. If slow saturation and lack of full saturation throughout the thermal period has safety consequences, it is clear that more work will need to be done with respect to very low hydraulic conductivity rock volumes. The key uncertainties continue to be the actual range of k for the rock mass at the low value end of the spectrum and the volumetric proportion of such values, the likelihood of tunnel-floor EDZ inflows

to DHs and the tunnel inflow estimates to DHs, if a less connected network of flow channels exists. Posiva has not dealt convincingly with the uncertainties that they already recognise, which means that calculated distributions of DH saturation times is not quantitatively convincing.

e. A major gap at present is in gathering head data, which can be highly informative. Heads are readily measured, although they will be highly variable and will change with time, and many measurements will be needed to evaluate the system probabilistically.
f. A plan to verify the hydrogeological model for the near-field rock. This may require instrumenting the existing boreholes to measure heads and also to do 'blind' predictions before construction of each tunnel and boring of DHs. A probabilistic approach to developing and evaluating predictions is essential in order to produce meaningful tests of the Hydro-DFN model. This should also be done with the Geo-DFN model, focusing on predicting and measuring the properties that are of primary concern for successful application of the RSC (principally fracture intensity and extent).
g. An alternative conceptual model (ACM) exists of groundwater flow in the fracture network and how this might be channelled. Different assumptions about the shape of flow paths (e.g. expressed as fracture wetted surface or flow channel aspect ratio) and their connectivity lead to the possibility of more 'dry' DHs, increased 'spot' flow rates in channels in the near field (e.g. in DHs or in disposal tunnel walls) and smaller wetted surface areas (reducing the critical 'F' factor used in radionuclide transport calculations, e.g. by ×10). This could affect the results of PA release calculations. This ACM should be explored alongside Posiva's current Hydro-DFN model, which has a more limited type of channelling within fractures that are generated based on the DFN conceptual model.

Posiva should make a thorough and wide-ranging review of its hydrogeological programme and reconsider the related parts of its RSC programme before it starts major excavation work.

6. **Monitoring:** The overall monitoring programme should be developed, improved and made more precise. It should be integrated with the RSC measurements that will be made and to monitoring work already in place (e.g. geodetic, GPS). Gaps in the factors being monitored should be filled (e.g. micro-seismicity; groundwater heads; trace elements in groundwater as indicators of anomalous conditions; microbiology). Clearer definitions and justifications of both action levels and tolerated amounts of critical materials should be presented. Response actions should be better defined. A reporting and inspection programme should be developed and agreed with STUK.

Groups 2 & 3: Requirements before and commitments beyond the OLA

1. **Progressive reduction of uncertainties in key parameters/models:** A strategy and plan should be presented for the continued and progressive reduction of critical uncertainties in fracture network, groundwater flow and chemistry characteristics during the construction period and in preparation for the OLA. The strategy should address at least the following topics:
   a. verification of models of redox conditions in disposal volume groundwaters;
   b. verification of models of the interaction of sulphide, methane, DOC and microbial activity in undisturbed and excavation-disturbed environments;
   c. verification of pore water / fracture water salinity diffusion behaviour and matrix diffusion history;

d. improvement of and rectification of problems in the Geo-DFN model;
e. improvement of databases on fracture size and transmissivity relationships;
f. identification of present-day groundwater discharge areas.

2. **Fracture response to heat and seismicity:** 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 possible that stress changes could shift some fractures out of their stability fields, causing shear movements. This could happen at any scale, from 'critical fractures' (in the earthquake canister shear scenario) to large brittle fracture zones (BFZ). In the latter case, small to medium magnitude earthquakes could affect the repository and any surface nuclear facilities that are present on the whole Olkiluoto site in the first decades to 1000 years after disposal. Posiva is starting a programme to characterise large BFZ properties in more depth, to help scope this issue. New modelling techniques are coming available to study the possible dynamic impacts on the rock mass and fracture system. It is not expected that this scenario would lie outside the bounds of the earthquake scenario already studied by Posiva, but it could occur much earlier.

Posiva appreciates this is an important area and has an impressive forward programme on several, but not all, key topics. Continued work is needed on an integrated thermal and mechanical model of fracture strain at all scales in and around the repository (see Group 1, above). This should fully integrate work on thermal fracture activation and the response of the fracture network to major earthquakes. The work should be closely integrated with the development of the stress model for the repository volume. Both modelling studies and characterisation of fracture properties at all scales should be included.

The seismic hazard work should be continued and should investigate: the geometry and stability of major BFZs at, around and below the site, including offshore; neotectonic data from LIDAR and other tools; geodetic and GPS monitoring; the scaling of earthquake magnitudes and frequencies under current and post-glacial conditions, including focal mechanism analysis for the stress modelling; the derivation of critical fracture sizes related to the RSC programme.

The central point is that Posiva needs to take a fresh approach to post-closure seismic hazard analysis and should take the opportunity of developing this new approach alongside the planning of its operational PSHA for the repository and its surface facilities. A seismologically informed approach is needed that integrates the following:

a. knowledge about how EQs initiate and propagate in the shallow and mid-crust in this SCR geological environment;
b. deterministic studies of specific BFZ behaviour scenarios in and around the site, using the latest lineament data and deep geophysical profiling of BFZ geometry that maps the deeper (>1000 m) structure of BFZs at the site;
c. observational evidence from LIDAR studies complemented with digital elevation models (DEM) of the bedrock surface;
d. strain budget modelling based on GPS data, EQ fault-plane solutions and in situ stress measurements;
e. probabilistic assessment of fracture and fault displacements (PFDHA) throughout the rock volume at site scale that assesses distributed displacements, triggered faulting, depth variation in displacements etc;

f. rock mechanical analysis building on discrete element modelling with the 3DEC approach and novel techniques, such as particle flow (PFC) modelling;
g. the combined impacts on target fractures of rock heating during the thermal period and induced EQ activity on fracture zones in and around the repository, where ongoing work by SSM indicates that large target fracture displacements could occur.

This degree of integration will require planning that incorporates Posiva's already impressive future work programme (e.g. on ice load and thermal stability of BFZs). STUK should request an outline of these plans that details work during the period between the CLA and the OLA.

The calculation of probability-weighted multi-canister failure releases is difficult to follow and, in future, Posiva should provide a more extended description of how this 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.

A **specific study** that is required in the near future is the evaluation of an EQ on one of the Eurajoensalmi bay BFZ structures associated with BFZ214. This should look at the M_{max} that could be associated with these structures under current conditions, informed by regional assessments such as SHARE and Posiva's own evaluation of the stress field, and under post-glacial conditions. The output of this should be a better justification for the choice of critical fracture radius and a sensitivity study showing how critical fracture radius is affected by parameters such as M, seismogenic BFZ distance (and whether the BFZ is lateral to or below the repository), stress orientation etc. This seems an essential input to further development of the RSC, hence its suggested early delivery.

3. **Further experimental studies in the disposal volume:** four topics have emerged where additional, new experimental studies, in the actual repository volume, could assist in uncertainty reduction:
   h. verification of the impact of excavation and pumping disturbances on the development of redox, sulphur and microbial characteristics of near-field groundwaters during the operational and immediate post-closure periods;
   i. repeating POSE-type experiments in different rock types (mineralogy, foliation, stress patterns etc) that are more relevant to those of the disposal rock volume, to assess the extent to which these factors could affect spalling, spalling dimensions, transmissivity and retention properties and thus constrain choice of deposition volumes and their long-term safety;
   j. characterisation of the strength and hydraulic properties of fracture zones at different scales, up to site-scale BFZs:
   k. testing of silica gel grouting technology and results.
4. **Dilute water penetration:** Global climate models indicate a possibility that there could be continuation of current temperate conditions for a considerable period of time – at least several tens and possibly some hundreds of thousands of years. The deep groundwater system will be progressively flushed with dilute meteoric waters, replacing brackish waters in fractures at disposal depth during this period. Dilution of groundwater salinity around deposition holes through the period of temperate climate, continuing due to melt water infiltration in a subsequent period of glaciation, could affect the stability of the buffer (to chemical erosion). Posiva says such conditions can give rise to large numbers of canister failures, depending, in particular, on the matrix

diffusion depth assumed in modelling. Clearing up uncertainties over the rate and history of interaction of rock mass pore waters and water in fractures would help to decide whether this is a possibility. A parallel point is that Posiva's conservative assumption of little dispersion in the fracture network for radionuclide transport is non-conservative if used in a reverse sense to evaluate penetrating dilute waters (as they 'see' less rock *en route* to depth).

5. **Climate change impacts:** Posiva has focussed its safety case by 'repeating' the Weichselian glacial cycle over the next c.150,000 years, after an interglacial period. Further studies for inclusion in the OLA should explore the sensitivity of the safety case to different possible timings and magnitudes of climate periods, including:
   l. prolonged temperate conditions (>50,000 years);
   m. earlier/later/longer onset of permafrost;
   n. earlier/later onset of glacial conditions with justified minimum and maximum values of ice thickness and residence time;
   o. possible rapid or abrupt climate changes in the next few hundreds or thousands of years affecting groundwater recharge, sea-level etc.
6. **LILW cavern:** The CLA includes a shallow LILW disposal cavern accessed from the SF repository ramp. It is located directly above parts of the SF repository and contains substantial volumes of cement. A separate safety case has been presented recently for this cavern facility (Posiva 2012-37) but has not been reviewed. A fully integrated assessment for the whole disposal facility should be required as part of the OLA, using common evolution scenarios and common approaches to modelling groundwater flow and chemistry. This will need to assess any potential for impacts of the LILW cavern on the SF repository and vice versa (e.g. cement chemical impacts on the SF repository and large-scale thermal rock strain impacts on the LILW repository) and evaluate integrated radionuclide release/transport and potential doses. It is understood that STUK has requested further information on Posiva's intentions for such work.