Part I: The disposal site and the natural barrier

Contents

1 Site characterisation

This Section addresses the overall site characterisation programme in terms of information coverage, the extent and quality of data and their interpretation in terms of site behaviour and its evolution.

1.1 Coverage and reliability of the geoscientific data for the site

This Section considers the amount of geoscientific data that has been gathered in the site investigations, its coverage of the proposed repository area and volume, its quality and how Posiva has addressed data uncertainties.

1.1.1 Data coverage

With few exceptions, data coverage in the central (ONKALO) area of the repository zone is dense and appears adequate for the purposes of the CLA. The exceptions mainly concern rock stress data and thermal data above level 350 m. Of course, further data gathering will continue throughout construction work and beyond, to enhance the existing coverage for all data types. STUK should expect continuous improvement of every dataset. Furthermore, requirements for when data might need to be available from the eastern part of Olkiluoto Island (potentially used for disposal in the future) should be considered.

OSD Section 4.12.1 refers to the presence of “white areas” in the modelled Site Area (to the NE, S and E of ONKALO, but predominantly in the E and SE) and acknowledges that the eastern area is only just being addressed by characterisation work and that the first results are only now available. Section 10.9.2 states that it is possible to assess the general suitability of the less-characterised rock volumes based on current knowledge. For example, Posiva says that there have been few surprises while drilling in the eastern area. Whilst this may be reasonable at the current CLA level, a more specific approach will be necessary to bring the database up to the same level as the western area before construction work takes place in this area. This would be a matter for the future. It is recognised that certain features may be present (e.g. sub-vertical features) that will need to be targeted (OSD p.842).

Sub-vertical faults large enough to affect layout could still be encountered in the central area due to the predominantly vertical orientation of surface-based boreholes. Posiva recognizes this (p. 844) but plans to rely on pilot holes and other tunnel-based methods of investigation.

OSD does not assemble the offshore data (discussed in Section 3.3) to show the continuation of lithology or structures offshore in the geological mapping. Given the transient nature of the coastline it would have been useful to see a geological and structural map without the coastal termination. This is of particular relevance to the issue of post-glacial faulting.

Conclusion: Data coverage for the central-western area around ONKALO is adequate for the CLA in all disciplines, but gaps must be filled and STUK should expect all databases to be enhanced by continued data gathering during construction. Data are inadequate for the eastern area, which is a project risk issue for Posiva. STUK should consider attaching conditions for any future proposals to use the eastern area that would require bringing the database up to a comparable level.

1.1.2 Recognition of uncertainties

Generally, Posiva’s approach to data and interpretational uncertainty is thorough and structured. At the bottom level, each OSD Section identifies uncertainties related to specific disciplines or datasets. These are brought together in Chapter 10 and reduced to a short list of key uncertainties. For hydrochemistry and, to a lesser extent, hydrogeology, the uncertainty treatment is reasonably systematic and has resulted in clear identification of additional data needs. In other areas, discussed later in this review, it is less clear that a formal path has been taken to address known uncertainties (e.g., some rock properties and stress data). It would be more robust if Posiva had used and recorded a formal expert elicitation approach to critical areas to ensure that possible uncertainties and alternative interpretations had been captured. The uncertainties and their significance tabulated by Posiva appear reasonable and address the issues that we are also aware of, but it is not feasible to be sure that they are comprehensive.

In propagating uncertainties into the safety assessment, there are no major issues of data uncertainties that have been neglected in the PAR, although there are some areas where sparse data and consequent uncertainties make the performance assessment vague and lacking definition. In these cases there is a lack of conceptual clarity in how these parameters impact on performance of the bedrock. Examples are microbiological and colloids data, where there are relatively large uncertainties, but their significance and impact on performance cannot be assessed because the process models involving these data have not been sufficiently well quantified.

Data that are used in the Safety Case are compiled and discussed in the MDR. Uncertainties in data have been identified and quantified as far as possible in the sections on ‘confidence in model and data’. For example, calibration of the thermal and rock mechanics block models in the RMM relies, to a large extent, upon a proper calibration and verification of the geological model. OSD Section 5.5.4 claims that the uncertainties relating to the lithology, rock stress, intact rock, fractures, rock mass quality, BDZs and thermal properties are known and that the implications of these uncertainties relate to the use of parameters in the analytical methods for the repository design. Data uncertainties must also be considered when numerical modelling methods are applied in the design process.

Uncertainties in modelled performance indicators are identified and discussed in the PAR in each theme of bedrock performance for each timeframe (operational phase; next 10,000 years; through a glacial cycle). This is a satisfactorily explicit way of accounting for uncertainties and showing how they should be propagated through into the safety case, but it is difficult to trace whether these proposals have been followed up.

Uncertainties in description of Initial State arise in properties that do not change significantly between natural state and post-construction, and in properties of the host rock that will be changed by construction/operation (e.g. grout injection; EDZ).

Specific examples of potentially significant uncertainties are identified in the MDR and throughout the supporting documentation and include:

- stress magnitudes and directions and their variability, where the number of data points and their spatial coverage is insufficient;
- effects of foliation and other anisotropy on rock strength and thermal properties;
- the proportion of fractures that constitute the transmissive network and the role of flow channelling;
- parameters that are input to the ECPM model, particularly, kinematic porosity and dispersivity, which influence the evolution of salinity and transport of radionuclides.

An area of data uncertainty identified by the review but not specifically included in the list above concerns the output of the Posiva Flow Log tool (PFL): see Section 1.1.5.

Conclusion: Posiva’s general approach to uncertainty and intentions for managing uncertainties is good and it is hard to identify omissions but, as a non-formal methodology, it is not possible to say how comprehensive it is of all reasonably identifiable uncertainties. Nevertheless, with the exception of the PFL uncertainties discussed below, we have not identified any significant uncertainties that are not already recognised by Posiva.

1.1.3 Tracking geological model updates

Application of the RSC criteria and evaluation of layout-determining features (LDFs) involves development of multiple versions of 3-D spatial models of LDFs, respect volumes, FPI fractures, etc., which are then used for repository design and layout decisions. It is not clear how these model configurations are managed. This needs to be adequately documented and accessible. During construction, it is likely that a large number of incremental model versions will need to be developed, to incorporate new information from characterisation of panels, tunnels and deposition holes.

Conclusion: A clear system will be essential for tracking these models and identifying which versions are used for which purposes. A key issue for

STUK as detailed construction planning begins will be Posiva's system and the procedures for deploying it routinely in the LDF and RSC workflows.

1.1.4 Rock mechanics data reliability

Rock stress magnitude and orientation are the key parameters for constructability and long-term stability of the repository. The two stress models in OSD are based on hydraulic and semi-integration results and the LVDT results derived from the new developed technique. The stress models were obtained after a long series of measurements with different methods performed by different groups. Even after removing poor quality data from the large data set there is a large scatter in the magnitude and orientation of the stress data. The LVDT technique with overcoring and inversion produces more reliable data than conventional overcoring with strain gauges. It is also better suited for measurements in the inhomogeneous gneiss. Although the new development of the LVDT cell measurement gives more reliable data, the number of data points and the spatial coverage is not enough for a final stress model. The new LVDT technique has now been applied in ONKALO tunnels and niches and in Äspö Hard Rock Laboratory and seems likely to become the best method to resolve the stress problems encountered at the site at the repository level.

In an attempt to constrain the stress model, data from hydraulic stress measurements, convergence and acoustic emission, and LVDT data were integrated to derive the stress field at a large scale. However, the large scatter in re-evaluated overcoring data prevented a definite conclusion with respect to orientation of the maximum horizontal stress, leading to a wide range of orientations, striking between NW-SE to SW-NE. Using microseismic information from ONKALO tunnelling, Posiva found that tunnel orientations in a NW-SE direction produced considerably less seismic events, which favours a NW-SE orientation of the maximum horizontal stress. An attempt to correlate the hydraulic properties of the major BDZs to the stress field gives no support to the estimated orientation of the maximum horizontal stress. Also, Posiva has yet to integrate the few existing focal mechanism data into the stress analysis.

Most of the existing stress data are derived from two deep boreholes close to ONKALO and from measurements in the tunnel, shafts and niches. Stress data are lacking from the eastern part of the site. The LVDT method cannot be applied in deep boreholes, so Posiva will have to use conventional overcoring and hydraulic methods to gain data in this area. Rock stress measurements have been conducted on outcrops at the surface close to and north of ONKALO. The orientation and magnitude of the estimated stresses shows a large scatter and the data cannot be used to estimate the stress field of any part of Olkiluoto, or be applied in the integrated stress analysis.

Neither OSD 2008 nor OSD 2011 reports the sampling points for strength and deformability testing of intact rocks and fractures. All the gneiss types have the same strength and deformability and similar distribution functions. The properties of the pegmatite granite are close to those of the gneisses, with the exception of tensile strength and anisotropy. Posiva only presents data for these two rock types. Lumping together the mechanical properties for all the different gneisses finds support in the mapping results of the distribution of the Rock Mechanics Foliation number RMF (OSD, Figure 5-22), but lumping together the tensile strengths of gneisses and granites (Posiva 2012-23, Table 3-3) is not appropriate. The effect of anisotropy (foliation and folding) on strength and deformability is judged to be included within the large data variability. Also, Posiva compares rock mechanics test data for altered rock samples with fresh, unaltered samples, with minor differences of strength and deformability. Laboratory testing of altered rock samples should be repeated using another laboratory and a proper sampling method should be developed.

Conclusion: Posiva has identified the uncertainties with the stress measurements conducted with existing conventional methods of overcoring and hydraulic fracturing and has decided to develop and apply a new, alternative method to obtain reliable data. In the current reference layout of the repository at 420 m depth the deposition tunnels are oriented NW-SE, which is the most suitable orientation with respect to the recent results from applying the new LVDT overcoring technique. Posiva has not conducted stress measurements in any of the deep boreholes in the eastern part of the site area, so the data coverage is not adequate for design and safety assessment of this area. The number of mechanical tests of intact rock and fractures shows that the coverage of the data is adequate for the site area planned for disposal. However, testing of altered rocks needs to be repeated to confirm any relevant differences compared with fresh intact rocks.

1.1.5 Hydrogeological data reliability

Sources of error in the PFL measurements and their correlation to brittle structures have not been evaluated and understood to a sufficient degree, particularly with regard to the possibility of false or doubled anomalies resulting from head losses in the bypass tubing, particularly at the high hydraulic gradients encountered in pilot holes. Transmissivity values from the PFL tool play a major role in Posiva's hydrogeological modelling, which is relied upon for several key aspects of the safety assessment. Posiva's investigation and discussion of this issue (AMEC memo 2014-01-29 in response to RAI and further discussion at the DFN workshop in February 2014) have not resolved this matter. Some transmissivity values that were assessed using the PFL have been re-evaluated due to concerns about disturbance effects, primarily pumping in nearby boreholes, during the original measurements (WR 2011-65, p.37). WR 2012-99 addresses some issues, but not those stemming from high gradients in pilot holes and not all sources of error have been investigated. The potential for head losses in the PFL bypass tube to affect cross-hole hydrogeological tests as well, has been recognized (WR 2014-14, p.17), but no analysis is given of the significance.

Nearly 10% of the PFL anomalies could not readily be related to a geologically mapped fracture (OSD, p.847). Posiva includes a brief discussion of this issue in AMEC memo 2014-01-29, explaining that additional manipulations of the fracture database allowed reduction of this percentage to around 2%. An explanation of these manipulations is given in WR 2012-32.

Posiva's suggestions of reasons for these "unlinked" PFL features (as being due to cm-scale differences in core vs. borehole diameter, or exact location of the mapped fractures, or minor differences in interpretation of core fractures) are not sufficient to justify the ad hoc approach used by the Hydro-DFN modellers to build an "enhanced fracture database". This has been done by assigning orientation data to "unlinked" PFL features (OSD, p.423): e.g., by searching for any fracture within +/- 20 m of the unlinked feature. According to WR 2012-32, a window of +/- 2.0 m was used in developing the Hydro-DFN model used in safety assessment calculations, which is more reasonable but remains a doubtful area of the analysis. The resulting "enhanced fracture database" is "only used in calculation of the P_{10} values" (intensities) of fracture sets in the Hydro-DFN model. However, intensity is a key parameter and can have non-linear effects on fracture network connectivity in SFR. A further implication is that if 10% of PFL anomalies could not be assigned to mapped fractures, others have probably been assigned to the wrong fractures. These two types of error, taken together, reduce the ability to discriminate among alternative models for the spatial distribution of transmissive features.

The procedure for recognizing conductive fractures in boreholes, described in WR 2011-12 (p.11-12), may introduce some bias in favour of inflowing vs. outflowing fractures. One of the criteria is visual indication of inflow. Posiva notes that outflow cannot be observed and there are cases in which indications of flow are seen on the images, but the inflow is below the detection threshold for the PFL. This means that outflowing fractures with similarly low flow magnitudes would be omitted.

Some omissions in the FDB are also apparent, as in a few cases (WR 2011-12, p.12) there are clear indications of visible fractures in wellbore images in locations where flow was measured, but for which the FDB did not contain a record of an open fracture. If these comparatively open and visible fractures were missed, it seems likely that fractures of smaller aperture were also missed.

Conclusion: Posiva's treatment of data uncertainties is not fully systematic for hydrogeology. Uncertainties in PFL data and their correlation to brittle geological structures in boreholes are a key area where Posiva should carry out a comprehensive study. This is essential, owing to the ways this uncertainty could propagate through the complex Hydro-DFN models, as well as the proposed future use of the PFL to characterise disposal volumes and link to the RSC programme. This is a significant weakness in a key part of the hydrogeological data that needs to be resolved in the near future.

1.1.6 Geochemical data reliability

Prior to the ONKALO excavations, baseline groundwater compositions were interpreted from boreholes OL-KR1 to OL-KR13. Early samplings in 1994-5 were made from multi-packered installations. Later samplings for baseline, after 1997, were made in open boreholes using PAVE sampling equipment. Presumably, data from those samplings were affected by cross-flows, but this effect on data reliability was not assessed for the baseline at that time. Subsequently, a sample quality evaluation method was developed (Posiva 2007-05) and used to review the baseline data and some newer data, up to OL-KR28. Data judged to be potentially affected by cross-flow in open boreholes were classified as 'baseline' reliability (quantitatively reliable, B1, or qualitatively reliable, B2) or as 'time series' (T), but generally not as 'excluded' (E). The baseline data set thus includes samples for which cross-flow has caused a greater or lower degree of unreliability, reflected in the B1 or B2 classification.

Hydrochemical data used for interpretations in the OSD comprise the baseline data set plus data from subsequent boreholes and monitoring in multilevel installations in boreholes that had previously been left open for varying durations. The reliability of new samples and data has been assessed in the annual monitoring reports (WRs 2007-51, 2008-24, 2009-44, 2010-44, 2011-44, 2012-44). Most of the data with B1, B2 or T classifications have been used for interpretation. The relative magnitudes of uncertainty cannot be identified. It is not clear whether all data (except 'E') have been used with equal weight in the interpretations, with a possibility that interpretations have thus been biased by the less reliable samples.

Additional sample quality issues need to be taken into account for assessing reliability of isotopic and dissolved gas data for interpreting groundwater ages. Water samples for ^{14}C are particularly susceptible to sampling and handling artefacts that would have a significant impact on the reliability of interpreted ages, biasing them to ages that are too low. Posiva infers that samples of brackish groundwaters with >25 pmC ^{14}C must have suffered CO_2 exchange with air during sampling, and consequently discount these (OSD, p 610). Culling data in this way has the possibility of discounting a groundwater that has a genuine ^{14}C anomaly because of deep penetration of young water, for example along one of the highly transmissive HZs. Though this seems unlikely, data QC should not be subjective in this way, introducing a bias against detection of deep infiltration of young water.

DOC concentrations increase below 300-400 m depth, from values that are invariably <10 mg/L in fresh/brackish-HCO_3 and brackish-SO_4 waters above 300 m, to values that are mostly 10-20 mg/L in saline groundwaters. These analyses include dissolved hydrocarbons (predominantly CH_4) so the abundance of non-hydrocarbon component of DOC is not known. Posiva extrapolates a presumed trend of constant low concentrations of non-hydrocarbon DOC from 300 m depth downwards. This issue is relevant to the safety case because DOC may play a key role in redox and in reduction of SO_4 to HS^-, specifically as an energy source for microbes. Posiva suggests that the energy sources for microbial reduction of SO_4 might change from DOC in the upper part of the system with higher SO_4, to CH_4 in the deeper lower-SO_4 part of the system, at and below repository depth (OSD, p.608). For the safety case, it is necessary to understand how the balance in this redox system might be perturbed in the future.

Data reliability classification is not used in the MDR. Quality assurance procedures have been used for models and data (Section 2.3) although these are not formal. The qualification of data has been done in a reasonable way by discussing the sources of uncertainties and by prioritising the procedure in terms of impacts on safety. However, the uncertainties and other issues of data reliability should be systematically tabulated alongside the data values in Appendix I. The MDR has *"an important purpose … to bring forward QA aspects of the models and data handling process"* (p.597). This has not been done.

Conclusion: Generally, the geochemical data used to interpret the groundwater system can be regarded as reliable, although the accounting of data quality and uncertainties is difficult to trace.

1.1.7 Data on the geosphere-biosphere interface

Information on surficial deposits comes from various independent studies (OSD Section 3.3). Work has been underway since 2009 to collect all available data and to identify gaps, but has not yet been reported in detail. Acoustic-seismic soundings have been carried out to map the unconsolidated sediment layer and bedrock surface. Hydraulic properties (saturated hydraulic conductivity and soil water retention curve parameters) of the surficial deposits have been estimated for different facies by calibration to slug tests. OSD notes that systematic overburden mapping has not been carried out, but all available data have been collected for input to a new biosphere model. **Note: the biosphere is not covered by this review.**

A key aspect for the current review is the hydraulic connection with the bedrock, which has been modelled in some detail in OSD and is well understood. The present-day arrangement of surface deposits (along with uncertainty in their properties; OSD p.870) affects the coupling between the hydrological boundary conditions at the surface (sea level, meteoric precipitation etc.) and recharge to the bedrock. Since this recharge is estimated by calibration of the surface hydrological model (described in WR 2011-50), this ultimately affects the reliability of the bedrock hydrogeological models. According to Posiva 2012-30 (p.25), detailed soil thickness data for Olkiluoto are now available from the 'UNTAMO' geographical information system toolbox. The updated soil thickness map is used in the Hydro-DFN modelling for safety assessment (WR 2012-42, p.22-23).

The uncertainty in overburden properties is partly addressed by the infiltration experiment, investigating groundwater recharge to HZ19. Although this experiment was local in nature, it focuses on the surface trace of a HZ that is interpreted as having a strong influence on the bedrock hydrogeological conditions at repository depth, so it tests a key aspect of surface-bedrock coupling. The hydraulic head and groundwater level data from the infiltration experiment are used as a test case for the surface/near-surface hydrological model in Posiva 2012-30 (p.74-78). Reasonably good agreement is obtained, although there appear to have been difficulties in matching the magnitudes of drawdown for some pumping cycles.

Discharge estimates in the upper tens of metres of the rock show it to be occurring mainly offshore. However, there are some key uncertainties in the hydrology model that were not possible to evaluate by sensitivity analysis or proxy evidence (OSD, p.104). Generally, OSD's surface hydrology description lacks interpretation, or presentation as a dynamic system.

A substantial number of samples is available from shallow groundwaters in the overburden and shallow bedrock, from observation tubes and shallow boreholes. Sampling and analytical procedures were carried out to the same standards as for deep boreholes. Quality review and classifications are documented in Posiva 2007-05 and the data are judged to be adequate.

Conclusion: While the data on superficial deposits, hydrology, soil chemistry and ecosystems appear adequate for the purposes of the CLA, it is hard to get an impression of how the surface environment behaves and what the drivers are. Interaction between the surface deposits and the bedrock is a critical factor in controlling the Hydro-DFN results. Nevertheless, comparisons between the surface/near-surface model and the infiltration experiment in HZ19 show reasonable agreement, suggesting that the model is adequate for describing surface-subsurface coupling.

1.2 Bedrock characterisation at site and repository scales

This Section considers the bedrock mechanical and thermal properties, and the nature of fracturing at site and repository scales.

1.2.1 Documentation of structural data

During the site and repository scale investigations, Posiva has collected an extensive data set comprising structural elements characterising the products of both ductile and brittle deformation events. The level of detail in structural investigations and in the documentation of structural data is not great, which means that confidence in the general structural framework of the site that has been constructed is not optimal. This has led to poor correlations between the patterns of ductile and brittle deformation structures and interpreted lineaments, which then means that the full capacity of the structural data set cannot be applied in other areas of research and evaluation conducted at the site (see also Section 1.2.3). In contrast to the site-scale structural synthesis, the ongoing development of the RSC and work by Engström (WR 2013-62) has shown appropriate practises in recording and documenting structural data (e.g. constraints on fracture terminations).

Evaluation of uncertainty in structural models is based on expert judgements on the scientific credibility of the conceptual models and could be decreased by providing alternative conceptual models whose applicability could be systematically evaluated. Since no alternatives (or any schematic models, for example, on ductile evolution) have been presented, there is a risk that observations will be forced to fit the generally agreed model and the potential for developments in understanding the geology of the site are reduced.

The level of uncertainty in structural data may be considered low, but uncertainty in the structural models is higher. Uncertainty in the spatial model of ductile deformation zones, which are the most significant components of the ductile model, is considered low. Due to the discontinuous nature of the brittle structures, uncertainty in the brittle structural model is higher than uncertainty in the ductile model. However, the data are sufficiently dense that the uncertainty may be considered moderate.

Conclusion: Posiva should improve the synthesis of ductile structure and the data presentation, allowing better correlation between different data sets. This should lead to a more holistic understanding of the ductile and brittle structural geometries and their mutual relationships. Proposed improvements include:

i) compilation of structural form line maps of ductile foliation from the ground surface level and at 50m depth intervals, similar to the presentation of brittle structures in WR 2010-10, Appendix XI;

ii) compilation of structural cross-sections with ductile foliation in a similar way to the level maps;

iii) structural analysis, including analysis of orientations and orientation distributions on stereographic projections, to understand the spatial variations in attitude (dip and strike) of the main foliation, as observed from the form line level maps and vertical cross-sections. Understanding of local-scale structures and their geometries (e.g. deflections into shear zones: see WR2013-62), can be used as proxies for understanding site-scale geometries;

iv) these results could be used to evaluate the validity of the brittle structural model and as appropriate input data for further Geo-DFN modelling.

1.2.2 Site-scale fracture zone (BFZ) models

At the large scale, there is no alternative geological model presented in OSD (see p.872), nor an alternative to the large-scale hydro-structural model. If Posiva had been able to present a schematic model of the structural evolution it would clarify the linkage between the geometry and the kinematics of both ductile and brittle fracture zones and could be used in providing hypotheses on the occurrence of brittle structures. Constraining the kinematics of the ductile events would require improvements in the site-scale structural analysis (see Section 1.2.1), including kinematic understanding of the major ductile deformation zones. The latter could be achieved by collecting lineation data, so that the zones could be classified into strike-slip, dip-slip or oblique slip zones.

The 'thickness' of the model is only 1000 m, making extensive fracture zones appear as fences. This may not be satisfactory for evaluating a number of deep processes/interactions, but has to be accepted at this stage, as almost no data exist at greater depth. Seismic reflection data presented at the March 2014 EQ workshop indicate that major BFZs are likely to be listric, curving from sub-vertical to sub-horizontal, even in the upper 2 km of the bedrock. We note that the connection between the ductile and the brittle structures has been treated superficially and is poorly documented. Also, the systematic use of foliation data in modelling lithology has not been documented, or might not have been carried out. This would have increased understanding and provided more realistic lithological models, as well as alternative models on the 3D-continuation of the lithological units.

There seem to be limited and acceptable uncertainties with respect to the locations of the major fracture zones, although their length, connectivity and behaviour at depth (particularly of the sub-vertical zones) is based on significant speculation. BFZs are only included in the geological model if they can be correlated among multiple boreholes and/or with surface lineaments. Their extent is curtailed in regions with little data. This approach is credible, although the nature of the bounding lineaments remains uncertain (at least two may be inclined rather than sub-vertical). At the largest scale, Posiva states (OSD p.411) that knowledge of the locations and orientations of site bounding lineaments is not considered important as they simply offer possible connections between site-scale zones. This is supported by one of the Hydro-DFN variant calculation results (WR 2012-42), where stochastic HZs are placed outside the 'well characterised area'.

Speculative BFZs and extensions of confirmed BFZs are not included in the model, but certain types of interpretation bias are introduced that propagate to other models. For example, highly fractured sections in one borehole that do not correlate clearly with similar sections in other boreholes must be accounted for in the Geo-DFN instead, where their radius is limited to about 564 m. In the site-scale hydrostructural model, this minimalistic approach might result in fewer and more tortuous connections among site-scale BFZs than exist in reality, requiring transmissivities of these features to be increased in order to improve the match to cross-hole hydraulic response data.

Lateral extent of BFZs outside the central part of the island is discussed as an uncertainty (OSD p.865) but no significant alternative interpretation is offered, despite high uncertainty for the eastern area in particular (p.874-5); Posiva's view is that it is better to wait for additional data from this area than to develop alternative structural interpretations.

The ability of the geological model to predict BFZ intersections with tunnels in ONKALO has not been impressive. Of 40 BFZs encountered in chainage 990-3116, only four correlate to predicted intersections (OSD p.758-760). Posiva suggests that many of these zones are most likely small-scale deformation zones (smaller than the 1 km scale considered in the deterministic model). This explanation is plausible, but it is not the only possibility.

The frequency of steep N-S zones (observed in ONKALO) is underestimated by borehole investigations (OSD p.228), although geophysical surveys give more information. Posiva views these zones as usually much less transmissive than the gently-dipping HZs. Posiva's plan to adapt to these as they are detected in tunnel-based exploration is reasonable as a practical engineering solution, but leaves the question of how their models are affected by the likely omission of many of these structures. The possibility that local-scale sub-vertical faults may be missed by surface-based drilling programme is recognized (OSD p.865).

Posiva's approach to describing BFZs in terms of a fault core and influence zones (IZs) is in line with current accepted practice in structural geology. The internal characteristics of BFZs need to be understood further and Posiva recognizes the difficulty due to heterogeneity along a fault zone. The scale of natural variability of deformation zones is discussed under issue I21 (OSD p.860). Variations in thickness of the cores and IZs are discussed, but not how these vary as a function of distance along a given deformation zone. The LDF report recognizes this variation and takes a reasonable approach to evaluating it in consideration of the possibility of a diffuse, transitional boundary between BFZs and the country rock. The thickness variations of the LDF zones are attributed solely to progressively decreasing displacements from the fault origin towards the tip lines, with both the greatest displacements and influence zone thicknesses observed in the central parts of the faults. Random testing of the hypothesis in this STUK review shows that this hypothesis is valid in some cases, but it is probably more common to find that the thickest portions of the fault zones occur along the intersections with other brittle deformation zones. A further alternative for the fault IZ thickness variations is that they are linked to the changes in the fault plane geometry, with the greatest IZ thicknesses spatially related to the bends of the fault zones. By further investigating the fracture populations and their orientations in the fault bends (domains of thick IZs), the bends could be classified as constraining or releasing bends and the overall kinematic understanding of faults and fault systems could be improved. The issue of IZs, their relation to alteration and to layout planning is important and we discuss this further in Section 2.4.4.

At present, Posiva has taken a conservative approach by classifying BFZs mechanically according to their weakest regions (OSD p.303). The mechanical and stress modelling has shown that there is a problem in determining the relevant stiffness (deformability) and strength of the BFZs from the ONKALO tunnel mapping to match the recorded magnitude and orientation of the rock stresses (WR 2011-34). Posiva needs to resolve this problem in order to obtain relevant results from mechanical and stress modelling.

Conclusion: The site-scale brittle deformation model is credible but only represents one possible interpretation and its relation to the geological evolution of the site remains unexplained. The consequences of alternative interpretations should be considered. The treatment of BFZ internal structure in terms of fault core and IZs is scientifically credible. However, the variations of the IZ thicknesses need to be considered with respect to intersecting fault zones and geometry changes in the deformation structures. The LDF and RSC reports present well-reasoned procedures for taking heterogeneity of these characteristics along BFZs into account, as new information becomes available from pilot holes and excavations. Propagation of the consequences of this heterogeneity to the hydrogeological models has been done in a reasonable and defensible way. However, a STUK requirement should be to ensure that all major zones lying within the repository depth interval (e.g. 450 +/- 150 m) are properly located and mapped by drilling and geophysics as construction proceeds. This should be extended to include characterisation of internal mechanical and hydraulic characteristics of BFZs, the size and nature of their IZs and their influence on the stress model. Care needs to be taken with respect to saline waters upconing in deep drill holes. Conditions should be attached with respect to characterising structures and rock stresses in the eastern area.

1.2.3 Repository-scale fracturing

The Geo-DFN model development described in the OSD has apparently been separate from the other modelling activities, which has caused problems for its credibility and applicability in site characterisation and planning. These are outlined below:

i) Reasonable alternative definitions of the orientation sets were not explored; “hard-sectoring” behind the subdivision of fractures into orientation sets is not shown (although the method is manual and the interpretations should, therefore, be visually documented).

ii) The focus in at least the orientation aspect of the fractures is not optimal. Even though the same modelling principles for Precambrian crystalline rocks have been applied widely in the Nordic countries, here, a set of methods used in (for example) oil exploration in low/non-metamorphic rocks has been applied and given lengthy method descriptions (e.g., foliation wander diagrams). Understanding foliation patterns with respect to ductile tectonic evolution (regional folding and deflections into shear zones) and as a function of depth, would have deserved more focus. The potential for doing this is reduced owing to the unsystematic structural analysis, which lacks proper foliation form line maps from different elevation levels.

iii) The spatial scaling of the modelling is not in line with its end-use in the RSC work. The modelling (specifically, the update from Geo-DFN 1.0 to 2.0) was conducted with the aim of increasing predictability of occurrence of fractures outside the better-known areas of Olkiluoto Island. In contrast to this intended use, the fracture sets and their characteristics are also used as input parameters in the Panel Calculator to evaluate rock suitability at the scale of disposal panels – a much more detailed scale with respect to the scale of the DFN.

iv) Balance between the orientation sets: much effort is put into characterising the Liikla Shear Zone (LSZ) fracture populations, with three out of the total four “local” sets derived from the LSZ, although the zone is rather limited in size. The general role of deformation zones in defining fracture domains is unclear, since (ductile) deformation zone LSZ has been used in modelling, although *“fractures within deformation zones are to be excluded”*. The deformation zones in the Geo-DFN report refer to brittle zones but, since many of the ductile zones are known to be composite zones that also have brittle fracturing, the reasoning in selecting the fracture domains is not fully clear.

v) Understanding foliation-control on fracturing is an essential finding, but the subdivision of the site into fracture domains should have utilized the depth-dependency of changes in foliation attitudes; the fracture domains in the current model show very similar fracture distributions, as acknowledged in the report. It would have been justified to merge these domains and study the depth-dependency of foliation vs. fracturing in more detail and subdivide the fracture domains accordingly.

vi) Fracture size data: only two outcrops with the desired data quality and thematic coverage have been used in the DFN work and both are located in the central parts of the study area. Such sampling cannot be considered representative and leads to uncertainties in the fracture size models, e.g., in the selection of TCM or OSM size models for the fractures. Since size is coupled with intensity, such uncertainty is significant for all subsequent applications of the DFN.

vii) Lineament data: Since lineaments are interpreted manually, the results are unavoidably subjective. This will affect not only the interpretation of the fracture location and orientation but also the fracture scaling in the DFN. Evaluation of uncertainties should address the uncertainties arising from the manual lineament interpretation and future DFN work should utilise the uncertainty classification within the most recent lineament model.

The scientific basis for developing the Geo-DFN model is overstated in some places. For example, *"success in Sweden"* regarding Tectonic Continuum Model (TCM) variants of the DFN model (OSD p.215 and 219) is not a scientific argument and valid questions remain about the Geo-DFN models: e.g., the Geo-DFN for Forsmark did not reproduce lateral connectivity, so adjustment was necessary in the Hydro-DFN; alternative models were not fully explored; the Geo-DFN as defined was not actually implemented in the Hydro-DFN modelling. Furthermore, the "similar" geology is not similar from the viewpoint of rock mechanics: practically all the rocks at Forsmark are intrusive in origin and hence mechanically isotropic, whereas the Olkiluoto supracrustal rocks have primary anisotropies (bedding). The practicality of the TCM for downstream users seems a key factor. Whether it produces *"acceptable fits"* is arguable; they are usually only good for scales from one to a few meters, while the model is supposed to describe scales from a few cm to nearly 1 km (OSD p.215).

The Geo-DFN model presented in OSD is complex in comparison with most previous applications to crystalline rock. Over-fitting to a dataset that is large, but limited in terms of orientations and volumes sampled, may cause the model to mask actual variability due to, for example, structural characteristics not represented in the stochastic geometry models considered. The adaptation of the complex Geo-DFN for Hydro-DFN modelling shows numerous simplifications.

Fracture domains have been assessed with respect to variability of orientation. Posiva notes that size distribution is more important for safety-related calculations. Evidence of statistical homogeneity of fracture size/extent within fracture domains is lacking. Fracture intensity is modelled as varying in space; this allows better fits of the model but may mask structure-related variability. Simulations of variable fracture intensity (P_{32}) using a gamma distribution are recommended (OSD p.219) but it appears not to have been followed in the Hydro-DFN adaptation of this Geo-DFN model. Fracture intensity is not modelled as depth-dependent for most sets, which is reasonable on geological grounds, apart from a limited zone of near-surface sheet jointing. However, a contrary supposition is raised in justifying a depth trend in the Hydro-DFN model (OSD p.412). Trends shown in histograms to support a depth trend for the Hydro-DFN model (Figure 6-32) are not convincing; the top four 50-m intervals in terms of $P_{10,corr}$ occur from -450 m to -700 m. For transmissive fractures, a decreasing trend with depth is more intuitive (due to the effect of confining stress on fracture closure), and also better supported by the data (Figure 6-33).

WR 2012-32 also shows the extremely poor fitted depth v. transmissivity trends for the HZs (Figures 3-14 to 3-21), but this is not commented upon. Perhaps there is no significant decrease in T with depth in the larger HZs. The Hydro-DFN Phase III review of head data for the palaeohydrogeology work suggested heterogeneous hydraulic properties within both the HZs and between them (WR 2012-32, p.272) and the importance of heterogeneity as a key uncertainty in the palaeohydrogeology model that has not been tested is identified on p.318. WR 2012-42 has looked (p.93) at the impact on flow of assuming that a variant case with additional hydrogeological zones outside the well-characterised area (which, they suggest would be a better base case), but the results of the overall Hydro-DFN release and transport analyses are unaffected by their inclusion.

Conceptual uncertainties in the Geo-DFN model may include other alternatives to those considered for the fracture size model. Fracture size/extent is correctly recognized as a major uncertainty, especially for the range 20 m to 564.2 m, which is considered as the MDZ size range. Size-scaling data are not available for all fracture domains. Posiva correctly recognizes that significant reduction of uncertainty is unlikely without data from additional outcrops (for poorly characterized domains) and/or at larger (MDZ) scales.

Fracture terminations against other fractures (e.g. OSD Figure 5-49) are discussed with regard to rock mechanics but not the Geo-DFN or Hydro-DFN models. An attempt was made in the Geo-DFN to include terminations, but it failed due to lack of suitable data. Terminations have been considered in the recent RSC but, so far, not linked to kinematic understanding of fracture systems. Fracture termination can affect connectivity for a given size distribution. Significant termination percentages for deeper chainages are evident.

DFN prediction/outcome results are presented (OSD p.760-766) in terms of fracture orientation and occurrence or non-occurrence of particular fracture sets defined by their dominant orientations. As noted in the Geo-DFN and Hydro-DFN model presentations, sensitivity of safety to fracture orientation is very limited (mainly an issue for tunnel stability and rock-bolting reinforcement). In order to make more robust comparisons in terms of factors that actually matter for long-term safety, Posiva should give predictions of fracture intensity and fracture spacing (mean values, variability, and spatial correlation) and fracture trace length distributions (as a measure of fracture size/extent models).

Conclusion: The Geo-DFN model, which is used to represent minor deformation zones on scales less than 1 km, is poorly linked to geology and is highly complex, leading to questions as to whether it adequately represents the key features of fracturing at the site, particularly on larger and repository panel scales. To date, prediction/outcome exercises in ONKALO have only looked at fracture orientation, which is one of the least critical properties of the Geo-DFN, and even these comparisons have only been in terms of occurrence/non-occurrence of particular fracture sets. STUK should ask Posiva to include more rigorous measures (fracture intensity and trace-length distributions) as part of ongoing prediction/outcome studies, to ensure that aspects of the Geo-DFN that are more significant for safety assessment are being tested. From the DFN workshop in February 2014, it was clear that Posiva does not have robust plans for prediction and correction exercises regarding the DFN models. The Geo-DFN model would need to be revised to be of use in the RSC-work (Panel Calculator).

1.2.4 Rock thermal properties and thermal load on the rock

The thermal block model was created during the development of the ONKALO Rock Mechanics Model (RMM), starting in 2009 with Version 1.0 (Posiva WR 2009-55) and continuing to the most recent Version 2.3 (Posiva WR 2014-33). Posiva uses the 3-D lithological model GSM 2.0 and later versions and default values of thermal conductivity for each of the main rock types, with the orientation of foliation included for each block of the model. The data used are valid over the depth range 350 – 550 m. Above 350 m, the blocks in the RMM model assume material properties corresponding to veined gneiss. For the detailed repository design and thermal calculations, Posiva will have to fill this gap with measurements of real thermal properties.

Posiva acknowledge (OSD p.849) that they do not have detailed knowledge on thermal anisotropy at the critical, deposition hole and tunnel scales – only on laboratory specimens. This is a drawback for their operational and spatial economy work. The report on thermal dimensioning (WR-2012-56) addresses variability in thermal conductivity by applying a 5 °C safety margin in the maximum allowable temperature. The rationale and derivation of the value seems reasonable. This report uses a generally conservative approach. Nevertheless, the base case model uses average thermal properties of the rock rather than exploring the spatial implications of, for example, using a stochastic distribution of rock conductivities, as did SKB. Posiva notes (OSD p.329) that *"the [thermal conductivity] sample database is still too limited for an extensive geostatistical analysis"*, but give reasonable suggestions for potential proxy variables that could be investigated based on the understanding of the lithology, together with the thermal properties of the most common minerals. In the most recent version of the RMM (Version 2.3, Posiva WR 2014-33), Posiva presents the thermal properties and rock densities of the RMM model from the existing thermal data base and displays discrete values with a newly developed display profile tool. The RMM model is created with GEOVIA Surpac commercial software, which has a powerful geostatistical software package that would allow Posiva to apply a probabilistic approach.

The thermal studies performed by SKB at Forsmark and Laxemar indicated that the lower tail of the thermal conductivity distribution is of utmost importance in deciding canister spacing in the deposition tunnel. At Olkiluoto, the migmatitic structures of the gneisses cause large variability in the thermal parameters. If Posiva decides to use a mean value of the thermal parameters for each of the different gneisses, the value will not be applicable for some canister locations (e.g. a gneiss with low thermal conductivity) and the maximum temperature in the compacted bentonite buffer could be exceeded.

One uncertainty that is not covered by the content of WR-2012-56 is the possibility that the pellet gap between buffer and rock might be unevenly filled, or even have patchy voids, if QA is inadequate. In this case, the data (p.49) suggest that temperatures could rise above the 5 C safety margin. The report does not look at spacing issues for high burn-up fuel (>50 GWd/t), which seem likely eventually to be part of the inventory. Given the large canister spacings already required for lower burn-up EPR fuel (10 to 11 m), this will create a space issue.

Several devices and interpretation methods have been developed by Posiva in cooperation with the Finnish Geological Survey for determination of thermal properties in-situ in slim boreholes. Devices TERO56 and TERO76 comprise tools for both 56 and 76 mm diameter boreholes and allow logging down to 500 m depth. Experience with the two tools and an overview of the methods for interpreting logging data are presented in Posiva 2013-06.

Posiva has tested the new TERO76 device for estimating thermal conductivity and diffusivity from logging in four shallow vertical boreholes in DT 2 (Posiva WR 2013-3 6). The thermal properties of the rock mass are estimated by using both a numerical optimization method and an analytical method based on the theory of heat conduction of an infinite line source. The thermal conductivity can be determined directly from the measurements in the field. Thermal diffusivity can be determined indirectly by using the specific heat capacity and density of the rock type. Results from measurements in the short boreholes in the floor of DT 2 show good agreement in the variation of estimated values for conductivity and diffusivity with depth. The analytical values (3.19–3.99 $Wm^{-1}K^{-1}$) are on average about 10 % lower than the numerical values. A compilation of thermal data from laboratory testing of almost 400 samples from Olkiluoto gives an average conductivity of 2.91 $Wm^{-1}K^{-1}$ with a standard deviation of 0.51. The higher value of conductivity for measurements with the TERO76 device is due to the anisotropy of the gneiss. The device measures conductivity from heating in the radial direction in the borehole, so any rock anisotropy with an inclination relative to the borehole axis will change the thermal properties. The report advocates application of TERO76, as the method measures over a larger volume of rock compared with laboratory measurements on small rock samples.

Posiva has to make a decision about what data to be used as thermal parameters for the design of the repository. The thermal conductivity data from laboratory measurements are typically lower than the values determined by the TERO devices and theoretical determination of the properties from the mineral composition is difficult for the inhomogeneous gneisses. One way of resolving this problem can be to apply the existing field and laboratory methods for extracting thermal properties of the rock mass from a heater experiment in conjunction with thermal and thermo-mechanical modelling. If no heater experiment will be conducted in a near future in ONKALO, Posiva could be recommended to use the POSE experiment in the rock mechanics niche to increase knowledge about the thermal data to be used in the design work. The variability of thermal conductivity and diffusivity can be determined from a set of new boreholes drilled around the large boreholes and related to the orientation of the mapped schistosity in the boreholes. Anisotropy data can be fed into the rock mechanics modelling tool and the calculated temperature versus time correlated with the measured temperature for the given virgin stress field and heat input to the heaters.

Conclusion: Rock thermal properties, along with many other aspects of thermal dimensioning, will be an important matter for STUK to track, as they have a major influence on space, so Posiva's decision-making procedures for this critical aspect will need to be monitored closely, in particular the selection of thermal input data for design. For the CLA, however, this does not seem to be an issue, provided some of the points above do not affect overall spatial viability. The SDR points out that Posiva has allowed a 20% space margin in the layout, but this does not seem over-generous, given the acknowledged uncertainties in the location of the layout-determining features and the properties of the rock adjacent to them.

1.2.5 Basis for rock mechanics and thermal modelling

The Rock Mechanics Model (RMM) is used to predict the rock quality and the potential for stress-induced rock damage in the repository. The RMM is based on the geological model and its rock type domains and contains the rock mass classification data (Q-system and RMR) from boreholes, pilot holes, tunnels and laboratory data. Data on BFZs are included in RMM v.2, which gives a clear and concise picture of the increase in quality and strength of the rock mass with depth from applying the Geological Strength Index (GSI) calculated from the Q´-index (OSD, Figure 5-88). The RMM will be used for design of the repository tunnels and rock chambers. Geophysical and hydrogeological data have been used for calibration of the RMM.

Posiva has not attempted to get spatially comprehensive coverage from rock cores, so the model is based on extrapolation and interpolation and geophysical data (OSD p.252). There is considerable variability in properties owing to heterogeneity in rock types and foliation, and the core data show that some lower strength rocks exist at depth in the repository volume (e.g. Fig. 5-29), although this does not show up in the 3-D RMM (Fig. 5-88). OSD notes (p.307) that it is not possible to interpolate rock property data in tunnels for more than 40-50 m. Fig 5-15 (Posiva 2102-23) suggests that rock properties can be predicted reliably to a distance of 10 to 15 m. Also, geophysical data were not definitive enough to be used in constructing the RMM (OSD, p.339). Owing to the variability, Posiva draws no conclusions from the analysis (p.268) and simply presents information such as RQD as a function of location (e.g. tunnel chainage) rather than lithology. There is not a clear description of how Posiva correlates rock properties with lithology and fracture intensity zones, although OSD (p.342) says that lithology has been used in developing the RMM sub-models. Nevertheless, we regard the results of the RMM on assigned rock types, estimated RQD, GSI and rock stresses versus depth for Olkiluoto and the ONKALO tunnel to be generally credible.

In the most recent version of RMM, Version 2.3 (Posiva WR 2014-33) the values of individual parameters are stored in block model attributes that can be filled in by the existing raw data or by assessing values based on statistical information or interpretation. Thermal properties are assigned to block models based on the geological model of the blocks. The values of GSI, RQD and peak strength of the rock are estimated for the block model using an inverse distance method. The information about BFZs and their influence zones are treated as separate blocks. It is not clear from the description in Version 2.3 of RMM how the BFZ domains or blocks are treated, compared to the parameter domains outside the BFZs. The steps in development of block model estimation for GSI, RQD and rock strength are clear and well defined and tested. The next RMM version will be 3.0 and Posiva describes about a dozen new features that will be included, e.g., integrating DFN, hydrogeological information, information from grouting holes, P-wave velocity and other geophysical data. The coming version of the RMM has the potential to become a valuable tool in the engineering design and construction of the repository.

As discussed in Section 1.6.2 of this review, the strength and deformability of large rock discontinuities (major BFZs) is important to the safety case in the operational and immediate post-closure ‘thermal’ period, as well as with respect to seismic hazard. Definition and determination of these properties are difficult problems in rock mechanics and rock engineering, owing to the large variability of the dimension, geometry, orientation, persistence, rock material, strength and deformability and the fact that the mechanical properties cannot be tested. The RMM characterised 24 BFZs, of which 18 are located inside the RMM area. Posiva uses the Rocore program system to obtain parameters for strength, Mohr-Coulomb Fit friction angle and cohesion of the BFZs. Comparison with stress modelling in WR 2011-34 suggests that the OSD parameters of Mohr-Coulomb Fit are too high. It might be that the results from the empirical relations in Rocore are not applicable to the BFZs at Olkiluoto. OSD Section 11.7 admits that further advances need to be made in determining the rock stress and rock strength regimes for establishing the rock mass stability at repository depths. If future rock mechanics modelling of long-term stability indicates stable conditions for selected strength and deformability parameters according to Posiva’s approach, the additional loading during the thermal phase might exceed the rock mass strength, which can lead to large-scale deformation of BFZs and instability.

The geological and mechanical properties of the deformation zones are also presented in Section 3.3 of the Site Engineering Report (SER): Posiva 2012-23. Posiva describes how the strength and deformability of the BDZs were estimated using RocLab software based on the equations of the Hoek-Brown failure criterion. SER Table 3-5 presents the range of deformation modulus and compressive strength for brittle deformation zones and rock mass. The results of the comparison with stress modelling in WR 2011-34 are not presented. The comparison suggests that the OSD parameters of Mohr-Coulomb Fit (friction angle and cohesion) using RocLab are too high. Posiva has to resolve the discrepancies between calculated parameters from tunnel mapping and 3DEC stress modelling. It might be that the results from the empirical relations in Rocore are not applicable to the BFZs at Olkiluoto.

SER, Section 3.4.3, notes that work on the new disposal panel layout is on-going and is meant to be used in the rock reinforcement design. The input parameters for rock temperature and thermal stress evolution are presented in Table 3-7 of SER. For the in-situ stress field Posiva uses the maximum value of the principal horizontal stress at repository level (Section 3.5). For the intermediate and least principal stress, corresponding to the least horizontal and vertical stress, Posiva uses the recommended mean value as stated in Section 3.5, without giving an explanation.

Temperature increase from ventilation and the related thermal stresses have been estimated for the first time in the SER. The heat load from ventilation can cause an additional thermal stress at the periphery of the lower sections of the shaft of the order of up to 4 MPa. The additional thermal stress will be superimposed on the thermal stress from the spent fuel and the virgin stress and, according to Posiva, the stresses from the ventilation develop early, from the start of operation of the repository. Posiva will probably consider the temperature and related stress increase from ventilation for the transport tunnels in the centre of each panel.

For the stability analysis of the ONKALO access ramp, Posiva applied a linear elastic boundary element code to analyse stress distribution around the openings. Thereafter, Posiva has applied a probabilistic method to calculate the rock mass deformability and strength and compared the calculated stress distribution with the stochastic strength result. The ratio between strength and stress determines whether the tunnel section is stable. The stability of the access ramp is important as an indicator of the stability of the deposition tunnels and excavations in the central area of the anticipated repository.

The rock mechanics prediction-outcome work and the predictions of spalling have concentrated around the POSE experiment, at a depth of 345 m. This aims specifically to evaluate the excavation and thermal stability of DHs. These results and the early thermo-mechanical evolution of DHs are discussed later in this review (Section 1.7.3).

Conclusion: The basis for combined rock mechanics and thermal modelling is established and credible, but its application to large BFZs is at an early stage of development and this represents a significant input to understanding the large-scale response of the rock mass to thermal and seismic loads. The first version of the RRM came out in 2009 and version 2.3 is dated July 2014. With inclusion of the additional options and new data planned in the near future for version 3.0, the RMM has the potential to become a valuable tool in the engineering design and construction of the repository.

1.2.6 Evidence for neotectonic activity at the site

The main data on faults are in WR 2010-70, with the source report being WR 2009-130, but neither specifically addresses neotectonics. Fault gouge minerals exist, but only limited evidence is presented on dating fault movements. The maximum ages are constrained, but there is little to ascertain whether there has been any Quaternary (neotectonic) shear. Younger mineralisation includes calcite, with a youngest date of 130,000 years, based on work carried out in 1992. Posiva's neotectonic studies (e.g. Posiva 2012-34) focus on regional seismology and the potential for movement of the mapped BFZs, rather than on evidence for there having been any Quaternary movement on any of these fault zones. It also has to be recognised that the faults evaluated have necessarily been near-surface and there has been little geophysical characterisation work on deeper fault structure beneath the site that could be linked to these studies.

LIDAR surveying is currently proving a powerful technique to identify, locate and help establish the age of post-glacial fault movement. A nationwide LIDAR survey is being carried out by the Geological Survey of Finland, which involves Posiva. This is extremely encouraging in terms of getting the best available large-scale but high-resolution data on neotectonics over the next few years. It is important to note that the observations of possible post-glacial fault movement of around 2 m on BFZs immediately offshore of Olkiluoto Island[1] seem not to have been discussed in Posiva's documentation, indicating that evidence of neotectonics has not been thoroughly compiled.

A programme of GPS strain measurements has been underway using fixed stations, since 1995 and is combined with levelling and microseismic data (OSD p.334). However, no information has been generated yet that can be interpreted unequivocally as deformation across major fracture zones (and thus tied to possible neotectonic responses). Some possible ONKALO excavation responses are postulated. The period of observation is too short to be useful yet, but is improving and recently deployed techniques provide better data over shorter periods (WR 2013-16 and 2013-63). WR 2013-69 covers the results of precise levelling measurements, which are carried out every 4 years. The information presented in all of these reports is not interpreted in terms of geological factors and cannot be used at present. Posiva does not speculate on how long a programme of measurements will be required before meaningful interpretations can be made. The only indications that can currently be drawn from the reporting is that differential strain is occurring within Olkiluoto Island, which is in 'a subsidence area'.

The NORSAR review of Posiva's earthquake scenario approach observes that the GPS baselines are short, so that any relative station velocity may appear as a relatively large strain rate: relative station velocities are thus more likely to reflect site instabilities rather than tectonics. If this is the case, the network needs to be larger, with regional dimensions. One such network is installed in NW Norway and seems to give reasonably stable results, even after only a few years. This highlights the problems with missing regional and national GPS networks (beyond BIFROST) in Finland.

The NORSAR review also comments that GPS-based strain rates could eventually be converted to earthquake moment and magnitude rates, but the review was not able to identify any study that derives a strain rate based on the entire Finnish GPS network, which would be of great interest.

Conclusion: Neotectonics seems to be an area where there are no useful data based on actual observations of structures rather than on seismological modelling. This is a weakness of the site characterisation work and STUK should request that all the data currently arising (including GPS, LIDAR) are compiled with existing observations (e.g. offshore seismic profiling) in the frame of a DEM to evaluate whether there is any direct evidence of possible late Pleistocene or Holocene movements on the large BFZs in the Olkiluoto area. Posiva should be encouraged to consider extending its GPS network to a more regional scale and participating in any programmes to improve the national GPS station framework. For example, the local GPS network should be tied to the national one (possibly also using older geodetic data), in a search for significant differential motions that extends outside the very small site region. STUK should clarify Posiva's intentions over using the GPS and levelling data to abstract strain rates and thereby, estimates of possible earthquake moment magnitudes (e.g. using the Kostrov approach), even though there are recognised uncertainties.

1.3 Groundwater flow characterisation at site and repository scales

This Section deals with all aspects of the hydraulic characterisation and groundwater flow modelling at site and repository scales, which have a central role in affecting the safety case.

1.3.1 Site-scale groundwater flow

The MDR observes (p.143 and 191) that: *"Hydrogeological modelling is at centre stage of the TURVA-2012 safety case"*. …*"The challenge posed by the task was only successfully faced with an effort that should be regarded as state-of-the-art"*. These are important acknowledgements of the central role that hydrogeological modelling has in most of the core aspects of the safety assessment and the resources that Posiva has expended on it.

The site-scale groundwater flow field is derived by modelling, which depends on measurements and assumptions about site-scale hydro-structural prop-

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[1] Kotilainen A and Hutri K-L. Submarine Holocene sedimentary disturbances in the Olkiluoto area of the Gulf of Bothnia, Baltic Sea: a case of postglacial palaeoseismicity. Quaternary Science Reviews 2004; 23 (9–10): 1125–1135. See also STUK Report A-222 (2007) by Kaisa-Leena Hutri: An approach to palaeoseismicity in the Olkiluoto (sea) area during the early Holocene.

erties, and by comparison with hydrogeochemical data, especially by means of palaeohydrogeological models. Regional-scale flow is not characterized, although the present-day situation with Olkiluoto as a near-shore island gives support for Posiva's assumption that regional flows are not significant. Posiva suggests the possibility of a deep, offshore borehole to improve understanding of the regional-scale flow field and palaeohydrogeology.

Posiva has done a good job of assessing the large-scale hydraulic properties of the site-scale hydrogeological features, of utilizing data on large-scale hydraulic responses between boreholes during interference tests, of monitoring response to events in which pilot holes were drilled through transmissive features in ONKALO and of documenting how they have used interpretations of these responses to constrain the site-scale hydro-structural model. In general, the site-scale hydrogeological model presented in OSD Section 6 reflects current best practice in describing and modelling flow in fractured rocks by combining deterministic and probabilistic techniques. Posiva recognises (OSD p.365) that aspects of building the model (especially deterministic features) have inevitably to be based on expert judgement and thus contain subjectivity. No programme is defined to scope out the uncertainty or bias caused by this (e.g. a formal process of expert elicitation). The recently published reports WR 2013-34 and WR 2014-14 have brought the compilation and analysis of hydrogeological monitoring data, as well as cross-hole hydrogeological testing, substantially more up to date. However, an integrated analysis of pressure and flow monitoring data and updated assessment and application of the results to assess the site-scale hydro-structural model should still be expected.

Distinct fractures with transmissivity on the order of 10^{-5} m^2/s have only been encountered in a small number of cases (OSD p 362), but the occurrence of such features is of great interest for repository safety. The fitted trends for transmissivity vs. depth within gently dipping hydrogeological zones (OSD Figures 6-35 through 6-38 and WR 2011-65, Figure 7-1) are only weakly supported by the data. Heterogeneity should be included to account for the very substantial scatter around the fitted trend. The depth-trend models do not account for lateral heterogeneity (along strike) within a given zone. Lateral heterogeneity apparently is necessary to account for the wide scatter in transmissivity measurements for different borehole intersections with zones. This is in line with the along-strike variations in the thicknesses of influence zones of the BFZs.

Posiva points out the importance of sub-horizontal HZ20 for the whole site, noting that it is the most significant hydrogeological feature encountered in ONKALO and resulted in strong inflows. HZ19 lies above ONKALO and is said (OSD p.808) to act as a "hydraulic shadow or umbrella" to the excavations, meaning that head impacts of pumping/inflow are damped at the surface. HZ20 is interpreted (p.383) as being isolated from the well-connected network of hydraulic features and emphasises the lack of connection between tectonic units. Its isolation should be expected to have a significant effect on the performance of a repository located beneath it. A similarly oriented zone, HZ21, lies beneath the repository, but it is not possible from OSD to determine whether this is structurally or hydrogeologically significant in terms of future glacial response of the site – e.g., whether any of its flow or mechanical properties would be significantly modified by loading and unloading. The salinity data in HZ21 (p.557) do not clarify this; they show no relationship between salinity and transmissivity. OSD notes (p.533) that the salinity within HZ20A needs to be better characterised.

Heterogeneity in HZs is considered in the Hydro-DFN modelling (WR 2012-42, p.21) as ten realisations of a model in which transmissivity varies randomly on a scale of approximately 200 m. This is selected as "a representative spacing between the boreholes", rather than being based on any conceptual model or evidence for the actual scale of heterogeneity. The possibility of spatial correlation along a given HZ is not considered.

Head profiles for the upper 100 m of the bedrock, as computed with the surface hydrological model (WR 2011-50, Figures 4-1, 4-2, and 4-3) generally appear to give good matches to measurements, as well as the corresponding calculations with the FEFTRA bedrock hydrogeological model. However, calibration procedures and datasets are not described, so it is not clear which head data have been used for calibration of the model and the good match could simply be a result of calibration.

Conclusion: Posiva's assessment of the baseline site-scale groundwater flow field, and evaluation of the flow-controlling hydrogeological features is generally well supported, as are the arguments for limited influence of regional-scale flow. This has been used to establish the regional and site groundwater flow models (WR 2012-42) and is adequate for the CLA. Treatment of heterogeneity in the site-scale structures is a weak point in OSD, but has been partly addressed in safety assessment by use of model variants that include a stochastic representation of the apparently substantial lateral heterogeneity within HZs. STUK should request that further work on characterising and monitoring major HZs should continue during all subsequent stages of repository development. The Monitoring Programme report (Posiva 2012-01) begins to address how this will be done, but is vague and would need much more specific programme definition in order to be inspectable by STUK.

1.3.2 Upscaling and downscaling the hydrogeological model

Site-scale flow in the rock mass between major hydraulic features is modelled by upscaling the Hydro-DFN, estimating block-scale hydraulic conductivity (K) tensors from the Hydro-DFN model. The K tensors are fitted to block-scale flow simulations using CONNECTFLOW (OSD p.460), which is a reasonable approach and is generally regarded as necessary for large-scale simulations. The basis for doing this seems to be partially supported by the fact that flow connectivity between tectonic units is said to be weak (OSD p.367), so if a tectonic unit can be assigned properties of one or more hydrogeological domains (rock volumes with similar fracture characteristics, leading to 4 domains), then upscaling from domain-level should be justifiable. The process appears conceptually robust but is hard to validate by observations (e.g. in the P-O tests). No description is given of how blocks that cannot be described by a K tensor are handled, or whether this is tested. In SFR, there is no guarantee that a given block within a DFN can be described by a K tensor. Ignoring this leads to errors in the upscaled model, usually in the form of an overconnected large-scale flow model.

A related issue is that the MDR repeatedly refers to “Darcy flow” in fractured crystalline rock. The implication that Darcy’s law applies to this geological situation is misleading. This is part of an overly simplified explanation of the hydrogeological models and their data support.

Sub-division into four depth zones is supported by hydrochemical changes that evolve over more or less similar depth zones. This is an oversimplification, as more complex aspects of long-term groundwater circulation and mixing account for the depth patterns of chloride, sulphate, etc., than simply decreasing topographically driven groundwater flux. The fracture intensity trend (Figure 3-4, WR 2012-32) is for low-T PFL fractures outside the HZs, whereas the hydrochemical trends are almost certainly based on water samples that have been taken from highly transmissive fractures, in many cases the HZs. Recent progress in sampling low transmissivity fractures in ONKALO suggests that low-T fractures contain slightly greater proportions of pre-Littorina water than corresponding baseline samples from HZs and other high-T fractures that contain predominantly Littorina water (WR 2012-44).

The Hydro-DFN is based upon multiple simplifications of the Geo-DFN model and a number of assumptions. Consequently, the validity of the Geo-DFN is a key factor in the validity of the flow models. The Geo-DFN model for P_{32} fracture intensity implies randomly heterogeneous fracture intensity based on a gamma distribution, down to the ca. 10 m scale. This has not been carried through in the Hydro-DFN. Fracture size distribution is of central importance, but there are acknowledged uncertainties about the data used to build the stochastic distribution models and in the models themselves. OSD (p.843 and 857) identifies the difficulty of using tunnel PH and excavation data to get the fracture size and property distributions correctly for the DFN models. Each method has strengths and weaknesses with respect to different sizes of fracture, so neither gives an ideal picture. This is recognised by Posiva. The Geo-DFN model development work (Posiva 2012-27) identifies (p.329) uncertainties in many parameters of a factor of 5 or more, with the largest source of uncertainty being in the fracture size models, with the differences between alternative models of the MDZ being 1 to 2 orders of magnitude. Posiva notes that there is *“very little information on features of sizes critical to repository spacing calculations”* and points out that it may be important to obtain data at critical locations of the repository if these amounts of uncertainty are inadequate for design, construction or safety assessment. This MDZ range is *"by far the most uncertain"* and likely to have the *"biggest potential effect"* on the repository. Confidence in fracture orientation and intensity models is higher than in the size models.

Domains from the Geo-DFN model have been merged to leave 4 rather than 9 (OSD, p.369). This may obscure subtle differences between domains, and artificially increase variability within the merged domains, which may be conservative, but may also affect realism if the individual domains are more homogeneous in a statistical sense. Calibration of the site-scale hydro-DFN model is done for connectivity and flow, using PFL data. Connectivity calibration (Section 5.3, WR 2012-32) involves modelled intensity of 'open'/PFL/all fractures versus measured intensities of PFL fractures. The breadth of uncertainties in these calibrations seems to relate primarily to the differences between open, PFL and non-flowing fractures.

The PFL has been a powerful observational tool for looking at flow connectivity and provides compelling evidence for few highly ($>10^{-9}$ m^2/s transmissivity) conductive fractures at depth. PFL measurements have a strong influence on model calibration. Its continued deployment should continue to improve the database of transmissivity distributions as construction proceeds. However, there are problems with interpreting the PFL data, the PFL interpretations are not unique (OSD p.845), the Geo-DFN model only gives 'rough estimates' of open fracture frequency, so alternative Hydro-DFN models are needed to span the uncertainty. The assumed models for the probability that a fracture is PFL-transmissive (OSD p.437–439) are all quite speculative. Posiva's effort to test multiple assumptions is commendable but it is far from certain that these span the range of possibilities. Their diversity is limited and they depend on a few key interpretations, such as the character of a transmissive fracture, the meaning of PFL data, and (for transport properties) the nature of fracture fill secondary minerals. As discussed in Sections 1.3.4 and 1.3.6 of this review, more work will be needed to test how representative of connectivity and of flows the PFL data actually are. We are concerned that the tool will increasingly be used by operators who will be inexperienced in interpretation and handling, so its routine application could produce results of limited value. These uncertainties need to be explored and clarified by continued testing and verification of PFL results against other observations. In the short-term, POSIVA could make an effort to quantify the uncertainties in interpretation of the PFL and HTU tests. For example, POSIVA could assume a probability distribution on the influence radius (e.g., lognormal from 5 m to 25 m) and a distribution on a fraction of flow that bypasses the PFL (or that re-enters the system in the case of the HTU) and then produce PDFs of transmissivities.

The Hydro-DFN is built from three scales of model: regional, site and repository, with a mixture of DFN, CPM and ECPM approaches used in different regions. WR 2012-42 describes how it is used as the basis of particle tracking models to simulate transport from DHs to release at the surface. It is hard to identify which versions of the DFN are incorporated into each of the parts of the regional, site and repository scale models. The information is scattered. The same DFN case appears to be used in the regional and the site scale model, but the repository DFN is populated with more, small fractures (WR 2012-42, p.71). The regional model does not seem to have Depth Zones – or they are not mentioned – and there is no mention of the elaborated DFN model, which WR 2012-32 says is used for the site-scale model, with many small, connected fractures in the 50 m thick slice of rock at repository depth.

These points are relevant to the 'hand-over' of particles at the interface of the repository and site scale models. WR 2012-42 explains how the particles are transferred and restarted, but not whether the embedding procedure creates different boundary conditions at the interface that might affect far-field movement. This may be insignificant, but is not discussed.

Some of the particle tracking results presented in Section 12 of WR 2012-32 (e.g. Figure 12-4) appear physically unrealistic. The report notes that release, followed by penetration (in some cases) to 1800 m depth, takes dilute waters into the brine zone, which is not real. This clearly affects calculated transport times, the amount of rock 'seen' and radionuclide concentrations in groundwaters. The description of the actual application of the particle tracking presented in the next report (WR 2012-42) does not clarify whether this deep penetration problem is resolved in the application of the models. It is not clear how deep released particles descend. Only in the dilute water recharge scenarios in Appendix K, does water seem to penetrate to unrealistic depths (e.g. p.300).

Downscaling from site-scale flow simulations to tunnel and DH scales is done using a DFN model embedded in the EPM model. In order that pilot hole PFL transmissivity data can be used for calibrating the Hydro-DFN for modelling inflows at DH scale, the model is 'elaborated' to take account of the lower detection limit for T when PFL is used in pilot holes (Chapter 10, WR 2012-32). This recalibration results in additional generation of fractures in the network, i.e. those with very low transmissivities, to be represented because it is these fractures that would provide most of the inflows to deposition holes. This is a useful refinement of the Hydro-DFN because it implies a conceptual model for the inflows at DH scale that are the target of RSC methodology. While this approach is generally credible and reflects the state of the art for modelling SFR, the additional level of complexity in the Hydro-DFN (for depth zone 4 only) has now become too decoupled from reality. In-situ experiments in SFR (e.g., Stripa and Äspö underground laboratories) have had limited success in predicting the details of inflow to underground openings and its spatial variability, leading to suggestions that a more sparsely connected system of flow channels is needed (see Sections 1.3.4 and 1.3.6). P-O experiments in ONKALO have not tested this aspect of the models. Hence it should be assessed whether significantly different outcomes in terms of safety assessment would be obtained from ACMs that give rise to an even more sparsely connected flow system than the current set of Hydro-DFN model variants. For example, the current model could overconnect the Hydro-DFN at large scale and underconnect it at DH scale, which could result in less DHs being suitable for use. We discuss this in Section 1.3.4. The issue is how Posiva's elaborated model for DH scale will be calibrated and when that calibration will become reasonably representative to be used with reliably analysed uncertainties in the radionuclide transport model for safety analysis.

The OSD considers that the site scale Hydro-DFN is sufficiently well bounded (p.855), but acknowledges that it will continue to be updated "with no substantial changes" expected. At the June 2013 expert meeting with Posiva, we queried whether enough realisations of each of the Hydro-DFN alternatives had been done to capture the tails of transmissivity distribution. A notable feature of the PFL-based Hydro-DFN of the rock mass is the dominance of the sub-horizontal fractures amongst the flowing features, which has relevance to flow under glacial loading, for example.

Conclusion: The upscaling approach, using a DFN model to estimate equivalent porous medium properties, follows generally established methods for modelling fractured rock. However, Posiva glosses over the technical issues that arise from applying these methods in SFR, where an equivalent K tensor may not necessarily exist for a given block, and where dispersivity may be dependent on the scale of transport. The most likely consequences are an EPM representation that over-represents the hydraulic connectivity, and is unable to produce the scale-dependent dispersion effects that can occur in a fracture network. The method for downscaling to predict detailed flow distributions in tunnels and DHs should be regarded as highly uncertain, in the absence of P-O studies that confirm its applicability for Olkiluoto. Models leading to more sparsely connected flow systems should be considered to assess whether these could yield distributions of flow to deposition holes that are sufficiently different to affect the safety analysis. Posiva needs to continue its attempts to verify upscaled flow-related information in further P-O studies. Posiva does not present a thorough evaluation of the uncertainties underlying the hydrogeological modelling (e.g., Section 6.1.3 of the MDR on confidence in the model and data is not a broad or deep analysis).

1.3.3 Consistency of site-scale flow model with the palaeohydrogeology model

The palaeohydrogeological database and interpretation is discussed in Section 1.4.6 of this review. This Section considers whether the flow model makes predictions that are consistent with the palaeohydrogeological evidence. The elaborated Hydro-DFN model is tested against palaeohydrogeological information in Chapter 13 of WR 2012-32, with the Hydro-DFN being upscaled to an ECPM model at site scale. Hydraulic heads and salinity are used as the calibration data sets.

The predicted head profiles for the Base Case model (Figures 13-35 and 13-36) show a smoother variation of head with depth than is suggested by the measured head values from boreholes. If this cannot be explained by measurement errors, it suggests that the model of the rock mass (as represented by the Hydro-DFN) is too homogeneous in its flow properties. WR 2012-32 (p.295) suggests that the predictions of head are sensitive to the overburden properties, which are represented in a simplified way. The dominance of overburden properties in affecting the results of the palaeohydrogeological modelling (relative to any sensible variation of deep rock hydraulic parameters) might be taken as an indicator of the robustness of the deep system in terms of being undynamic, slow to respond and generally stable hydrogeochemically (p.295; 313). However, it cannot account for differences in variability (as opposed to mean values) of head at depth, which must reflect the nature of the bedrock model. For example, connectivity might be systematically underestimated in the model.

The synthesis of palaeohydrogeological considerations (WR 2014-27) reports that upscaled values of horizontal and vertical hydraulic conductivities, K_h and K_z, for each of the four depth zones of hydraulic properties represent anisotropy with horizontal conductivity dominating over vertical conductivity especially in the uppermost depth zone (Table 3-3). This anisotropy may be a further reason why measured head values give a heterogeneous trend versus depth. The site-scale flow model assumes that lateral flow through the side boundaries is zero. This simplification of the model may also contribute to its failure to represent the degree of heterogeneity in measured heads. The heterogeneity of groundwater compositions at any depth is consistent with anisotropy and lateral flow although the variability of heads is the other factor controlling the bulk movements of water and how the distribution of groundwater compositions evolves over time. Lateral and upward flow of saline water through the base of the site-scale flow model is postulated by the palaeohydrogeological interpretation of disparities between compositions of groundwaters in fractures and porewaters (WR 2014-27, p.172). This is considered further in Section 1.4.6.

The calibrated site-scale ECPM (upscaled Hydro-DFN) is used with palaeohydrogeological transient boundary conditions of pressure and compositions, plus assumed initial conditions, to simulate the evolution of present-day conditions from 8000 years ago, i.e. the start of Littorina infiltration. The graphical comparison of the assumed initial trend of groundwater stable isotope ratios and measured isotope ratios for present-day groundwaters implies that the model will simulate groundwater movements to 700 m depth, forcing mixing of existing isotopically-light water with isotopically-heavier infiltration, which goes against the assertion (p.289) that the isotope ratios should not change significantly below about 300 m depth due to low flow rates. The initial condition seems to be set too simply. Another issue in this respect is the assumption that the compositions of groundwaters and porewaters are set as identical, i.e. fully equilibrated, in the initial state (8000 years ago) for palaeohydrogeological modelling. This is inconsistent with the disparity between porewater and groundwater compositions and with the estimated timescale for diffusive equilibration between them. The direct and indirect implications of this for the site-scale transport model need further consideration, as discussed in Section 1.4.6.

Modelling SO_4 and HCO_3 with this palaeohydrogeological model is too simplistic because it ignores the fact that both these solutes are likely to have been affected by reactions (Figures 13-44 to 13-49, WR 2012-32). The processes controlling decline of SO_4 to nearly zero at 300-400 m depth are not understood. HCO_3 certainly has been affected by dissolution-precipitation promoted by mixing of the different components, i.e. meteoric and Littorina.

Overall, the palaeohydrogeological simulations of groundwater compositions are an interesting exercise in groundwater mixing but the assumption that all the modelled solutes are non-reactive, when only Cl^-, Br^- and stable isotope ratios are reliably conservative, makes the outcomes of limited value. The important interpretation of this would be a model of the future penetration of dilute water towards the DHs as Littorina water is flushed out by increasing meteoric infiltration.

Conclusion: Overall, the comparison between groundwater flow models and palaeohydrogeological evidence yields fair agreement and helps to build confidence in the flow model and site understanding. There is a credible consistency between the observed hydrochemical characteristics of the system and how it has evolved with the flows that are predicted from the Hydro-DFN. However, the detailed results as presented in WR 2012-32 show some qualitative as well as systematic, quantitative differences with measured data from boreholes. The generally smoother head profiles generated by the model indicate that the Hydro-DFN model is missing a component of heterogeneity that is present in the real bedrock at Olkiluoto. The palaeohydrogeology model and corresponding hydrochemical information are not discretised to the level of detail that would evaluate the heterogeneity of parameters for the site-scale flow and transport model.

1.3.4 Flow in and around deposition tunnels and holes

The hydrogeological model at deposition tunnel and DH scales uses information from the site scale model, from tunnel pilot holes and from the Demo area excavations. Using the pilot holes to assess tunnel inflows suffers from problems (OSD p.856) with respect to fracture size distributions. Predictions of higher or low (or no) flows are often found to be incorrect. OSD suggests further work that could be done, including numerical analysis of correlations between closely spaced PHs and detailed hydrogeological characterisation of a niche. The RSC report highlights the problems that Posiva has had so far with using PH data for both fracture and flow suitability estimations. The first attempt to apply the old RSC-I criteria in the access tunnel (WR 2012-19, Fig 6-1) shows that the final suitability estimates after excavation were closer to the first geological prediction and the PH data simply confused the picture. The subsequent work in the DTs reported in the RSC (2012) report reinforces the view that reliable application of PH data will need a lot more testing.

For predicting gross flow rates into the repository as a whole, Posiva has presented a simple empirical approach (WR 2014-16) that appears to yield practical predictions based on the overall distributions of fracture transmissivities. The model needs further development to reconcile differences between data from surface-based boreholes and pilot holes in ONKALO (WR 2014-16, Figure 2-1), as well as the poor match to fractures that produce inflows in the range 0.1 to 1 litre/min, which are also of concern for more detailed evaluations (WR 2014-16, Figure 2-2). However, for the limited purposes of this model, these discrepancies do not have a strong impact. The results obtained are comparable to those obtained with a model based on a much more complex Hydro-DFN approach (WR 2012-48).

At tunnel and DH scale, the hydraulic properties of the EDZ and the crown space are important and are analysed in depth in the Hydro-DFN modelling (WR 2012-42) by means of variants on the base case flow calculations. It would have been reasonable for Posiva to look at the impact of a variant with a continuous tunnel floor EDZ combined with a continuous crown space. If the EDZ is continuous and it is impossible to avoid a crown-space gap, then this situation would seem to be the default characteristic of the disposal tunnels. Nevertheless, Figures 7-1 to 7-5 indicate that crown space has a minor impact on initial flow rates (U) and F_r. The most significant impact comes from assuming a continuous tunnel floor EDZ, which does not affect F_r much, but substantially increase flow. The effect is magnified proportionately if a larger conductivity for the EDZ is assumed. If there is no spalling in the DHs, this also has a marked positive effect on initial flows.

The individual particle tracks used as illustrations of flow behaviour in and around DHs and tunnels (WR 2012-42, Figure 6-2 and 6-3) show particles 'visiting' several deposition holes and, presumably, releases from neighbouring holes are mixed in the tunnel and EDZ. The report does not speculate on whether any concentration effects or chemical impacts could occur via this hole-to-hole interaction and it is not mentioned in the main safety case reports. The huge (x 10,000) variation in F_r for the shortest and more convoluted particle tracks (Figure 6-5) is notable.

An important finding of the base case flow calculations (WR 2012-42, p.111) is that screening out of high inflow deposition holes does not improve overall transport resistance (does not mitigate against low values of F_r). In other words, it does not affect retardation/retention under normal conditions. The DH inflow RSC can thus be seen as almost entirely focussed on buffer preservation ('almost', because screening also reduces the number of holes that can have any significant release into the natural fracture network on the QF path). Screening has no impact on the QDZ and QTDZ releases.

The plots of screened out DHs (e.g. Fig. 6-14 and p.116) show them to be mainly associated with large (stochastic) fractures, which, in the 'real rock', would most likely be FPIs. In this case, those DHs identified as having too high inflows would probably already have been screened out as locations using the FPI criterion.

Additional Hydro-DFN modelling has been carried out in support of the RSC programme (WR 2012-48). This work investigates several aspects that are relevant to assessing the potential usefulness of inflow criteria in pilot holes and in DHs during the open-repository period. The aspects treated include the influence of grouting on the redistribution of flow to open tunnels and DHs, the impacts of different construction schedules that result in different numbers of tunnels being open at one time, the relationship between inflows to pilot holes and open DHs, the correlation of DH flows during open-repository vs. post-closure conditions and the effectiveness of different screening criteria, including FPI and estimates of the size of large hydraulic fractures (although it is not clear how this last could be done in practice). A general weakness of this work is that it is predicated on the Hydro-DFN model with homogeneous fractures, both for grout penetration and for water flow. The resulting relationships between pilot-hole inflows vs. deposition-hole inflows, and regarding the efficiency of grouting, may therefore be overly optimistic. The modelling of the number of DHs that would experience dilute water penetration (WR 2012-42, p.128) indicates that the prolonged temperate period (50,000 years or more) is a much more significant risk of dilute water conditions than the ice sheet scenario (assuming the stated glaciation conditions). Moreover, the number of DHs at risk increases to more than half of the total if matrix diffusion is not capable of attenuating the dilute water 'plume'. Thus, the prolonged period of temperate conditions is the most significant scenario with regard to the potential risk of buffer erosion.

WR 2012-42 presents, but hardly comments on, particle transit times from DHs to the surface. In the base case, even with screening of DHs, 70-90% of the particles reach the surface within 1000 years; 20% within 100 years of leaving the DHs (Figure 6-19). Unretarded (by sorption or matrix diffusion) transport times are thus fast. In PA terms (e.g. plots of dose v. time), this implies essentially instantaneous release of unsorbed or poorly sorbed radionuclides once they escape the buffer, without the need to consider changing climate/surface environmental boundary conditions.

In modelling drawdown to ONKALO, a calibration factor is applied to the hydraulic conductivity of tetrahedra representing the SFR adjacent to ONKALO (OSD p.803). This calibration can be seen as a way of correcting for an overly connected system (continuum model) versus convergence effects in a more sparsely connected fracture or channel network. This diminishes the value of inflow calculations as a test of the conceptual model water flow in the SFR. The calculated inflows from the SFR are evenly distributed along the tunnel because single fractures are not represented (OSD p.807). This diminishes the value of this type of prediction-outcome study as a test of the ability of the Hydro-DFN model to represent heterogeneity of flow, which is important for safety calculation.

The hydrogeological characterisation programme for further demonstration excavations and for the main construction phase appears to need significant work. It is not clear that there is a planned programme of measurements that will (a) lead to better validation of the limited DFN 'predictive' capability for spatial utility, (b) be able to gather the most appropriate data necessary to qualify DHs and tunnels, (c) test alternative conceptual frameworks for flow in the rock mass or (d) continuously improve confidence in the DFN model and its results, as applied to PA and the qualification of near-field rock. Although difficult to measure the area density (intensity) of inflows to the tunnels, this measure, when compared to the pilot borehole inflows for the same rock, is the key measurement for reducing the uncertainty in any discrete *feature* network model. An obvious gap at present is in gathering head data, which could help with all of these issues. 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. We suggest that Posiva should be asked to make a thorough and wide-ranging review of its hydrogeological programme (and reconsider some parts of its RSC programme) before it starts major excavation work.

POSIVA should develop a plan to 'validate' the hydrogeological model. This may require instrumenting the existing boreholes to measure heads and also to do 'blind' predictions before construction of each tunnel and boring of deposition holes. 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).

The results of Posiva's Hydro-DFN modelling in support of RSC (WR 2012-48) suggest many possibilities for how Hydro-DFN models (or alternatives) and associated RSC concepts could be verified by P-O studies during repository construction. For example, the tendency for inflow points to cluster around large hydraulic fractures appears to be sensitive to the different assumptions of the Hydro-DFN model (intensity-size and size-transmissivity relationships). Therefore, these results should be taken into account by Posiva, as part of the development of a P-O programme for testing and validation of the DFN conceptual models.

Conclusion: The hydrogeological model at tunnel and DH scale is well-established and has been subject to considerable development work and computational testing by Posiva. It is at the core of the safety assessment, but there is very little confirmatory observational work to support the predictions of the stochastic DFN, where we already identify potential problems with its representativity with respect to channelling and DH flow rate variability in SFR. At the February 2014 DFN workshop we had the strong impression that Posiva's hydrogeological testing programme at tunnel scale was not well conceived or state of the art. A programme of head measurements and interpretation appears not to be included, yet is essential to understanding the tunnel and DH-scale flow regime. More stringent P-O tests are needed, to test the ability of the Hydro-DFN model to predict heterogeneity of flows as well as distributed average values. At the February 2014 workshop, Posiva outlined numerous ideas for elaboration of the ConnectFlow model, but no plans for more stringent P-O tests. This needs to be rectified in the period immediately after licensing as it impacts directly on RSCs and STUK should request a plan for such tests as a license requirement, in order to ensure that a robust understanding of the groundwater flow system is achieved during construction.

1.3.5 Matrix diffusion and porewater chemistry: indicators of flow and retention

The palaeohydrogeological modelling raises a fundamental issue both for site understanding and for radionuclide transport modelling: pore water and fracture water equilibria and the matrix diffusion penetration depth. Matrix diffusion is important because: (i) it affects transport of anionic species, (ii) it impacts on the evolution of the hydrochemical system over the next thousands of years temperate period and (iii) it has to be understood properly in order to interpret the palaeohydrogeological evolution of the system and its present 'initial state'.

The palaeohydrogeological evidence, including pore water compositions, and the model have been compiled and discussed in WR 2014-27, which was received at a late stage of producing this evaluation. The main issues of relevance to solute transport modelling are the likelihood of solute exchange disequilibrium between pore waters and groundwaters in contrast to the assumption for model initial state that the depth profiles of pore water and groundwater compositions would have been identical, and the evidence in support of the matrix diffusivity being significantly lower than has been assumed in the transport model. These issues are described and discussed in Section 1.4.6. In summary, the measured dilution of pore water compositions relative to groundwater compositions poses a number of questions about the validity of initial conditions and parameters used in the site-scale transport model.

WR 2012-42 notes (p.288) that the modelling assigns the same compositions to both pore and fracture waters and thus assumes equilibrium. OSD observes (p. 577) that the markedly lower salinity waters found in the matrix compared to that in the fractures at depth is "surprising" and postulates that this indicates that the more saline waters have entered the site "recently". For the observed salinity contrast to be sustained, hydrogeological model calculations indicate a diffusivity an order of magnitude lower than that obtained from laboratory measurements (OSD, p.937). This discrepancy seems to be a fundamental problem with the palaeohydrogeological modelling, given the considerable importance of density. In the palaeohydrogeological modelling, the available depth (accessible porosity) does not seem to be varied as a sensitive parameter. It is taken as the maximum value (all the matrix is available) and is thus the half-distance between conductive fractures. Specific fracture surface area is varied (reduced) in the sensitivity test and this *"increases the depth of matrix diffusion"* (WR 2012-42, p.318), which makes it appear a variable that is being altered. In fact, Posiva simply increases the fracture intensity (P_{32}) by filling the space with more fractures (p.291), which are thus closer together: the whole matrix is still considered to be available for diffusion.

The accessible matrix for diffusion is important in controlling the development of dilute water conditions in the temperate period, where many more deposition holes could be susceptible to erosion than during dilute intrusion under ice sheet conditions (and at probably much earlier times). It has to be assumed that the entire matrix is accessible for diffusion in order for this effect to become insignificant. However, the palaeohydrogeological chemical data suggest that dilute conditions will never prevail at repository depth.

The June 2013 expert meeting with Posiva noted that the hydrochemical data suggest little interaction between these two bodies of water, which is explained by possible anion exclusion, but significant credit is taken for matrix diffusion in the safety case. In PA variants studied by Posiva, the assumption of high matrix diffusion overwhelms convective transport. Posiva did not provide a clear answer as to whether the field data and the PA assumptions were entirely compatible or bounded one another. OSD notes that laboratory data would overestimate pore diffusivity, perhaps by an order of magnitude, compared to what could be inferred from the natural evidence (p.579).

The available porosity for RMD diminishes rapidly in the first few mm away from fracture surfaces (OSD, p.694), except in altered rock (clay-coated fractures) where porosity profiles are highly variable. Type porosity profiles have been developed for a set of fracture classes, which appear reasonable. Diffusivity data are relatively sparse, but a credible diffusivity v. porosity relationship has been generated from a combination of samples from Olkiluoto and other Finnish sites (Fig. 8-9) and this seems fit-for-purpose. Whether all the porosity is available for RMD is discussed in Section 8.5.2. The possibility that connected porosity exists up to several metres from a fracture is raised but it is noted that there are no data on connectivity of porosity at Olkiluoto, although work might be carried out in ONKALO (p.739). As Posiva says, this uncertainty can be dealt with by variants in the values used in the SA.

The variant calculations in WR 2012-42 for penetration of dilute waters to repository depth under receding ice-sheet conditions are heavily dependent on assumptions about the available matrix diffusion distance into the rock from fracture walls (p.128 and 304). This sensitivity is particularly evident when comparing Figures K-8 and K-9 and it is notable that there are no plots of times for dilute water penetration for the most restricted diffusion depth of 0.1 m. Table K-3 indicates that, if matrix diffusion is restricted, then most of the DHs will experience dilute water penetration within the next 10,000 years of temperate conditions. Even with the assumption of infinite matrix availability, 20 DHs are expected to receive dilute waters in the next 10 ka. This means that the buffer chemical erosion scenario would not be focussed mainly on glacial water penetration at much later times. The report notes (p.303) that the regional 3-D simulations *"….suggest that under temperate conditions there is time for significant diffusive exchange with the rock matrix, and so an effectively infinite matrix can be assumed….".* This seems to be counter to what we understand about the pore and fracture water chemistry at the site and seems thus to be an important issue.

Posiva acknowledges that *"more data are needed from the matrix pores and poorly connected fracture system"* (OSD, p.853) to establish groundwaters and salinity in different groundwater conditions in the past and present. Posiva is considering an additional deep borehole in the eastern area to evaluate fracture/matrix groundwater interaction at depths of 1 km or more. A deep offshore borehole to measure porewater and groundwater salinities as well as groundwater pressures, in an area undisturbed by local topographic effects of Olkiluoto Island, is also suggested to gain information on the regional groundwater flow field and possible slow upwelling of saline groundwater (p.853).

Conclusion: The combined issue of matrix diffusion depth and pore/fracture water equilibria is important, but unresolved. There is a gap in testing sensitivity to key chemical parameters. This is highly important with respect to the ability of dilute waters to penetrate to depth and for the matrix availability for retardation of poorly sorbing radionuclides. Posiva needs to look into this in more detail and make further geochemical measurements and tests in the repository volume.

1.3.6 An alternative conceptual model of flow in the SFR

The DFN models are at the core of site hydrogeological understanding and at the heart of the safety assessment calculations. This is illustrated by the PSA results presented in the Release Scenarios Report (Posiva 2012-09), Section 9.4. For the radionuclides considered (135-Cs and 14-C), the near field flow rate (Q) for the F and DZ release pathways, along with the geosphere transport resistance (WL/Q), also for the F and DZ release pathways, are amongst the most sensitive parameters controlling calculated releases.

Two significant uncertainties surround the DFN approach: it is hard to verify predictions of flow in the SFR (compared to flow in the HZs) and it is hard to verify models of channel connectivity, by direct observation. In the latter case, there are alternative conceptual approaches to connectivity in SFR that challenge the degree of connectivity predicted by the stochastic Hydro-DFN. Posiva presents several versions of the hydrogeological DFN, most of which amount to parametric variants rather than alternative flow concepts. The version that comes the closest to being an ACM is one that uses the DFN concept but with only a fraction of the area of each fracture open (Case C, OSD, p.916; described further in WR 2012-32 and 2012-42). This is more realistic than the other variants, in which each transmissive fracture is open and has uniform properties throughout its extent. However, it still falls short of being a strongly channelized fracture model (the main alternative possibility that we envisage), because there is no spatial correlation of non-transmissive patches within a given fracture. Posiva has not presented calculations based on any ACMs for flow and flow connectivity in sparse fracture networks, such as channel network models, or channelized DFN models with correlation of flow channels between fractures and/or preferential flow along fracture intersections.

WR 2012-32 (p.40-43) suggests high and unquantified uncertainties in establishing the number of open fractures in the Geo-DFN database. This number is used as the basis for the Case A Hydro-DFN flow model, which is used as the Central Case in the PAR. Although it compares with data from Sweden, the same method/logging data are likely to have been used to define 'open'. It is significant that the number of PFL (flowing) zones is <20% of the number of open fractures (Table 3-11). This implies a lot of channelling, or poor connectivity, or poor identification of 'openness', or all three. The report says that the meaning of a PFL measurement of T is not that there is one flowing fracture present, but that a detected flow could be representative of the transmissivity of a larger volume of rock (p.118). With a 20 m radius of influence, this raises the question of what a PFL transmissivity value actually means in terms of the open fractures in a DFN model and whether PFL data can be used to condition a DFN flow model if the T values are not connected to actual fractures. WR 2012-42 says that *"…additional manipulations of the fracture data was (sic) performed to ensure all PFL measurements were linked to a fracture when calculating the intensity of PFL fractures"* (p. 15). We raise the overall problem of what PFL data really represent in Section 1.1.5.

The 3 DFN Cases (A, B, C) seem not to be sufficiently independent. Case A connectivity is calibrated to be consistent with PFL intensity (i.e. the basis for Case B). Case C open fracture area is 'adjusted' to give sufficient connectivity to be consistent with the PFL intensity. It seems that both A and B are calibrated on B, so uncertainties in PFL data used in B would also be present in A and B. Also, in Case B, Posiva acknowledges that connectivity is forced by ensuring that most of the generated fractures are not connected and larger fractures are not generated. At the other end, the DFN model is prevented from producing large numbers of small fractures (WR 2012-32, p.103), which must affect connectivity significantly. This will increase the number of unconnected fractures in the model and thus the number of fractures that are removed. It also leaves large rock volumes with no flow. It is also notable that Case B (using the PFL data) has connected fractures that are larger and more evenly distributed than the other Cases (p.107). If all 3 Cases might be dependent, it could explain why they tend to yield consistent estimates (e.g., of block K values: p.156).

As noted above, the Phase I DFN work ended up with large blocks (c.100 m) with no flowing fractures (p.183). In Phase III, Posiva 'elaborated' the DFN and introduced more, small, low T fractures into the rock in the repository volume, which they say allows access of water to more rock (affecting retention) without significantly increasing bulk K or flow-rates. This is in a volume of rock where there are few PFL data. Not surprisingly, all the Cases show considerably more connectivity (e.g. Figure 10-13), with a huge increase in the number of DHs that are connected to release pathways (from 1% to 28%: p.225).

When this elaborated DFN model is used for the site-scale model it generates lots of small, connected fractures in the 50 m thick slice of rock at repository depth. There is no discussion of how this approach affects migration and release. Fundamentally, it seems that Posiva has allowed a lot of connection in the repository, but constrained connectivity in the rock above, which is more openly fractured. This may underestimate the connectivity and flow through the far-field release path, to the extent that this path goes through the DFN rather than the HZs

The amount of 'adjusting', 'modifying' and reiteration during calibrations and 're-calibrations' is hard to track and of some concern. It is hard to know (without a detailed forensic review) the extent to which this is obscuring real uncertainties. No reference is given to a report that explains these manipulations. AMEC memo 2014-01-29 lists several types of manipulations, including corrections for inferred depth errors in the fracture database, and enhancement of borehole images. However, no report or project memorandum is cited and this manipulation is not explained in any of the appendices to WR 2012-32 or WR 2012-42. The calibrations for Depth Zone 4 (the repository) on p.187 seem to introduce circularity and tie the three Cases more closely together. Section 13 mixes up calibration with confirmatory testing of the model, introducing terms such as *"slight calibrations"* (p.248) and *"non-unique adjustments"* (p.257) and acknowledging the *"inherent subjectivity involved in the calibration process"* and that other changes could results in *"equally valid calibrations"*. Terms such as *"calibrated predictions"* (p.263) or statements such as *"confirmatory analysis…. involves calibration against …tests"* (p.262) equate, and thereby confuse, the processes of confirmation, calibration and prediction.

The adjustments include one that prevents generation of large fractures that can extend down from a shallower Depth Zone to a deeper and thus connect the flow. As noted on p.157, this may result in lower values of K being calculated. But it seems unrealistic, especially as it was intended to prevent *"excessively large flows"* penetrating down large fractures. If the depth v. T correlations for HZs is so poor, perhaps it is also true of other large fractures and such flow could occur. The report (p.168) points out the dominance of the large HZs in transporting water to depth.

The overall conclusion of WR 2012-42 on variant calculations is that there is little significant difference in system performance. For the different DFN model bases, the choice of Case A for the base case seems justified in that it gives marginally more conservative behaviour than Cases B and C (p.184). The DFN model is also conservative when compared to results from ECPM simulations (p.185). The most significant impact comes from the variant with an ice front over the repository, where initial flows at DHs are increased by a factor of about 5, with large flows in DHs near major fractures that cut several tunnels. An important point to follow up is that the report proposes that this may require an additional RSC.

The obvious ACM to the 'standard' DFN statistical approach is that developed by Black and Barker[2] on weak connectivity in SFR (sparse channel network model: SCN). Their position is that 'standard' DFN models tend to over-estimate connectivity at larger scales, especially when fractures are large compared to the scale under consideration, and they do not work well at smaller scales, where a completely probabilistic approach to flow would perform better. Their work shows that fracture shape is a major influence on model outcomes and the fracture data at Olkiluoto could be interpreted in a way to produce a wide variety of geometric models that considerably affect calculated connectivities, channelling and percolation through the SFR. This approach would result in less connectivity and thus more 'dry' deposition holes, affecting all aspect of the SA that cover saturation and early period near-field behaviour. For example, it is understood that, in SR-Site, SKB could only match flow observations by reducing the transmissivity values of about 50% of the anticipated intersections to below the measurement limit. Phenomena that are predicted by Black and Barker's approach (the "skin effect" due

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[2] Black, J.H. and J.A. Barker (2014 in review). Understanding groundwater in fractured crystalline rocks based on flow in sparse channel networks: connectivity and percolation. Submitted to Water Resources Research.

to flow convergence in a sparse network of hydraulic conductors around underground openings) have, however, been invoked (OSD, p.802) to explain the lack of match between predicted and measured tunnel/shaft inflows in ONKALO.

An alternative conceptual framework for groundwater flow in fractured rock that considers flow in an SCN could lead to different behaviour of the EBS. Channelling has the potential to (a) lead to higher velocities in channels that could affect piping erosion rate or chemical erosion rate of the buffer, (b) result in smaller flow wetted surface areas (more limited sorption) and consequently also smaller values of the transport resistance factor, F, because the W x L values of channels are smaller than those of disc-shaped fractures and (c) result in there being more 'dry' rock than predicted by the DFN model. In addition, a channel network might not be stable over long periods; flow might jump to new channels in response to changes in the stress field and (possibly) geochemical rock-water interaction processes. Effects of grouting could also be more complex and less predictable than suggested by the results of Hydro-DFN modelling, as presented in WR 2012-48.

Currently there is no SCN channel-flow modelling tool that is sufficiently well developed to evaluate quantitative differences in the factors described above. Based on the requirement of sensitivity analyses, there is a need to develop SCN in parallel to the DFN modelling and we consider that Posiva should now incorporate such assessment into its R&D programme, as channelled flow could be more representative of the actual conditions that will be encountered as excavation proceeds.

Nevertheless, scoping calculations of the potential impact of an SCN model were carried out by Black for this review. This work found that the calculation of flow-related transport resistance, F_r, is almost entirely dependent on the field measurements of fracture density and transmissivity derived by the PFL method. The previously standard method involving two pumping rates was not followed in the sub-surface measurements in the pilot holes and the results are severely compromised both in terms of density and maximum transmissivity. It is possible that the values of F_r, derived in WR 2012-42 could be more than an order of magnitude too optimistic. The current distributions of F_r are strongly dependent on the large proportion of small fractures used in the DFN model and the application of a size-transmissivity relationship that dominates outcomes. The value of area density derived by the PFL method in the PHs seems unlikely and all the likely errors lead to improvements to the repository performance measures. Black considers the value of area density to be too high, possibly by an order of magnitude. This has significant impacts on the number of DHs that will be intercepted by 'flowing pathway' fractures.

The presence of fracture clusters reported in WR 2012-32 represents a factor for which there is currently no model. Posiva has not propagated clusters into the analysis, saying only that they don't affect the spatial distribution of flowing factures by more than 5% (p.90). Fracture clusters could conceptually be viewed as minor deformation zones. These clusters should be given more attention: 5% (of PFL features) is a significant fraction, especially if these are indicated to be extensive fractures or minor deformation zones. This needs to be tracked into the growing knowledge of fracture distribution that will come from construction work.

Posiva notes that the overall uncertainties in the DFN and connectivity models are being transferred out of the OSD onto the "RSC implementation process" (OSD p.846).

Conclusion: With recognised uncertainties discussed by Posiva and raised in the points above, the Hydro-DFN model is as reasonably consistent with the Geo-DFN model and the fracture data as is required for the present CLA, but there are significant doubts about whether it overpredicts flow connectivity at a large scale and underpredicts connectivity at the small (DH) scale, and hence the number of 'wet' DH. It affects all considerations based on EBS saturation rates. Our overarching view is that there seem unlikely to be major issues with the numerical results in the PAR, given the large 'margin of safety', but these uncertainties need to be resolved in the future and Posiva should certainly be testing alternative conceptual frameworks and improving the representativity of the flow models to real conditions. There is at least one ACM of flow at DH scale that has not been discussed by Posiva and its inclusion in the site assessment would improve consistency and credibility of the interpretations. This leads to STUK requirements about continued confirmation and testing during construction.

The Geo-DFN concept of heterogeneous fracture intensity on a tunnel scale has not been carried over into the Hydro-DFN. There are also discrepancies with data, in terms of accounting for fracture clusters, PFL anomalies and fracture database manipulations. Posiva should develop a specific procedure continuously to improve the size distribution data as all stages of construction proceed and to explore further the evidence for connectivity and the most appropriate way to evaluate this. The OSD suggests (p.857) that more work on fracture size is needed, including re-mapping using alternative techniques. Posiva should enhance its hydrogeological measurement and monitoring programme to provide data to improve the utility of the DFN as a tool for forecasting spatial utilisation as excavation proceeds. Posiva needs to develop a probabilistic framework for prediction and evaluation of these measurements in order to provide meaningful tests of the Hydro-DFN model.

1.4 Hydrogeochemical characterisation at site and repository scales

This Section considers the hydrochemical characterisation of the site, in terms of the data gathered, their completeness and quality and the way in which geochemical processes have been modelled. Posiva is confident that they have characterised the hydrochemistry in the more transmissive regions of the bedrock thoroughly and have a good understanding of the origins and evolution of the waters. Posiva has devoted considerable energy and resources to this and OSD Section 7 on hydrochemistry is impressive for its depth and the considerable thought that has gone into interpreting the data and exploring alternative explanations of system evolution. Posiva observes that the hydrogeological system at the site appears to have a strong resistance to external change. Nevertheless, the hydrochemical system is recognised to be in a process of change (responding still to changes in and recovery from the last glacial cycle) and is not at steady state.

1.4.1 Hydrochemical database

The hydrogeochemical data cover chemical, isotopic and microbiological information from surface waters, precipitation, borehole waters and underground sampling. Posiva presents comprehensive and painstaking data compilations, with appropriate supporting information in most cases. The data have been managed well and subjected to sample quality classification. Uncertainties and error ranges are included for many parameters, but not all. In some early borehole samples, cross-flow caused mixing and the samples are not then representative of the depth at which they were taken. Uranine tracer contents suggest that most of the samples are acceptable in terms of contents of flush water.

Reported tritium (^3H) has many non-zero values down to at least 100–200 m depth. This suggests that recently infiltrated water circulates quite rapidly down to this depth range at least and would be an indication of where the geosphere-biosphere ‘interface’ might be located. There are a few significantly positive ^3H values for water samples from deeper than about 200 m and down as far as disposal depth (e.g. 2.7 TU in OL-KR5_T446_2). If significantly non-zero, and if they are not due to flushing water, these imply fast water infiltration down to disposal depth. Further QC and interpretation is needed to identify the most likely explanation.

The data include various trace solutes that are relevant in terms of indicating hydrogeochemical behaviour of ‘analogue’ solutes or of monitoring environmental hazards (e.g. U, Cs, I, Rn, As and F). Ra data are not reported, although Ra behaviour as a daughter of U and as the parent nuclide of Rn should be understood for the long-term safety case. No noteworthy anomalies of U, I and As are in the data set.

Conclusion: Overall, the PAR indicates that the hydrogeochemical properties of the site have been characterised and that the processes are understood to an adequate degree, and that stability of these properties is sufficient as the host for the engineered barrier system. The hydrogeochemical models relevant to performance assessment are, with some qualifications that are discussed elsewhere in this review, credible.

1.4.2 Geochemical modelling

The description of geochemical modelling (MDR, Section 6.2.1) lacks a description of the objectives, the numerical methods, the simplifications and assumptions, and a critical assessment of how well the objectives are achieved and what are the uncertainties. The use of the FASTREACT code for simulating hydrogeochemical evolution is not well documented and justified (Note added in revision: WR 2014-09, Trinchero et al., on hydrogeochemical evolution of the site became available at a late stage of this review; it describes coupled flow-reaction modelling with FASTREACT; see Section 1.6.1), and is insufficiently verified and tested. The aim of using FASTREACT is to simulate heterogeneous hydrogeochemical reactions in pathlines arriving at individual deposition holes using a Monte Carlo analysis with travel times to normalise reaction progress between individual pathlines. The results are similar to other hydrogeochemical modelling outputs from the PHREEQC code being directly or indirectly coupled with a flow model (e.g. PHAST).

Despite the apparent sophistication of the FASTREACT numerical method for transport and mixing, the conceptual model for hydrogeochemical reactions is still basic and is therefore unlikely to be realistic. There is inadequate discussion of whether this is representative of the reactions that buffer water compositions and whether this modelling meets specific objectives regarding forecasting of future groundwater compositions at repository depth. No evidence is presented to support the validity of this conceptual model. Numerous issues arise from the model and key data descriptions in MDR, Sections 6.2.1 and 6.2.2. The 'homogenisation procedure' for particle trajectories (p.196–197) is unclear and it is uncertain whether this procedure is appropriate with respect to water-rock reactions. It assumes geochemical homogeneity (p.199) but that may not be an adequate representation of the system in a heterogeneous rock mass. Mixing is attributed to heterogeneity and local scale dispersion, and to exchange with matrix pore water, but the cumulative effect of mixing due to transient changes of boundary water compositions over long timescales are not taken into account (p.200). There are various other assumptions and simplifications that are not justified: for example reaction kinetics data and control of redox by Fe^{2+} originating from Fe-bearing calcite.

A more conventional approach to hydrogeochemical modelling is reported in WR 2014-06. Mass-balance calculations with PHREEQC have been used to elucidate the mixing proportions of end-member reference waters in analysed groundwater samples and to calculate the mass transfer of major chemical components due to water-mineral reactions. Mixing between component waters from different sources and with different ages is anyway the dominant factor in compositional variations, with water-mineral reactions playing a minor role. Nevertheless, quantifying these reactions and showing that water compositions are reasonably consistent with reactions that are expected from geochemical principles is necessary to building confidence that processes controlling key chemical properties such as redox, pH, alkalinity and cation ratios, and buffering their long-term evolution, are adequately understood. The mass-balance model contains a limited set of minerals and processes, i.e. dissolution/precipitation, ingassing/outgassing, and ion exchange, superimposed on the physical mixing of end members. Uncertainties due to simplification and geochemical heterogeneities remain unresolved. Calculated mass transfers, with relatively small residuals, however correspond well with general hydrogeochemical principles, i.e. DOC consumption, iron sulphide precipitation and calcite equilibrium in groundwaters above repository depth (WR 2014-06, p.35 and Fig.4-3). This indicates that the data are reliable and that the basic buffering processes are being represented by the model.

Mass transfers due to water-rock reactions are a minor influence on groundwater compositions compared with the influence of hydrodynamic mixing. Definition of the reference waters, specifically the 'sub-glacial' reference water, is a problematic aspect of the mixing and mass-balance modelling. This end member in the mixing model is essentially comprises the deep brine diluted by water with unspecified and probably varying source which is presumed to be very old, i.e. pre-glacial. It identifies a palaeohydrogeological component that adds salinity when mixed with dominantly glacially-derived groundwaters or younger (Holocene) groundwaters above repository depth (WR 2014-06, p.17). The presumed composition of the sub-glacial reference water has been reassessed and slightly adjusted from previous similar modelling (p.18). Anyway, this is a rather arbitrary specification that has little significance for palaeohydrogeology and mixing calculations. The problematic outcome of the mixing modelling is that the application of this poorly-defined reference water in mixing modelling produces results that contradict palaeohydrogeological interpretations elsewhere in the safety case. Thus the mixing model suggests that there are significant amounts (>10%) of glacial reference water as deep as 500 m and dominant amounts (>50%) of sub-glacial water even as shallow as 200 m (WR 2014-06, Fig. 4-5 and Table 4-7, pp.40-44). These model results are probably artefacts of the ill-defined sub-glacial reference water. In reality, there is not such a single mixing component but many deep pre-glacial groundwaters with varying Cl^- and $\delta^{18}O$ compositions. So the mixing modelling in this respect is illustrative of the temporal and spatial pattern of hydrogeochemical evolution rather than quantitative and definitive. The interpretative inconsistencies need to be resolved by better identification of what is definitive and what is qualitative interpretation. This adds to the evidence from pore water compositions (Section 1.4.6) for complexity in pre-glacial palaeohydrogeology with implications for how the groundwater system might evolve in a very long timescale.

Conclusion: The hydrogeochemical modelling is inadequately verified. The conceptual model for reactions that control the long-term evolution of groundwater compositions is simplified and not necessarily appropriate, although overall the calculated mass transfers show a consistency suggesting that the basic hydrogeochemical processes are identified. Calculations of mixing between reference waters suffer from the introduction of an arbitrary and poorly sub-glacial defined end member. This results in groundwaters being resolved into mixtures that contradict palaeohydrogeological interpretation of other lines of evidence. No variants have been considered. The results are outputs from a complicated and unverified model. The modelling description is disconnected from the much more detailed and well-considered description of hydrochemical data, of safety functions and data requirements for safety analyses and safety case, and of hydrogeochemical mixing/reaction modelling for the reference evolution and variant scenarios.

1.4.3 Performance targets for hydrochemical properties

The target properties primarily concern anoxic and chemically reducing conditions, concentrations of corrodants (HS^- and N species), and biogeochemically-active solutes (i.e. S_{tot}, DOC, H_2 and CH_4), pH, salinity and ionic strength to mitigate chemical erosion of the buffer. Many of these target properties are constrained only qualitatively in terms of 'low' or 'limited' concentrations and can therefore only be assessed in terms of expert judgement. There are quantified targets for pH, salinity and cation concentrations. A few water samples have relatively high pH values (9-9.5) but are within the target property range for pH and might have been transiently influenced by nearby grouting. Observed salinity values (TDS and chloride concentrations) are all well within the maximum of the target properties, as also are the cation concentrations. Modelling has assessed how these properties could be affected by future evolution in relation to their targets; this is considered in later sections of this review.

These target properties, whether qualitative or quantitative, are the basis for defining and implementing design requirements (DBR, p.19). The DBR lacks discussion of how measurable design requirements, in this case the hydrochemical properties of the site, have been used to show that target properties will be achieved within acceptable deviations for the initial state and for the reference scenario. One aspect of this that is open to expert judgement is the rationalisation of 'low' and 'limited' values for those properties with unquantified targets.

For some of the target properties, data are incomplete (e.g. DOC) or have varying degrees of uncertainty (e.g. Eh, CH_4). Eh measurements are the primary line of evidence for anoxic conditions. A number of Eh values recorded in the hydrochemical database are positive and thus indicate oxic conditions. Posiva's judgement is that those positive Eh values are erroneous, probably due to oxygen leakage into the sampling equipment, and that the initial state will be anoxic and chemically reducing except for transient oxygenation in the periphery of excavations. Accepting this source of error in Eh measurements, it can be accepted that Eh data, as well as other geochemical considerations, indicate that redox conditions are generally reducing. However, this has to be confirmed for the groundwater system at and around repository depth.

HS^- concentrations are generally <1 mg/L, confirming that HS^- concentrations are generally 'low' or 'limited' in the baseline. There is a localised anomaly, up to 12 mg/L, at around 300 m depth and occasional anomalous HS^- values occur elsewhere. Ongoing studies should explain the likely cause of the localised transient high values and give confidence that these high values will not persist, or go higher, in the future. Expected evolution of redox as the relevant target property is of primary importance in meeting the target for HS^-. Other target properties, DOC and CH_4, are involved in redox evolution as potentially important redox-active solutes and energy sources for microbiological activity (e.g. SO_4 reduction to HS^-). There needs to be more confidence about distribution and sources of DOC and CH_4.

It is expected that there should be some relationship between sulphide, SO_4, DOC, CH_4 or other microbial energy source, and microbial activity. That is not yet proven and needs to be studied further to give confidence about the potential causes of SO_4 reduction and bounding conditions on HS^- concentrations. In this data set, there does not seem to be any correlation of high HS^- with higher DOC contents.

Data for colloids are not fully adequate as there is no explanation of the compositions of the observed size fractions or of the uncertainties in the SEM data. The total concentrations are $< 2\times10^{-1}$ mg/L, which is very low compared with the measured DOC values. This raises the question of whether any of the DOC exists as colloidal material which has not been analysed by the SEM technique. The target property is for colloids to be 'low' and there is no evidence to suggest that concentrations are otherwise. More comprehensive studies of colloids are needed. The effects of natural colloid contents that are not 'low' are not explained and the issues associated with natural colloids are not adequately covered in TURVA.

Conclusion: Although there are several areas of continuing uncertainty, some anomalous values and a need for continued and improved interpretation, overall, none of the reliable data indicate any significant breaches of the target properties. There is inadequate evaluation of natural colloids (but see conclusions to 1.5.3).

1.4.4 Distribution of groundwater bodies with different origins

The depth zonation and the reactions controlling the distribution of sulphate-rich and saline waters (OSD, Section 7.3) are thoroughly evaluated and interpreted, although there is a persistent problem of understanding the factors controlling production of sulphide and the relative roles of methane and microbially-mediated processes in that.

An assessment of dissolved sulphide data, a discussion of the likely processes controlling production of sulphide, and the reactive transport model of long-term evolution of sulphide concentrations through future operational, temperate climate and glacial climate phases have been reported in Posiva 2014-01 (received at a late stage of this evaluation). It provides a comprehensive account of the modelling of possible ranges of sulphide concentrations in the future and is considered in Section 1.4.5.

The evolution and mixing of waters has been comprehensively explored using both the basic hydrochemical/isotopic data and palaeohydrogeological modelling, with the deeper, more saline waters showing empirical evidence of very slow and undynamic, diffusion-dominated processes below 300 m. Even the shallower, bicarbonate waters appear to have residence times of 1000 to 2000 years (OSD, p.534). However, this simple picture of deep, stagnant conditions has been challenged by the pore water data and there is a significant uncertainty in the total flow picture. Posiva proposes a concept where there has been upwelling of deep saline waters in the "pre-historical" period but notes that it would be at flow rates that are below detection limits (p.579).

The lateral variability of water compositions at and around repository depth is minor in relation to compliance with target properties. This is illustrated by depth plots of hydrochemical data (OSD, Fig.7-8) and maps of TDS and Cl^- concentration variations in plan format (Figs. 7-24 to 7-28). Data are absent for the southern and south-eastern parts of Olkiluoto island. Variability could be related to the HZs but the data are sparse and more discussion of the relationship with hydrogeological properties is needed. The latest hydrogeochemistry monitoring report (WR 2012-44) has some relevant analysis. If this variability is an indication of more and less transmissive bedrock, then it could give an idea of heterogeneous drawdown and heterogeneity of future infiltration of diluting groundwater.

Within the overall hydrogeological evolution regime, the behaviour of some of the major fracture zones (e.g. HZ19) remains open to further interpretations, as they may behave differently in different regions (e.g. depths) or at different times in a glacial cycle. The distribution of water compositions with respect to variations of hydraulic transmissivity (T) of HZs and fractures in the bedrock has been a focus of investigation. This is relevant to the safety case because water entering deposition zones will derive from very low-T fractures in intact bedrock. Considerable progress has been made in identifying water samples that come from the major HZs and obtaining water samples from rock with lower T. Sampling in ONKALO has focused on low-T fractures and there is now a reasonable amount of data as illustrated in the 2011 hydrogeochemistry monitoring report (WR 2012-44). Water compositions in these fractures and HZs can be compared with the improving knowledge of compositions of static pore water in intact rock matrix. Posiva indicate that water compositions do vary with T, with brackish-SO_4 water (i.e. Littorina-sourced) in higher-T HZs and brackish-Cl water in lower-T fractures (OSD, p.545). This suggests that the palaeohydrogeology and, by implication the future hydrochemical evolution, is heterogeneous through the bedrock, depending on fracture T and connectivity, as should be expected. The compositions of groundwaters that will enter deposition zones located in lower T rock will tend towards brackish-Cl rather than brackish-SO_4 compositions (i.e., will tend to be relatively depleted in SO_4).

The apparently transient disequilibrium between Cl^- concentrations in static pore waters and flowing fracture waters indicates that initial state must consider compositions of pore water in the intact rock matrix as well as compositions of waters in fractures. Rock matrix is the volumetrically dominant reservoir of water at repository depth. Pore water data have corresponding fracture water compositions available only to about 400 m depth (Fig. 7-30). OSD observes (p.577) that the markedly lower salinity waters found in the matrix compared to that in the fractures at depth is “surprising” and postulates that this indicates that highly saline waters have entered the site “recently”. There is a significant gap in knowledge about potential disequilibrium between compositions of pore waters and fracture waters below repository depth. This adds to the uncertainty about composition of water that would enter deposition zones. It is noted that anion exclusion during the pore water analysis procedure has not been excluded as a possible explanation for the apparent difference between pore waters and fracture waters.

Posiva recognises (OSD, Section 10.9.2) that this is one of the two principal hydrochemical issues that they say remain to be dealt with. The Performance Assessment report observes (p.212–213): *“All the modelling results show that the estimation of the salinity evolution and the groundwater evolution in general is sensitive to the parameters affecting salt transport: flow and diffusion porosity and dispersivity and the buffering effect of the matrix. Therefore an understanding of the interaction between the fracture water and matrix pore waters will be further developed in the next research period 2013–2015”.*

The gradient of increasing salinity beneath repository depth and the potential impact of upconing is a significant issue for the safety case. A linear extrapolation of salinity beyond 1000 m depth suggests that saturated brine (i.e. ~300 g/L TDS) could be reached by ~2000 m depth (OSD, p.550). Posiva notes that ‘saline groundwater may have been slowly upwelling through the fracture system’ (p.583), but their interpretation of palaeohydrogeological evidence in terms of saline water upconing is inconclusive. Posiva has presented a preliminary analysis of network effects in a Hydro-DFN on saline water upconing to DHs in the repository (WR 2012-48), but the model was in a development stage and requires further verification and validation as a tool for predicting heterogeneous upconing.

Posiva resolves the present-day groundwaters into mixtures of different end-member components or reference waters, using the PHREEQC geochemical code. This contrasts with the approach used by SKB, where a statistical tool (‘M3’) has been used to resolve a large set of groundwater compositions into components. Posiva’s approach is robust, within the limitations of a model for complex mixing using a complex data set, and makes it easier to identify the origins of uncertainties. Posiva’s assumptions of end-member water compositions inevitably smoothes over the real complexity of hydrochemical evolution. This is acceptable, given that detailed resolution of mixed groundwaters in the ‘initial state’ is not critical for the safety case. An area of uncertainty is the detectability of minor, but potentially significant, proportions of a reference water. It cannot be claimed that small proportions are present nor that small proportions of reference waters are definitely absent. This leads to cautious statements such as (p.639) ‘intrusion of melt water is mainly limited to the upper 400 m’.

Conclusion: The variations of salinity and general compositions that are apparent in water at repository depth have various sources of uncertainties, but the magnitude of variability in present compositions at repository depth does not represent any highly significant safety-relevant issues. The reasons for the distributions of groundwaters of different composition or origin are credible and plausible. The deep matrix porewater story needs to be resolved, by better fracture-to-matrix profiles and/or deep boreholes, coupled with reduction of uncertainties in analysed compositions, as it has implications for dilute water penetration scenarios.

1.4.5 Buffering capacity of the rock to perturbations

Buffering capacity is required to ensure that there are not large changes away from the initial geochemical state such that compliance with target properties might be lost. The benefit of the chosen disposal depth in safeguarding hydrogeochemical stability needs to be evident. Critical factors are redox conditions and sulphur chemistry, as these affect the stability of the canister and the spent fuel.

Data uncertainties in the principal redox couple (sulphide/sulphate) mean that it remains uncertain what redox couple controls Eh and what redox couples are active. However, Posiva is justified in saying that the present redox conditions at repository depth are anoxic and reducing. There is a need to show that present-day redox processes in high-SO_4 and low-SO_4 groundwaters are understood and are consistent with measured Eh values, and that this understanding can be translated to forecasts of how redox will be buffered for various scenarios for DO, HS^-, SO_4^{2-}, CH_4, DOC and Fe in the evolving system.

Measured concentrations of dissolved sulphide, HS^-, are mostly low, in the range <0.01 – 0.6 mg/L, although localised higher concentrations up to around 12 mg/L are reported (Posiva 2014-01; Sulphide Fluxes and Concentrations in the Spent Nuclear Fuel Repository at Olkiluoto). These anomalous higher values are transient and are considered to occur when hydrochemical perturbations in boreholes stimulate microbial activity and sulphate reduction. This is the most plausible explanation, though the details of biogeochemical processes are not understood. Therefore the likely frequency, locations and persistence of similar future anomalous HS^- production in relation to excavation and operation of a repository are not understood. Further monitoring and investigation of the phenomenon is necessary. A particular aspect is uncertainty about the identity of the electron donor(s) that is/are responsible for reduction of sulphate. Dissolved organic carbon (DOC) and/or methane (CH_4) are candidates. It is argued that any influx of DOC is attenuated before it penetrates to repository depth by reaction with the abundance of SO_4^{2-} at shallow depths.

There is no compelling evidence that anaerobic oxidation of methane (AOM) is a significant route for reduction of SO_4^{2-} in crystalline rock groundwaters. There are various lines of reasoning that it is probably not significant at Olkiluoto, though a possible role of traces of higher hydrocarbons associated with methane is mentioned (Posiva 2014-01, p.27). The source(s) of CH_4 is uncertain and probably spatially variable: it is currently well below saturation level at depth, although losses during sampling mean that CH_4 concentrations are likely minima (OSD, p.626). Isotopic evidence indicates both bacteriogenic and thermogenic components, with indications that it is mostly from an abiogenic 'deep geological' source. The fate of CH_4 is also unclear: whether the decrease of CH_4 with decreasing depth is due to dispersion or to oxidative reaction. In summary, considerable uncertainty remains in the sources and reactions of CH_4, specifically in the reduction of SO_4 to HS^- (OSD, p.632). The reactions that account for SO_4 and CH_4 changes occur in the depth interval 200-400 m, just above the repository location, so an understanding of potential biogeochemical reaction of SO_4 and CH_4 is of direct relevance to the corrosion model of EBS performance. The production rate of HS^- remains an open question. Overall, however, it is a reasonable argument that the production and flux of HS^- in groundwaters at repository depth will be constrained particularly by supply and reactivity of electron donors, as well as by hydraulics and SO_4^{2-} concentrations.

Fe^{2+} is the other redox-active solute, in addition to HS^-, in groundwaters and rock. It has a greater potential buffering capacity than HS/SO_4^{2-} because of its occurrence in silicate minerals, but Posiva states that a Fe-oxide mineral buffer is lacking (OSD, p.592), so there is an open question about what buffers dissolved Fe^{2+} and therefore redox. This question needs to be addressed to give confidence in the redox buffering capacity of the rock, especially at repository depth.

Information about populations of microorganisms is complementary for a description of the redox initial state. The reporting of the microbiological aspects of redox is inconclusive. Populations are higher and more diverse in the groundwaters that contain both CH_4 and SO_4 (OSD, Fig. 7-50). This suggests that redox, HS^- production and CH_4 oxidation might be coupled by biogeochemical reaction pathways, although Posiva has concluded that there is not compelling evidence of straightforward anaerobic oxidation of methane (AOM; see above). Additional research would be needed to resolve this more conclusively. OSD Fig. 7-51 shows depth-dependent variations of microbial populations and numbers with a suggestion that this is indicative of redox trends. This suggests a hypothetical role of microorganisms in redox processes. The reproducibility of microbiological samplings and analyses needs to be demonstrated to establish whether this represents in situ heterogeneity. The conceptual model for a biogeochemical redox reaction sequence that couples DOC, SO_4, CH_4 and H_2 is compelling (OSD, p.608). It requires additional confirmation so that the possible changes of the system due to short-term perturbations and long-term evolution can be forecast. Perturbations of the system due to excavation and operation would promote temporary microbial activity and transiently accelerate biogeochemical redox reactions. The state of the redox system when these disturbances cease needs to be considered and confirmed for the initial state in the post-closure safety case.

It is evident from the points above that there is inadequate understanding of HS^- production and of what controls the maximum concentrations of HS^-. A coherent, evidence-based interpretation and mass budget of S hydrogeochemistry is required. A more comprehensive understanding of redox reactions, including potential release of Fe^{2+} from rock, is also needed.

A reactive transport model is used to forecast the likely variability of HS^- concentrations in the long-term evolution of the groundwater system through operational, temperate and glacial stages of future climate (Posiva 2014-01). In general, it is argued that HS^- will be limited by precipitation of an iron sulphide solid phase, most probably amorphous FeS. Apart from the possibility of local transient high HS^- due to biogeochemical perturbations or limited Fe^{2+} availability, long-term average concentrations 'well below 2 mg/L' are expected (Posiva 2014-01, p.9). This is a strong argument and is generally supported by data from a range of natural systems.

The reactive transport model, FASTREACT, of hydrochemical evolution of groundwaters at Olkiluoto is constructed by coupling the flow model FEFTRA and the RW3D-MT random-walk particle-tracking model with the PHREEQC geochemical model (WR 2014-09; see Section 1.4.2). In effect, it seems that the groundwater flow and particle-tracking calculations are used to identify discharge flow paths from repository depth to surface and to calculate travel times. Travel time is then used as the parameter that represents distance along a 1D reaction path in PHREEQC (Posiva 2014-01, p.41). The model involves many simplifications and assumptions and produces an illustration rather than an accurate spatially-discretised representation of how, assuming FeS equilibrium and specific sources of Fe^{2+}, HS^- concentrations might vary in the long-term future. In particular, HS^- is modelled as originating from pyrite dissolution only, whilst the microbial reduction of SO_4^{2-} is not included in the model because there is insufficient information for a quantitative assessment (Posiva 2014-01, p.39). This is a major limitation on how representative the model is (p.68). Another comment about the model is that it assumes that Fe^{2+} is derived from, amongst other mineral sources, dissolution of a ferrous calcite. This is a reasonable simplification for modelling but is not supported by mineralogical data. Overall the reactive transport model is too simplistic to produce a credible forecast of spatial and temporal variability. Nevertheless it is indicative of how HS^- concentrations will be controlled given the validity of FeS equilibrium for which there is strong supporting evidence.

Conclusion: It remains uncertain what redox couple controls Eh and what redox couples are active. Further work is required on the biogeochemical controls on redox and sulphur chemistry at disposal depth. It would be valuable to have a clearer picture of how methane concentrations in groundwaters around the disposal zone could evolve after closure and affect near-field chemistry. FeS equilibrium is the basic principle underpinning control of sulphide concentrations in groundwaters at repository depth. There is a lot of evidence that this is a robust and generally applicable concept for typical sulphide in the long term, although uncertainty remains about the likely occurrence of transient localised higher concentrations of sulphide. The numerical model of hydrochemical evolution in the long term provides an illustration of how HS^- might vary in general on the basis of some simplifying assumptions about geochemistry. However it cannot be regarded as an accurate representation because it omits the microbial reduction of sulphate and simplifies the complexity of how dissolved iron might be controlled.

1.4.6 Palaeohydrogeology

Evaluating the past evolution of the groundwater system and its response to perturbations depends on interpreting data on the distributions of groundwaters with different compositions, origins, ages and residence times, and calibrating and testing a hydrogeological model for transient groundwater movement and solute transport over long time periods to be consistent with the natural evidence. Report WR 2014-27 was received at a late stage of this review. Its content is significant for the alternative constraints on palaeohydrogeological evolution and alternative parameterisation of the flow and transport model that are proposed on the basis of interpretation of hydrochemical and isotopic data, especially those for pore waters in the rock matrix.

Hydrochemical and isotopic data for groundwaters (i.e. mobile water in fractures) and pore waters (i.e. immobile water in the rock matrix that exchanges with fracture water by diffusion) have been used to test the assumptions and parameterisation of the hydrogeological flow and mass transport model. Data for porewaters are limited, due to analytical practicalities, to chloride, bromide, stable oxygen, hydrogen and chloride isotope ratios, and helium and methane contents. Data are available from three cored borehole profiles: two are surface-based boreholes, one to about 400 m depth in the target volume and one to about 800 m at the northern edge of the island; the third is a 60 m length of a sub-horizontal borehole at about 300 m depth, drilled from the ONKALO tunnel so that it intersects fracture zone HZ20B. Chloride concentrations in pore waters from all of these profiles are significantly lower than those in corresponding groundwaters. A clear relationship between chloride content and distance from the nearest fracture is not evident, so the timescale of diffusive equilibration between groundwater and pore water cannot be inferred. The difficulty of estimating the relevant fracture frequency in 3D that controls diffusive exchange further complicates that approach to interpreting the evolution of pore water compositions in terms of palaeohydrogeology.

The main implication of the pore water data for palaeohydrogeology and the flow-transport model is that the water compositions must have been established by in-diffusion from relatively dilute groundwaters in fractures for a period of tens to hundreds of thousands of years. The stable isotopic compositions of pore waters indicate that the relatively dilute water was not just of glacial origin. Therefore the dilute groundwater condition must have persisted through the interglacial periods and possibly also in pre-glacial times. Thus it is likely that the ‘normal’ evolution of groundwater in the future will be dominated by similarly dilute compositions.

A further issue for palaeohydrogeology, accepting that groundwaters in the long term past have been dominated by deep circulation of relatively dilute compositions, is the origin and hydrodynamics of the ‘brackish-Cl’ and saline groundwaters that are in the deeper parts of the observed groundwater system. This salinity is attributed to in-mixing of very old ‘Shield’ brine under the influence of an upwards hydraulic gradient. The interpretation of this in WR 2014-27 is that, unless matrix diffusion is much weaker than assumed, ‘the depiction of nearly stagnant deep groundwater environment is unavoidably incorrect and highly saline groundwater must have entered the site relatively recently’ (p.171). Thus, overall, the palaeohydrogeological interpretation in WR 2014-27 suggests a more dynamic deep groundwater system persisting over a very long timescale, influenced by regional flows and upwards gradients at depth and relatively dilute water circulation down to at least repository depth.

The potential implications of this for the modelling of future groundwater evolution and solute transport are various – some of more direct relevance than others (WR 2014-27, p.149). They leave a number of open questions that need to be resolved, amongst which is the reliability of the porewater data. Firstly, the relative dilution of porewater compositions invalidates the assumption for initial state of the hydrogeological model at 8,000 years ago that pore waters and groundwater compositions were identical and equilibrated. The significance of that assumption impacts on the forward modelling to present-day pore water compositions and ‘calibration’ of the model by comparing modelled with observed data. Secondly, the preservation of dilute compositions in porewaters irrespective of proximity to transmissive fractures suggests that the in situ pore diffusivity is lower than the values that have been assigned for matrix diffusion in transport modelling. This has a direct impact on modelled radionuclide retardation. Thirdly, the inference of an upwards gradient in the deep saline groundwater affects the calibration and validity of the site-scale hydrodynamic model although it is probably a second-order influence on long-term solute transport.

Groundwaters with different compositions and origins are physically modelled as mixtures of five reference waters, which is adequate for simplifying the physical mixing model but smoothes out the pre-glacial palaeohydrogeological complexity. There is a problem with having a single pre-glacial water composition, in that the proportions of 'brine' and other pre-glacial groundwater components would probably have varied in different parts of the system. It is understandable that Posiva have made this simplification, because the focus of interest is on post-glacial mixing, but there should be discussion of the implications for not resolving pre-glacial mixing especially in the light of the pore water evidence. It is to be expected that there is complexity in the palaeohydrogeology over the million-year timescale of interest, which is reinforced by the evidence of very old, relatively dilute water being found in matrix pore waters. Overall, the palaeohydrogeological model is heterogeneous. For example, Littorina 'brackish-SO_4' water penetrated further in the more transmissive HZs whilst less transmissive fractures retained 'brackish-Cl' water (OSD, Fig. 7-16). The evidence supports a concept of 'compartmentalisation' of flow connections, which should be reflected in the models for past and future groundwater evolution. The hydrogeological model appears to produce less heterogeneous geochemical profiles than are indicated by the site data, suggesting that the Hydro-DFN component may not adequately represent the heterogeneity and anisotropy of the rock mass. The overall behaviour of the site-scale model appears to be dominated by the HZs, so the heterogeneity of profiles in the rock mass may represent the best means for assessing the Hydro-DFN component with respect to hydrogeochemical data.

The numerical palaeohydrogeological model has an initial condition set at 8,000 years ago, i.e. post-glacial, so it cannot test any concept of glacial water infiltration. The assumed initial distribution of water types ('glacial' water at 0–200 m, 'sub-glacial' water at 200–600 m, and 'brine' at >600 m depth) is consistent with data interpretations, but the assumption that fracture water and pore water compositions are equilibrated is not consistent with the evidence of pore water origins (see discussion above). There is considerable uncertainty in the hydraulic conditions for the palaeohydrogeological model. This is safety-relevant with respect to whether the past and present hydraulic gradient affecting saline groundwaters below repository depth is directed upwards or downwards, or is hydrostatic, and whether that gradient is controlled by site-scale influences or by regional-scale groundwater flow (OSD, p.579; WR 2014-27, p.149). This implies uncertainty about how the hydraulic gradient will evolve in the future. This uncertainty is reinforced by the findings of matrix pore water analyses (p.581), which suggest a long period (>1 Ma) of fracture waters in deep bedrock that are less saline than at present and having a predominantly meteoric origin.

The conceptual model should take into account the degree of large-scale anisotropy caused by the distribution of sub-horizontal and sub-vertical HZs, and the (probable) low connectivity in the fracture network and resulting 'compartmentalisation'. Long-term evolution of hydrochemistry, i.e. location of the brackish-saline-brine groundwater masses and specifically the variability of where brackish-Cl groundwater appears, would be controlled primarily by dispersive mixing between circulating meteoric water and almost-static, deep, Shield-type brine. The suggestions that 'saline water may have been slowly upwelling through the fracture system; and 'upwelling of saline groundwater may have hindered infiltration of Quaternary meteoric waters to depth' (p.583) would be better reconciled in that concept with the evidence from groundwaters and pore waters.

A question for future stability of the groundwater system is whether a long period of temperate climate and meteoric water infiltration, along with continuing uplift and increasing hydraulic gradient, will disturb the existing stratification and make the groundwater system more vulnerable to flushing by a future meltwater intrusion.

The effect of permafrost on the groundwater systems is enigmatic. Posiva's interpretation of palaeohydrogeological evidence is that permafrost had little if any impact on groundwater at repository depth during the Quaternary. Evidence for salinisation due to 'freeze-out' or SO_4-enrichment due to mirabilite precipitation is absent.

Absolute or relative groundwater ages are potentially an important contribution to palaeohydrogeology. Carbon-14 (^{14}C) and water stable isotope data are the two main methods. The qualified ^{14}C data cannot be interpreted quantitatively in terms of groundwater ages, but ^{14}C is still a key qualitative indicator of groundwater ages and the qualified data should be interpreted and integrated with water stable isotopes, ^{4}He and ^{36}Cl, which have both been measured (OSD, p.535-539). The conclusion that Cl has resided in these rocks for >1.5 Ma is justified, as is the inference that the water associated with that deep-sourced Cl also has an age of >1.5 Ma. The pattern in Fig. 7-11, of decreasing ^{36}Cl from dilute groundwaters towards brackish-SO_4 groundwaters, with an increasing trend towards the secular equilibrium value, is compelling evidence that the deep 'brine' is very old and contains rock-derived chloride. The depth trend of ^{4}He (Fig. 7-12) and the estimated in situ production rate also support the idea of very old deep saline/brine groundwaters.

Section 3.1 in the PAR gives a concise summary of the palaeohydrogeological interpretation of groundwater and pore water compositions. It has dilute water replacing brine groundwater through the Phanerozoic period of many millions or tens of millions of years (based on evidence from pore waters), then brine rising to replace dilute water, due to changes of regional gradient through the Quaternary period of glaciations over the past 2 million years. This hypothesis is compelling and it has implications for the modelling of long-term salinity evolution – for example, how the groundwater system will respond to boundary condition changes over multiple glacial cycles through the next million years. The PAR (p.309) states that 'The understanding of the dilute water circulation at the Olkiluoto site is based mainly on palaeohydrogeological evidence'. The idea that saline and dilute waters might have oscillated in the system in the past is reflected to some extent in the conceptual model that underlies Posiva's numerical modelling of hydrogeology through the next glacial cycle: for example, with regard to saline groundwater upconing due to the hydraulic gradients in the vicinity of an ice sheet margin. Posiva needs to reassess critically the robustness of the palaeohydrogeological interpretation as a basis for modelling the reference evolution and preservation of target properties.

Conclusion: The palaeohydrogeological interpretation of past salinity changes is a conceptual basis for the modelling of future evolution, especially the extent of groundwater dilution during temperate and glacial periods and transient upconing of deep saline water during glaciation. Posiva needs to reassess and confirm the robustness of their palaeohydrogeological interpretation in the context of rock properties for flow and transport and of observed disequilibrium between pore water compositions and groundwaters. Possible alternative interpretation and model constraints need to be considered, that might have implications for how the long-term evolution of the system is modelled, especially with respect to target properties.

1.4.7 Buffering of infiltrating water in the surface-biosphere region

Oxygen only occurs in the very shallow oxic layer of the groundwater system (typically at 10% saturation level). Empirical evidence for the stability of a 'redox front' at a few tens of metres below the surface over geological time periods (with anaerobic conditions below this) is illustrated by the manganese data (OSD, p.521), supported by the presence of well-preserved sulphide and calcite grains (Mn is present in the calcite) and the scarcity of iron oxyhydroxides on fracture surfaces at depths greater than 10 m (p.591). This depth stability is described as a "constant feature of the site".

An Infiltration Experiment has set out to understand some of the processes at the early stages of hydrogeochemical evolution of infiltrating water in and around a HZ. One of the aims is to observe the reactions whereby dissolved oxygen (DO) in infiltrating groundwater is consumed in the shallow subsurface, which would be a strong argument against the possibility of DO reaching repository depth in the future. It is reported that DO is not detected, nor any changes of redox species, in two years of pumping from the shallow extraction well in the experimental array (OSD, p.678). It is inferred that reaction with DOC accounts for DO consumption, consistent with findings of the REX experiment in the Äspö HRL in Sweden. The hypothesis of DOC being the reductant that consumes DO raises the question of how DOC, and therefore O consumption, will change in future environmental conditions. DOC derives primarily from soil, in which organic contents will vary in the future. DOC will be depleted, or soil completely removed, by a future glaciation. If organic C ceases to be available, then there is a question over what reductants are available in the bedrock to react with DO. Geochemical information about the distribution of sulphide and Fe^{2+}-containing minerals, and their potential reactivity towards DO being transported through HZs, is needed.

Conclusion: Geochemical processes in the shallow waters are reasonably well characterised and the field and experimental evidence for rapid redox buffering by consumption of DO is good and supports studies elsewhere. In general, biosphere-geosphere interactions are understood well enough in the perspective of geosphere understanding and representation.

1.5 Characterisation of solute transport properties of the bedrock

This Section considers how Posiva has characterised and modelled the transport pathways and processes that could lead to migration of radionuclides from the repository to the surface environment.

1.5.1 Required retention properties

Retention properties are included at a high level (as good containment properties of host rock) in the upper levels of VAHA, but the only specific mention is in L3-ROC-33 *"The properties of the host rock shall be favourable for matrix diffusion and sorption"*. This subsystem requirement is not translated into a L4 requirement and, of course, does not appear in the RSC (which cover L4 and L5), so any quantitative definition of 'favourable' consequently seems to be missing from the VAHA requirements. Posiva considers the transport resistance WL/Q as *"more significant for geosphere retention"* than the detailed retention properties of different rock types and fractures. This places the burden of justification on the Hydro-DFN model that is used to calculate WL/Q distributions for flow paths from deposition holes. The L3-ROC-20 requirement for a high transport resistance in the rock in the vicinity of a DH is based on a parameter that cannot be measured, only inferred.

Conclusion: With no development in VAHA, the target retention properties are not clear in the documentation. In fact, performance targets for retention are arguably irrelevant to the site and the safety case – the site was not selected for its retention properties and this would have been an inappropriate requirement anyway.

1.5.2 Characteristics of flow and transport pathways

The transport pathways are derived from the Hydro-DFN, hence the core factor in the robustness of the advective radionuclide transport model is entirely dependent on that of the DFN, which has been discussed in detail earlier, in Section 1.3 of this review. The transport model in the Hydro-DFN is based on retention classes (OSD p.707–708 and Figure 8-11). Posiva presents a good geological basis for the retention classes. The model randomly chooses a retention class based on probabilities for given hydraulic unit, fracture orientation, and depth zone. The model includes the possibility for different fracture segments to have different retention classes. This is a reasonable model, but leaves an open question as to whether correlation of retention classes between segments along a given path could be significant. We also note that the boundary between depth zones 3 and 4 is close to repository depth. The transport (volumetric) aperture is estimated by the Hydro-DFN to be simply 10 times the hydraulic (frictional) aperture (OSD p.709-710). Posiva recognises high uncertainty in generic relationships, but alternatives ought to be considered for scoping purposes. Posiva argues that advective travel time is not a major uncertainty for radionuclide retention, relative to matrix diffusion properties.

An *"elaborated Hydro-DFN model"* is introduced for transport-property calculations in OSD Section 8.3.3 and explained in WR 2012-32. This represents an extended version of the Hydro-DFN, taking advantage of higher-resolution data from PFL logging in pilot holes to give more information about low-transmissivity fractures. Small differences among Hydro-DFN models for the near-field are noted for the low-F tail of the distributions (OSD p.713). This is the portion of greatest concern for radionuclide retention.

Fracture fill, matrix diffusion properties and retention properties are the key factors controlling retardation. Table 4-10 of WR 2012-32 shows no correlation at all between fracture fill materials and PFL fractures: both PFL and 'all' fractures have the same ratios of fill materials, suggesting little correlation between fracture mineralogy and flowing features. The interaction of the fracture and pore waters was discussed in Section 1.3.5 of this review. The selection of sorption parameters (MDR, Appendix L) appears to have been via an informal and limited expert review process, not 'expert elicitation', as it is purported to be. The reports covering this area are Posiva 2012-39 and 2012-40. The Radionuclide Transport report (Posiva 2014-02) simply lists sorption data without giving any reference to where they come from. The Release Scenarios Report (2012-09) has just one paragraph that outlines how K_D values are obtained.

The Monte Carlo simulations for PSA (WR 2013-25) are useful to assess sensitivity to uncertainties in flow-related and non-flow related transport parameters. The model is simplified to consider only one type of fracture, rather than the 4 types that are described, with a comment implying that the fracture coatings that characterise the other 3 types of fractures have no effect on transport because they are considered to be non-sorbing. It is not clear whether there is any significant effect being tested with the 4 fracture classes.

The FEPs report also discusses precipitation and co-precipitation (FEP 8.3.2), stating that precipitation controls are unlikely because of dilution of radionuclides. An example of co-precipitation given is the retention of Ra by barium sulphate. This FEP is omitted from the transport model in safety analysis as a conservatism: ignoring it represents transport pessimistically. We note that U transport is more complex than simple sorption and matrix diffusion. U has a natural abundance in the groundwater system at Olkiluoto. Depending on overall concentration and speciation of natural and waste-derived U combined, co-precipitation or even precipitation may occur, which is not mentioned in the FEP description.

Non-linear sorption is introduced as a FEP but is not then represented in the safety analysis. There is no discussion of why it is omitted, as a justifiable simplification, from further consideration. In fact, the whole issue of mechanistic (thermodynamic) sorption modelling is omitted from discussion, as is discussion of uncertainties and justification of Kd as a simplification of a more complex thermodynamic process, dependent on other variables. We consider that the simplifications of the Kd approach potentially introduce uncertainties, but it is generally agreed that these are manageable in the transport model for safety analysis.

In general, the conceptual basis and method of constructing the transport model from DFN and other data, looking at different flow and transport classes of fracture, then applying them in a stochastic fashion along a transport pathway, is realistic and has been carried out well.

Conclusion: Posiva's approach to modelling the properties of transport paths based on allocating fracture segments to different "retention classes" consistent with the geological characteristics of the fracture sets is reasonable and is well supported by geological arguments. The approach depends strongly on the Hydro-DFN, underscoring the need to ensure that uncertainties in the Hydro-DFN are progressively evaluated. Comparison with the alternative model of flow and transport through the SFR is advisable, given that in-situ verification of network transport properties is extremely difficult and unlikely to produce unambiguous results. The geological properties and classifications of transport pathways are sufficiently well characterised and modelled for migration analysis purposes. Reporting on the retention parameters of bedrock was not available when this review was carried out.

1.5.3 Natural colloids

Posiva says (OSD, p.689) that the concentration of natural colloids is low and, under reference case conditions, colloids generated within the repository will be filtered out by the buffer. The probability of colloid-facilitated radionuclide transport being significant is not considered to be great, although it is studied in calculation cases of the SA. OSD presents almost no colloid data, simply saying that concentrations are, "for example" 0.2 and 0.7 mg/l and that, in addition to organic colloids, inorganic colloids "may be found…" and that the limited measurement work reported in WR 2009-108 is "not used in SR2011" (p.62). The 2009 WR reports only two new measurements (although there are some data from earlier samplings) and identifies both sampling problems (possible grout contamination) and an intention to do further work, which seems not to have happened.

MDR, Appendix K, provides an overview of natural colloid concentrations and radionuclide sorption onto colloids, including kinetic desorption. This is a rather thorough summary of what is known. It recommends that a colloid-facilitated transport model and both reversible and irreversible sorption should be included in the safety case (done, as CS3-COLL). This is an appropriate input to the safety analysis.

Conclusion: Natural colloid characterisation is sparse and contains uncertainties, although Posiva clearly considers this not to be an important safety-relevant issue. This is a justifiable position to take with respect to natural GW colloids. A more important source of colloids would seem to be bentonite and any cementitious materials that might be in the vicinity of the repository. There is a specific calculation case that looks at the latter (CS3-COLL), which is introduced in the Release Scenarios report (Posiva 2012-09, p.75–77).

1.5.4 Discharge of transport pathways at the surface

Two approaches are presented to evaluating discharge areas: the head values from the surface hydrology modelling presented in OSD Section 3.6.6 and the particle transport modelling from the repository, presented in Section 8 and in WR 2012-42. Although the bulk of discharge currently occurs offshore, there are also areas where discharge is modelled to occur on land (Fig. 3-7).

Advective travel times from deposition holes within the 200 m repository near-field model are mostly <1000 years (Figure 8-19), with the median at “a couple of hundred years” (OSD, p.717). When the whole site-scale path to the surface is assessed, median travel time is about 1000 years (p.729), so any requirement in the safety case for geosphere containment must depend on retention on surfaces and in the rock matrix porosity. Transport resistance for the entire release paths are similar to those in the 200 m near-field model (p.725), so proportionally most of the retardation occurs within the repository scale.

OSD Section 8.3.4 describes the transport paths and release points arising from the stochastic model. Release points have been identified and cluster offshore to the N and S of the island (e.g. Figs. 8-22 to 8-25). The reason for this clustering at these locations is explained in WR 2012-42 and appears reasonable and justified. The description of how recharge flowpaths will evolve through the development and retreat of an ice sheet is unclear with regard to depth of penetration of recharge.

Conclusion: The OSD identifies discharge locations of groundwaters into surface waters and biosphere to support its model of the present day behaviour of the site. However, there is no evidence presented (other than proxies, such as the presence of hollows) to indicate that discharge is actually occurring in these areas. There is limited discussion about the possible discharge role played by HZ19. The OSD identifies the topic of discharge areas for deep groundwaters as one that needs to be pursued further (p.838).

1.6 Long-term response of the site to climate evolution

The response of the site to long-term climate evolution, particularly glacial cycling, is a key issue in the safety assessment. It is important that the deep system and the repository volume remain resilient to the varying TCHM conditions and stresses to which they will be subjected. The Appendices to the Scenario Report (Posiva 2012-08) discuss the choice and limitations of three key areas of evolution modelling: the forecasting of future climate, of glacially driven groundwater flow and of permafrost depth.

1.6.1 Climate evolution and its impacts

Posiva argues that existing climate models are good at simulating past glacial cycles but should not be used to make detailed forecast of future conditions, as they cannot be validated. We agree with this, as knowledge of the drivers and feedbacks in the global climate systems is still inadequate to make strict conclusions about past conditions or predictions extending to tens of thousands of years in the future. The simulations of climate and permafrost really describe possible conditions in the future and are best considered as stylized or speculative illustrations. The uncertainties involved are acknowledged by Posiva.

However, the simulations can be used to explore the inception of glacial conditions and the build up to those conditions. Posiva has simply reprised the last (Weichselian) glacial cycle (conditions which can be modelled with some confidence using the climate models) and has then repeated this seven times, over the next 1 Ma. Whilst this seems to be a reasonable approach, there is no description of how the decision was taken to go for a repeat

Weichselian as the only climate scenario. A more comprehensive evaluation would have been to explore the impacts of changing some of the key parameters in variant climate scenarios. Section 4 of the Scenarios Report outlines how Posiva has translated the climate modelling work to 10,000 years (Posiva 2012-26) and to 120,000 years (Posiva 2011-04) into scenario development.

The weakness of the evaluation concerns downscaling of coarse-resolution global climate models to predict future local conditions at the site. Also, uncertainties in future precipitation have not been evaluated. Changes in the amount and/or seasonality of precipitation during the ongoing temperate period could affect the rate of penetration of meteoric waters to repository depth. For the global climate models (GCMs) that were used, the geographic resolution is a major limitation. In the two GCMs used for projections on a 10,000-year time scale in the present report, the Baltic Sea is either absent or represented as a closed lake. The result is a climate based on a more continental situation for Olkiluoto than is likely to be realistic for the ongoing temperate period. The authors recognise this issue in terms of mean annual temperatures, but do not discuss the difference in seasonality of temperature and precipitation, which should be expected for a marine-coupled Baltic coastal climate as opposed to a continental climate. The GCMs disagree in terms of the consequences for precipitation that would result from the North Atlantic Meridional Overturning Circulation.

Apart from sea level change, precipitation is the primary outcome of interest from a hydrogeological perspective. However precipitation is given minimal treatment in Posiva 2011-04 and 2012-26, and uncertainties are not discussed. We are aware that the role of precipitation has been ignored in many studies dealing with palaeoclimate and glaciation history. It is usually noted that climate cooling and decreasing precipitation go hand in hand, but this makes it hard to explain what causes ice caps to grow. When taking into account partial melting, run off and evaporation, the time needed to build-up a thick ice sheet would arguably take well over ten thousand years, suggesting that precipitation should increase substantially.

The uncertainties in precipitation for a future warm (and plausibly, more humid climate) at Olkiluoto must be regarded as large, in the absence of relevant predictions. The influence of precipitation changes on groundwater conditions at repository depth may be muted to a large extent by other controlling factors, such as the slowing rate of land rise, which controls the potential gradients, and the low hydraulic conductivity of the bedrock, which limits infiltration. However changes in the seasonality of precipitation and infiltration (e.g. earlier spring snow melt in a warmer climate, or an extended rainy season) could extend the season over which infiltration is driven by a high water table and saturated soil conditions. Significant changes in annual precipitation could also affect the rate of flushing of the Baltic by freshwater, and hence the salinity and density of Baltic waters which control the boundary conditions for hydrogeological models.

Uncertainty regarding future precipitation regimes has not been assessed by calculation cases in the hydrogeological models. The hydrogeological models described in WR 2012-42 use a mixed-recharge condition for the upper surface, in which infiltration is limited by the precipitation. This is likely not conservative for evaluating the possibility for meteoric waters to penetrate to repository depth in an extended temperate period, in comparison e.g. with a model in which groundwater infiltration is driven by topographic heads, to simulate a future wet climate. Complementary hydrogeological calculations based on such an assumption would be one way to address this gap in the climate model predictions.

The two GCMs also give a poor match to absolute temperatures in comparison to observations for the modern period. The authors recognize this and use relative changes in temperature (and correlated climate variables) rather than the absolute values. However the poor match in absolute temperatures gives low confidence in the results for detailed predictions of local climate. The GCMs lack the capacity to account for dynamic behaviour of ice sheets, apart from melting and accumulation. This is most significant with regard to the potential collapse of the West Antarctic ice sheet, and the consequences for global sea levels in the near future.

The 120,000 years report was intended to support the formulation of scenarios for the Posiva safety case, but did not conclude by establishing either a single climate change scenario, or a set of scenarios, for the safety assessment. This problem was addressed in the Scenario Report, where the climate sequence mentioned above (Q1) was defined, based on these reports. A feature of the forecasts is system behaviour over the next few hundreds to around 1000 years – a period of rapid and (for some parameters), massive change, after which values achieve relatively steady values for the remainder of the 10,000-year period. Given the acknowledged general uncertainties in all the simulation models and the point made by the authors about the inability of ice sheet models to capture current rapid changes, this suggests that the next 1000 years is going to be a period of considerable uncertainty in terms of both global and local climate. Uncertainty in climate behaviour in this unstable period is compounded by the uncertainty in the driving rates of future greenhouse gas emissions, which define the scenarios analysed.

This suggests that, for the 10,000-year period, Posiva would be better to be conservative and *take a wide and pessimistic set of bounding conditions for assessment work (especially for the critical first 1000 years) and then to assume that any value is equally plausible.* The 10,000-year report identifies what these bounding values could be (temperature, sea-level, precipitation). For example, rapid sea-level rise is possible during the next hundreds of years (although possibly owing to an unlikely confluence of events and also partially matched by uplift of a couple of metres) with the report postulating a maximum of 8 m. The average elevation of the site is 5 m and the maximum 18 m. If this sea-level rise were to occur during the operational period (which might conservatively be assumed to extend out to 2150 or later) then there could be both immediate and longer-term consequences, and this possibility needs to be considered by Posiva.

A central climate scenario seems to be inappropriate without a set of matching scenarios that looks at alternative possibilities of sea level, permafrost development and ice cover. These scenarios do not need to use the results of climate models to develop sequences and timings – this is too uncertain. Over the longer term (say, 5 to 100 ka), a set of simple bounding scenarios (different onset times, magnitudes etc, justified by reference to the model results) can be selected, as alternatives to a continuing interglacial reference. There has been no test of 'best estimate' evolution that might arise from a group of climate experts. A quantified elicitation of degrees of belief in alternatives among a group of experts would have been a valuable means of gauging and managing uncertainties.

Posiva chooses the 400 ppm atmospheric CO_2 climate evolution scenario as the one to use for surface hydrology simulations, which provide the boundary conditions for deep groundwater simulations for the resulting prolonged temperate period to 50,000 years, but this is actually slightly less than current CO_2 concentration levels. The Release Scenarios report (Posiva 2012-08) says (p.62) that it makes no difference to use the 280 or 400ppm precipitation models, but does not mention the S1 scenario of unmitigated CO_2 emission, which would push levels up much higher still. These affect the biosphere more than the geosphere (along with the range in sea-level changes between the high and low emissions scenarios) but Posiva discounts some of these as largely insignificant (Posiva 2012-08, p.72–73) and use a constant climate of the Base Scenario. Sea level changes reflecting S1 and S2 emissions scenarios are, however, included in VS(B) variant scenario.

Possibly the more important impact could be the duration of the current temperate period. The Posiva climate model uses 50 ka prior to the onset of glacial cycling. This value can be derived from a number of studies and a range of values of CO_2 concentration (even as low as 250 to 260 ppm: Posiva 2011-04, Table 3). It seems inappropriate to use constant CO_2 concentrations over 100,000 years, when the temporal variations in this factor are so central to the model results. A critical and undiscussed question is whether the scenario of unmitigated emissions (burning 5000 Gt carbon) over the next century or so, leading to a CO_2 spike up to six times those modelled in 2011-04 and a portion of which lasts for up to 100,000 years (7% is suggested: Archer and Ganopolski[3], and Eby et al[4].), is going to dominate climate for 100,000 years. Table 3 notes that burning this amount of carbon would give rise to an interglacial lasting more than 200,000 years (e.g. from BIOCLIM modelling) and possibly more than 500,000 years. It would seem not only prudent

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[3] D. Archer & A. Ganopolski (2005). A movable trigger: Fossil fuel CO2 and the onset of the next glaciation. Geochemistry, Geophysics, Geosystems, 6. DOI:10.1029/2004GC000891.

[4] M. Eby, K. Zickfeld, A. Montenegro, D. Archer, K. J. Meissner & A. J. Weaver (2009). Lifetime of Anthropogenic Climate Change: Millennial Time Scales of Potential CO2 and Surface Temperature Perturbations. Journal of Climate, 22, 2501-2511, DOI: 10.1175/2008JCLI2554.1.

but also quite reasonable to assume that all known carbon reserves will be burnt. The implication is that the repository could undergo a very long period of temperate conditions that is not included in the current scenario analysis. The impact of this will be on the salinity of waters in the disposal volume. WR 2012-35 models the decreasing salinity in the repository out to 50,000 years, with TDS being reduced to well below 10 g/l in several cases by the end of this period (average value of 5 and minimum of 1 g/l: p.94). This is seen more clearly in Figure H-1 (p.172), where in the case presented, dilute waters (<0.4 g/l TDS) are found in some regions at disposal depth after 25,000 years. If the temperate period were to extend to 200,000 years or more, this effect would presumably become more prevalent, such that larger regions of the repository could experience dilute water penetration.

A footnote at p.99 in Posiva 2012-04 appears to be the only mention of a protracted temperate period: *"Note that the future climatic evolution scenario considering the (up to one million years) continuation of temperate conditions is not treated within this report due to the lack of meaningful events for long-term safety (no permafrost or ice sheets or meltwater)"*. This makes no mention of dilute water penetration and buffer erosion, which could be safety relevant, albeit some hundreds of thousands of years into the future. The impact can be seen in Fig. 7-8 of Posiva 2012-04, which indicates (from the Hydro-DFN modelling) that >200,000 years of dilute water penetration would push the number of canisters seeing dilute conditions up above 10% (several hundred canisters). The impact of this has not been explored in the CLA documentation and all the reports refer only to the 50,000 years temperate period and it being prudent to assume it 'likely' that there will be glacial conditions in the next 100,000 years. Groundwater evolution including salinity changes over the first 10,000 years after closure has been modelled adequately but there is inadequate modelling and qualitative forecasting of the evolution of flows and salinity for a more prolonged period of uplift and freshwater infiltration.

WR 2014-09, on hydrogeochemical evolution, became available at a late stage of this review. It describes coupled flow-reaction modelling of the long-term evolution of groundwater compositions using a new code, FASTREACT, which incorporates 1D reaction modelling with PHREEQC (see comments in Section 1.4.1). Essentially, the flow model assumes steady-state flow along a collection of streamlines and uses travel times along the streamlines as the metric to translate points on the streamlines to points on a 1D reaction-transport model in PHREEQC. Reference waters are used to define initial conditions and added components during evolution of groundwater compositions. The reactions included in the PHREEQC model are equilibrium with calcite, pyrite and kaolinite, kinetic dissolution of K-feldspar, albite and illite, and precipitation of siderite, iron oxyhydroxide and silica. Diffusive exchange of solutes between fracture waters and porewaters is also simulated in the long-term modelling, though only a single porosity concept is used for modelling of the early post-closure stage. This model set-up and method is a simplification of the hydrodynamic and hydrogeochemical system and involves various assumptions about reacting minerals and reaction parameters. The model compares reasonably with other state-of-art approaches to coupled flow-reaction modelling, though evaluation of this new model code needs to be supported with more complete documentation and verification. The modelled output of evolved groundwater compositions and buffering capacity with respect to redox and pH is reasonable and comparable with results of similar modelling. It is noted that the resulting sulphide concentrations have been used as boundary values for the analysis of sulphide fluxes in the EBS (Posiva 2014-01). The results for cation concentrations during dilution by glacial melt water indicate that the sum of cations is likely to exceed the target property value, owing to mineral dissolution. However, this dilution modelling has apparently not been done for the extended timescale of tens of thousands of years that is relevant to hydrogeochemical evolution through the temperate period. More work is needed in that respect, although the processes of mixing between water masses with different salinities, diffusive exchange with matrix porewater, and water-rock reactions make it highly probable that water dilution will be moderated above the target property value for chemical erosion of the buffer, even for the variant scenario of an extended period of temperate climate and dilute water infiltration.

A further issue is whether using the Weichselian as a model for the repeated sequence of glacial cycles modelled for the next 1 Ma is appropriate.

Posiva presents this as an alternative to making a forecast of future climate conditions, as forecasting uncertainties are large (being mainly centred on atmospheric CO_2 levels) and because there is the most knowledge about conditions and processes in the most recent glacial cycle for use in their performance models. We agree that this approach is reasonable: owing to the ready availability of geological observations and datable sediments, the Weichselian Stage is the best available baseline when evaluating possible scenarios of future climate. However, the Weichselian in Finland was a more complex and variable stage than the simple model used by Posiva. The formal chronostratigraphical term "Weichselian Glacial Stage" for sediments representing the time span from 116,000 to 11,500 years ago (MIS 5d–MIS 2) is somewhat misleading, because the climate during that time was highly variable, including both cold and temperate events. A number of former and, especially, many recent studies, indicate that the whole of Fennoscandia was glaciated during only a minor part of Weichselian time. The climate, as well as the limits of the Scandinavian Ice Sheet (SIS), fluctuated during this time span. Thus, rather than strictly linking certain climatic events to certain times in a timeline from 120,000 years ago to the present, it would be better in future studies to use approximate durations of certain type of climate. The climate was on average more severe during the Early Weichselian (116–74 ka BP; i.e. MIS 5d–5a) and in the beginning of the Middle Weichselian (74–~60 ka BP; i.e. MIS 4) than that prevailing at present, although the SIS had only a limited extent. Also, fairly temperate events occurred during that time. However, exact timings of different climatic events are still inadequately known. Additionally, as stated previously in this Section, an approach that scoped the impacts of extremes of climate based on the whole Quaternary database should also be looked into. However, we acknowledge the difficulties of doing this, as it is not clear whether such extremes (e.g. longer, colder periods in the preceding Saalian and Elsterian Stages) would actually cause more severe conditions (such as greater ice thickness) than those modelled for the Weichselian and thereby make Posiva's analysis non-conservative. Present knowledge of the timing and duration of cold periods, thickness of ice cover and the rate at which the ice front advanced or retreated across Olkiluoto during pre-Weichselian glaciations is too sparse and fragmentary to make valid comparisons to Weichselian conditions. Indeed, it is commonly assumed that the behaviour of previous ice sheets did not deviate substantially from the Weichselian ice sheets. The ice divide zone of the Scandinavian Ice Sheet was situated approximately at the same place during different glaciations. There is no valid proof that previous ice sheets would have been substantially thicker or thinner, or their movements faster or slower, than during the Weichselian.

In this context, Lagerbäck and Sundh[5] suggest that the Weichselian might be unique among Quaternary glaciations in having led to major PG faulting. They note that: *"Therefore, if, as it appears, previous deglaciations did not generate analogous faulting in northern Sweden, the question of what was atypical for the most recent ice sheet and its deglaciation remains the principal scientific question awaiting a solution. … A circumstance that, tentatively, may be of some interest in this context is that the last ice sheet apparently was cold-based throughout its entire existence in wide areas of northern and central Sweden…. The ice sheet most likely accumulated over a deeply frozen landscape and in wide areas the permafrost persisted to the very deglaciation (Figs. 92, 93). This raises the possibility that the development of residual fluid overpressures may have been a contributory factor in triggering this phase of faulting. … Fault stability margins would be significantly reduced under conditions of raised fluid pressures. This could tentatively explain what was unique both about the Weichselian deglaciation, and the particular circumstances of northern Fennoscandia, for the generation of this extraordinary episode of faulting".*

OSD Section 7.7.1 speculates on the very slow (below detection limit heads and flows) upwelling of deep saline waters as a result of regional gradients. However, this process, if it exists (it is not seen in the hydrogeological data – p.584), would appear to be continuously masked by changing, dynamic conditions in shallower waters caused by glacial cycling, which displace or mix (diffuse) meteoric waters with deep-source waters. The OSD also indicates that there is no trace of dilute glacial waters below about 300 m. Appendix 2 of the

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[5] R. Lagerbäck & M. Sundh (2008). Early Holocene faulting and paleoseismicity in northern Sweden. Sveriges geologiska undersökning, Research Paper C 836.

Scenario Report explains why Posiva has chosen the models it has used in its Variants and justifies not having modelled groundwater flow and chemistry during ice sheet advance (only modelling static ice front and retreat conditions). The rationale for its approach is reasonable and the statement that the basis for VS2 (static ice front over the site for 1000 years) is sufficiently cautious for the safety analysis is supported.

Evolution in the period between 10,000 and 50,000 years is of high interest because of the continuing dilution of groundwater compositions at repository depth. The output from the model of groundwater flow and salinity evolution for this period is represented only in Figure 7-5, Posiva 2012-04 as two variants of the hydrogeological model with heterogeneous properties of the HZs and the SFR. There is a large contrast in the extent of dilution between the two variants at 50,000 years, which indicates large uncertainties in the dilution model for the prolonged temperate period. The model estimates that about 2% of the model nodes (from a total of ~9000 nodes) at deposition tunnel depth have salinity <0.4 g/L after 50,000 years.

The arguments presented for the choice of permafrost models (described in detail in WR 2012-34 and an earlier 2006 report) are summarised in Appendix 3 of the Scenario Report. Repeating the last glacial cycle does not result in permafrost penetration to repository depths, so the main point that has to be addressed is whether the deep penetration modelled in the prolonged 'dry glacial cycle' scenario is likely to occur. As shown in Figure 3A-5, continuous dry (i.e. no ice sheet cover) conditions cause progressive increase in penetration depth until a depth of 450 m is reached at 100 ka. The local variations in permafrost depth (i.e. gradient of permafrost edge) appear surprisingly steep, as permafrost also spreads horizontally. The difference between permafrost and perennially frozen ground is not clear in the definition on p.5, WR 2012-34. In many articles these terms are used synonymously. We consider that current evidence indicates that permafrost probably did not penetrate deep in glaciated areas of Fennoscandia during the Weichselian. The thick ice prevented very cold temperatures from reaching the ground below the ice. However, it is not known how deep the permafrost penetrated during cold periglacial times during the Early and Middle Weichselian, when these areas were not covered by ice. However, relict permafrost (usually taken as an indicator of deep permafrost penetration that has remained resilient to warm interglacials) has not been encountered in southern Finland. We consider that, apart from being extremely far into the future and thus of limited consequence in any case, Posiva presents reasonable evidence that the situation of continuous cold dry periods leading to deep permafrost penetration is highly unlikely to arise for sufficiently protracted periods (many tens of thousands to 100,000 years).

Salt exclusion (FEP 8.2.9) is the main source of uncertainty in the impact of permafrost on groundwater composition. This is a contentious and poorly understood aspect, both in terms of the extent to which the process might happen and also in terms of the significance for groundwater movements and compositions in the safety analysis. Posiva's discussion depends on a small number of research outputs from Finnish and Canadian studies. Interpretations about the significance of salt exclusion at Palmottu and other sites including Olkiluoto have changed over recent years and are dependent on hydrochemical and isotopic data. With respect to glaciation and permafrost impacts on groundwater movements and compositions, it is surprising that there is no reference to the findings from the Greenland Analogue Project (GAP).

Conclusion: Posiva has carried out extensive work on past climate and the controls on future climate evolution at the site, which provides an adequate framework for the safety case development and analysis. There are difficulties in using the coarse-scale GCMs to forecast future climate variables (especially precipitation) at Olkiluoto. We would have preferred to see a broader approach that explores changing some critical parameters, such as magnitudes and timings. In particular, the lack of analysis of a protracted (several hundreds of thousands of years) temperate period on water salinities and buffer erosion impacts at depth seems like an omission in the safety case that should be further evaluated by Posiva in the future. Also, the potential impacts of possible major, dynamic changes during the next few hundred years (including the operational period), have not been evaluated. It should be noted that some experts think that the Weichselian cycle, used as a repeated sequence for the future by Posiva, might be conservative in at least one aspect – PG faulting. It is currently not possible to demonstrate whether this approach is conservative or not in other aspects (e.g. ice thickness). However, considering the simplified and stylized treatment of future climate situations in the CLA, these weaknesses are not likely to strongly impact the safety assessment. Scoping calculations with hydrogeological models to consider the possibility of more infiltration over a longer saturated season would ensure that the penetration of meteoric water to repository depths, during an extended temperate period, has been conservatively assessed. More work is needed on dilution modelling, although it is highly likely that dilution will be moderated above the target property value for buffer chemical erosion, even for an extended temperate period.

1.6.2 Shear movements in the rock caused by heat and ice loading

In the safety assessment, rock shear is a 'disturbance scenario' caused by tectonic or post-glacial seismic activity, with two variants, RS1 and RS2. In RS1 canister failure due to rock shear is assumed to happen at an entirely arbitrary (i.e., not connected to any climate process) time of 40,000 years and, in RS2, at 155,000 years in connection with the establishment of the next temperate period after ice-sheet retreat at the end of the next glacial period.

Canister failure due to rock shear is presented in MDR, Section 2.6, and is a scenario required to be addressed by STUK in YVL D.5 as an 'unlikely event'. The likelihood, timing, magnitude and location of a rock shear movement are the main uncertainty. Section 2.3.3 of this review addresses these aspects of the earthquake scenario in detail. Shear is assumed only to take place by triggered displacement (caused by a large earthquake on a nearby major BFZ) on 'critical fractures' of greater than 150 m radius that intersect or propagate into DHs. A displacement of >5 cm is to be avoided and Posiva aims to do this by identifying and avoiding critical fractures, using fracture detection and mapping in deposition tunnels prior to locating DHs. The approach is a key part of the RSC and is discussed later in this review.

Neither Posiva nor SKB has considered and analysed the possible fracturing and micro-fracturing, and related seismicity, during the thermal phase of the repository. The rock volume expansion will generate stresses of the order of 20 MPa and displacements could be triggered on any fractures and BFZ in the repository that are in a critical stress stage. This would trigger earthquakes in the deposition areas. The related tremor or earthquake from the faulting could need to be taken into account in the nuclear installations at the surface, including the NPPs. It will be the first time in history that such a large heat load will be imposed on a large rock volume in the relatively shallow underground.

Posiva has followed the opinion of SKB that fracture propagation from the tip of an existing fracture or BFZ is not likely to develop, saying that it can only take place in a tensile mode (Mode I) and that confinement around the tip of the fracture prevents fracture extension. SKB and Posiva are of the opinion that the maximum displacement of an existing fracture or BFZ will appear as elastic deformation at the centre of the fracture and not at the tips. Fracture mechanics modelling of the near-field rock movements around the deposition hole by SSM shows that fracture extension (propagation and coalescence) from the tips of pre-existing fractures generates shear fractures (Mode II) as a consequence of one or several combinations of thermal loading, buffer swelling and excess hydraulic head from deglaciation (SSM Report 2011:26). The possibility of large slips and related permeability change along BFZ and major faults in the far-field of the repository has also been modelled (SSM Technical Note 2012:55).

Conclusion: Posiva has identified seismicity as the main mechanism for shearing of existing fractures and has carried out extensive studies of where and how this could develop with respect to acceptance criteria for DHs. However, Posiva has not looked in depth at the possibility of fracture propagation and coalescence, or at the potential for displacements caused by the total thermal load and the effect of excess water pressure from glaciation on the near and far-field rock. There are seismic hazard implications of thermally induced displacements that have not been analysed by Posiva and which could affect surface installations at the site.

1.6.3 Restoration of long-term baseline conditions after closure

DBR, Section 10.1.4, states the requirement that *"Closure shall restore the favourable, natural conditions of the bedrock as well as possible"* and that the original hydraulic and chemical conditions in the host rock should gradually be restored, without short-circuits or preferential transport pathways being formed. The report notes that: *"One of the most probable places where preferential flow path(s) could develop is at the interface between the backfill materials and the rock. Advective flows in the backfill are most likely to form during the installation period and their significance diminishes after the disposal facility has been closed and once the swelling backfill materials become saturated".* It is also a requirement that the closure components should be able to do this whilst withstanding the impacts of glacial conditions and permafrost.

The hydraulic property specifications for the backfill, plugs, and EDZ, as stated in DBR Sections 9.2.3 and 6.4.2.6, if achieved in practice would be adequate to ensure that the backfilled tunnels do not act as anomalously conductive paths for groundwater through the rock mass. The specifications for the deposition tunnel plugs in terms of initial properties, lifetimes, and long-term properties (DBR, Sections 9.2.3.2 and 9.2.4) should be adequate to maintain this requirement during the various planned stages of disposal facility completion. However there are important practical questions that remain to be addressed, including whether:

- buffer can be installed at sufficient density in the irregular tunnel cross-sections formed by drill-and-blast excavation to avoid formation of a crown space;
- a continuous EDZ can be avoided during routine "production-line" excavation of deposition tunnels, and considering transient stress concentrations during the excavation and post-closure thermal phases;
- rock bolts and nets can be removed before backfilling of deposition tunnels begins;
- the plugs can successfully cut off flow through the EDZ;
- the proposed limited use of low-pH grouts can adequately reduce inflows to the open excavations, such that upconing of saline waters and down-welling of meteoric waters can be adequately inhibited over the full excavation and operational periods.

These questions can best be addressed during the demonstration phase.

The possibility of short-circuits via inadequately sealed exploration boreholes has been addressed as a model variant in WR 2012-42, although the presentation leaves significant questions regarding the conceptual and parametric representation of boreholes as thin, high-transmissivity fractures and the numerical difficulties that can be expected from including such features using the finite-element method.

The 100-year plug lifetime design criterion in the DBR provides a limited factor of safety in the event of serious difficulties during the operational phase – for example if discovery of a canister manufacturing problem leads to a requirement to retrieve some of the canisters. It should be checked whether Posiva has a contingency plan for reinforcement of the tunnel plugs in the event that difficulties during the operational phase lead to a need to keep the central tunnels open for longer than 100 years. Such a plan was not found in the UOPL.

Overall, there is no information currently available to assess quantitatively whether baseline conditions can be re-established. The System Description report notes that: *"The design of the closure is still under development and alternative solutions and materials for backfilling the disposal facility are being investigated allowing technical development of the closure before the time of installation".* Section 3 of the Closure Production Line report (Posiva 2012-19) provides information on the target hydraulic conductivities of different sections of the tunnel and shaft backfills, but does not explain why the values were chosen or why the different regions being backfilled have particular target properties. Presumably this has been modelled in terms of groundwater flow in the rock, but the flow modelling reported in OSD (for example) has looked so far at the impact of an open system only. Further comments are provided in Section 3 of this review.

Conclusion: Posiva does not provide sufficient information on long-term baseline conditions after closure and will need to consider it as construction plans develop. Further comments are made in Section 3.

1.7 Repository evolution during the early stages after closure

Posiva's overall position on the early evolution of the system is summarised briefly in the Synthesis Report (Posiva 2012-12, p.21):

"In summary, the properties of the EBS and host rock will conform to the performance targets and target properties over the period up to 10,000

years, with some possibility of incidental deviations: an undetected penetrating defect in one or a few canisters; higher flow rate or lower transport resistance than the target values for a few deposition holes and groundwater composition outside the target range for a short time during repository operation and soon after closure for a few deposition holes; and local lower density areas in the backfill where there is the possibility that sulphate reduction may occur".

These perturbations are those that are propagated into the performance assessment and are dealt with below.

1.7.1 Resaturation of the repository and EBS saturation after closure

Section 5.1.4 of the PAR summarises the modelled resaturation behaviour of the repository openings and the assumptions made in the modelling. A simplified construction schedule has been assumed, with all the 20 tunnels in a panel opened and closed at the same time. Full saturation is assumed to take place instantly at the closure of the tunnels. Hydro-DFN modelling (WR 2012-48) looked at operational schedule and the PAR outlines some semi-quantitative results. The hydrogeological simulations of flow evolution at the site (WR 2012-35) assume the openings to be backfilled and saturated. Calculations of the saturation behaviour of the buffer (Safety Report, Section 6.4.2) use stylised 'wet', 'typical' and 'dry' inflow ranges to tunnels, based on the DFN model statistics (Appendix A of PAR). This produced a wide range of buffer saturation times (100 to 6000 years), although more recent work (p.221) is said to show faster times. A key conclusion of this study is that the tunnel backfill hydraulic conductivity limits the rate at which buffer saturation occurs more than the water supply from the illustrative fractures considered (Safety Report, p.220).

The early stages of this review identified a need for Posiva to consider and identify possible changes in barrier properties arising from delayed resaturation, and provide lines of evidence regarding whether such changes will or will not occur, and impacts on safety if they did occur. Posiva was asked to provide more information on the near-field impacts of slow saturation of the EBS to provide information and analyses on whether an EBS that endures a long dry period can and will reach the same performance target after delayed saturation as an EBS that saturates quickly. In response to an extensive RAI, Posiva provided further information and calculations on water inflow to DHs and buffer saturation times in July 2014. In this CRR, only those aspects of the lengthy RAI response that are related to near-field water fluxes are commented upon below. The concern is with situations where there is low delivery of water, either because there are no hydraulically active fractures in a DH or because flow in any fractures present is very low. At the limit, inflow is from the 'unfractured' rock mass, so the permeability of this becomes a central issue.

Posiva's response (POS-0188093: Table Q1, using the DFN data) indicates that 43% of DHs are 'dry' in this sense, with inflows $<3 \times 10^{-6}$ l/min. This equates to an intrinsic permeability of the rock mass (k) of about 10^{-21} m^2 (Posiva's reports use an inconsistent mix of intrinsic permeability and hydraulic conductivity values). Wetting the buffer in these holes requires inflow from the tunnel backfill or an EDZ, with inflow rates in the 10 metre long tunnel section above a DH needing to be $>2 \times 10^{-4}$ l/min to exceed the delivery from the rock mass around the DHs. Figure Q1-2 does not extend down to DHs with the same low intrinsic permeabilities considered elsewhere in the RAI (i.e. 10^{-21} m^2 or lower).

If k is $<10^{-21}$ m^2 and there is no delivery of water from the tunnel/EDZ, then saturation takes thousands of years. A new report (Olivella et al., submitted as part of the RAI response) extends to values of intrinsic permeability of the rock mass that are lower: around 10^{-22} m^2, which generates saturation times up to 7700 years. Thus, the value of k and the proportion of DHs that are in rock with such low values of k is critical. Posiva regards 10^{-21} m^2 as a bounding lower value (p.11) but has few data from Olkiluoto and none available from ONKALO – the most direct are some 1996 He-gas permeability data (Posiva 96-22) from samples taken from the (shallow) VLJ repository. A report *"Kuva et al., 2014"* is cited as a source of data on ONKALO but is not listed in the references and is not on Posiva's website. A k value in the range 10^{-21} to 10^{-22} m^2 does seem justifiable as a lower limit for the unfractured rock, but this should be confirmed for the actual rocks of the disposal volume.

The intrinsic permeability *distribution* of the rock mass has been estimated from PFL and HTU data, but the acknowledged uncertainties in these data (see this CRR, Section 1.1.5) are not fully dealt with. Posiva notes that the HTU-measurements are likely to overestimate hydraulic conductivity and, of the data available, roughly 50% are below the measurement limit. For the corresponding PFL-logging results, over 90% are below the measurement limit. This calls into question the actual distribution of low-k values derived from Figure Q1-1. For the Q1-4 histogram, Posiva assumes that there are <1% of DHs with k <10^{-21} m^2 (K = 10^{-14} m/s on this diagram). Figure Q1-1 could be interpreted, with its obvious uncertainties and the dubious validity of the log-normal fit curve, to give values more than an order of magnitude greater than this.

In addition, Figure Q1-3 shows that, for any given value of k, there is a range of a factor >10 in the different methods and assumptions used in estimating saturation time. A key report is Posiva 2012-48, which looks at 'dry' conditions and concludes (p.119) that *"For rock with a conductivity three orders of magnitude lower and no fractures intersecting the deposition tunnel, i.e. dry conditions, the buffer saturation time will be more than 10 000 years"* (the value of k referred to would be 1.52 × 10^{-22} m^2). In bold text, the RAI response insists strongly (p.16) that we discount this completely, as "unrealistic". Given the above discussion, the value of k does not actually appear unrealistic (at least, it seems possible that relatively large volumes of rock could have such a value), so Posiva presumably is emphasising more the lack of fractures in the tunnel as being unrealistic. In fact, Posiva 2012-48 models a 'dry' tunnel as one with an inflow of 0.01 L/min, rather than no inflow at all. That this is effectively 'dry' is supported by the threshold value for tunnel water to contribute to wetting of the buffer given in the RAI response (mentioned above) of >2 × 10^{-4} l/min for a 10 metre long section above a single DH. This equates to 0.06 l/min over a full tunnel of 300 m length – six times 'wetter' than the 'dry' case in Posiva 2012-48.

As seen on p.73 of that report, in the 'dry' case (with wetting coming only from the tunnel fractures and not the rock mass) it takes several thousand years to saturate the buffer in DHs and *"a minimum period of approximately 2000 years appears to be required to saturate the buffer from the deposition tunnel"*. Once wetting from the rock mass is included, however, saturation times are smaller and an interesting case is shown (p.83): *Case C5_7 consists of a group of three deposition holes surrounded by rock of extremely-low hydraulic conductivity* (here, they mean k = around 10^{-22} m^2) *while the rock in the remainder of the geometry has the reference value for hydraulic conductivity.* Here, full saturation takes a few hundred years. This seems a useful illustrative case to consider.

Overall, however, it seems quite clear that the system is rather sensitive to the balance between distribution of 'wet' tunnel fractures, tunnel inflows and rock mass intrinsic permeability. Even though whole tunnels with inflows <0.01 L/min are discounted as improbable by the DFN modelling, it is not certain that long stretches of deposition tunnel could not have such low fracture inflows (especially if considering sparse channelling), or that there could not be volumes of rock of DH-scale with low k, so Posiva needs to take care not to be overly assertive yet about 'unreality'.

All of these uncertainties are not properly presented in the RAI response in Table Q1-4 and Figure Q1-4 (which has no uncertainties shown). If the actual values of bulk rock intrinsic permeability include a significant proportion that is equal to or <10^{-21} m^2 (as the HTU/PFL uncertainties could be taken to suggest), then the actual number of DHs taking >500 and into the thousands of years to saturate could be measured in the hundreds, rather than the 45 (1%) proposed by Posiva.

The role of an EDZ is not treated clearly in the RAI. It is not clear where/when/whether Posiva is considering a DH-wall EDZ or a tunnel-floor EDZ. It is recognised that an EDZ could contribute to water delivery to saturate DHs. For example, Table Q1-1 indicates that a discontinuous EDZ (Posiva's 'preference' for the safety case) reduces the proportion of 'dry' holes (i.e. with inflows <3 × 10^{-6} l/min) from 43% to 3%, but it is not clear which EDZ is being assessed. There is no discussion of the impact of a continuous tunnel-floor EDZ (which seems to be what is observed at the moment), which could presumably entirely mitigate the slow saturation problem if it transects the DH tops and has higher transmissivity than the tunnel backfill and the intact DH rock. Note: when Posiva cites (on p.12) the recent POSE reports as evidence of a discontinuous EDZ, they are referring to the DH walls, not the tunnel floor. This CRR agrees with this conclusion (see Section 1.7.3).

As discussed in Section 1.3.6 of this CRR, the estimation of the proportions of rock volumes with low values of k using the DFN model may be non-conservative if, as suspected, the DFN model over-connects the fracture network. A more sparsely connected network would increase the % of DHs that see no inflow from fractures and thus rely on the tunnel/EDZ inflows to saturate in short times. It would also produce longer sections of tunnel with small or no inflows.

A closely related issue concerns buffer piping erosion in the saturation period. At a June 2013 working meeting, Posiva explained that it expects there to be large voids in the tunnels at the backfill interface before the whole system saturates and the backfill expands, which is the time when piping could occur. A figure of around 670 m^3 has been calculated for the full length of a single disposal tunnel. There is also space between pellets in the deposition hole where eroded bentonite could deposit. Piping erosion is 'expected' in up to 30% of deposition holes: the PAR notes that *"Before full saturation, some buffer and backfill material may be lost through piping and erosion. Based on calculated inflows to deposition holes, some limited buffer loss* **is** *expected in roughly one third of the positions"*. Almost any flow above some threshold (which we have not identified) appears capable of causing some erosion. PAR, p.232, notes that: *"…the exact physical process remains unknown and therefore the theoretical approach is being further developed"*. The role of flow in the EDZ at the top of the deposition hole (as opposed to a fracture intersecting a deposition hole) in this process is not really clear.

Conclusion: 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 on the above aspects of this topic. The net result of the RAI response is simply to confirm that some DHs will not fully saturate until after the thermal period: 'some' could be tens to, perhaps, hundreds. In the response, Posiva has not dealt convincingly with the uncertainties that they already recognise. Consequently, the histogram of DH saturation times is not quantitatively convincing. 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. This work can be done as initial construction in the repository volume takes place. A sensitivity analysis in which the rejection threshold value of the deposition hole inflow rate is varied to see how buffer erosion, as well as overall performance, is affected would be useful. It is clear that the saturation model for backfilled openings is statistical and is entirely dependent on the validity of the DFN model and would be affected by any alternative model of flow connectivity in the near-field, which could require saturation behaviour to be re-evaluated.

1.7.2 Early hydrochemical evolution

Evolution of hydrochemistry in the operational and early post-closure period is presented in Section 5.3 of WR 2012-35 and is principally concerned with the salinity of water that could affect the buffer/backfill. The general picture presented is that, with continued operation, saline waters are drawn upwards (upconing) beneath the repository and fresh waters are drawn downwards from the surface into the openings. Although the maximum salinity so far measured below repository depth is high (up to 84 g/l from water samples in WR 2012-44 and around 120 g/l at around 900 m depth estimated from *in situ* EC measurements in OSD, Fig. 7-17), upconing is localized under the shafts and does not enter the disposal volume. Both the maximum values (below the repository) and the minimum values (in the disposal volume – but localized in the larger fracture zones and probably not representative of the panels, according to PAR, p.136) continue to increase/decrease the longer the repository remains open – so this will be an operational management issue to be considered in the distant future (>90 years time). The PAR notes the possibility of salinities close to 0.3–0.4 g/l (at the minimum acceptable total charge concentration of 4 mM), but these only occur if reactions in the overburden or water-rock interaction are not taken into account. Posiva states that this issue will be studied further in the 2013-15 period.

Monitoring of hydrochemical changes due to ONKALO gives an indication of the hydrochemical disturbances that might occur during future construction and operational phases. Monitoring data shown in OSD Fig. 7-62 (also in Fig. 4-4 in WR 2012-44) show considerable heterogeneity in SO_4, Cl and DIC concentrations, some of which is considered to be due to ONKALO. Dilution due to progressive drawdown is most evident at monitoring points in HZ19 (OSD, p.642). Increasing salinity over time was observed in monitoring points in HZ20, but it is unclear whether these are due to an open-hole problem. Additional monitoring should establish whether or not saline upconing is detected in HZ20 – so far there is evidence of both saline upconing and dilution in HZ20A and 20B respectively, although earlier data suggested increasing salinity in HZ20B (p.644).

Additional monitoring data for SO_4, HS^-, CH_4 and Fe^{2+} are required to achieve a greater degree of confidence on whether the perturbations 'activate microbes' and stimulate SO_4 reduction to HS^- (OSD, Fig. 7-64f). In particular, the issue of whether variations over time in HS^- concentrations are localised artefacts around boreholes or are caused by excavation disturbances needs to be resolved with more confidence. The reported variations of HS^- are not trivial, for example OL-KR13 (360m depth) is located in HZ001 and repeat analyses gave 13 to 5 mg/L, corresponding to a salinity reduction from 8000 to 5000 mg/L and a SO_4 reduction from 130 to 85 mg/L (Fig.7-65). The initial state concentration of HS^- in HZ001 is not known and the process accounting for high HS^- is not understood. Corresponding Fe^{2+} concentrations are low (<0.07 mg/L Fe^{2+}), suggesting that the capacity for HS^- control by Fe^{2+} release and FeS/FeS_2 equilibrium should be studied.

Section 8.2.6 of the FEP report addresses the processes of *"erosion and sedimentation in fractures."* Posiva judges these processes to be of limited importance based on a lack of geological indication of *"significant erosion or sedimentation processes in geologically recent times."* The discussion is cursory and lumps chemical processes of precipitation/dissolution with mechanical processes of sedimentation/erosion. The possibility of localized effects around underground openings in a disturbed state is not well described. Some of these issues are discussed in FEP 8.2.7 under the process "rock/water interaction," which is mainly focused on groundwater stability. A better discussion of the potential impacts of erosion/dissolution processes on local fracture system hydraulic properties, distinct from the "erosion and sedimentation" and "rock/water interaction" FEPs, would be valuable to support Posiva's decision to neglect these effects in the CLA. Nevertheless, we agree that this conclusion is reasonable.

In terms of coupled THC behaviour, WR 12-35 presents calculations (p.93) showing that the decay heat of the fuel will not significantly affect either flow or salinity in the disposal volume or below. It is important to note that Posiva has only done thermal impact calculations for one of the model cases, the oldest flow model, which is also the one with only 5500 tHM. Presumably the thermal impacts for the 9000 tHM inventory models (which are also the most recent flow models) would be greater. After closure, flow rates remain higher than under natural conditions and it takes around 2000 years for salinities to recover to pre-excavation values. The effect of the decay heat is to increase flow rates for 2-3000 years (p.95).

Conclusion: The THC evolution of the near-field has been modelled in detail (WR 2012-35) and the implications for target properties appear to be minor, although there is a doubt concerning the thermal impacts of the larger fuel inventory, which are not modelled. A further point to consider is that all of the THC impacts get progressively worse the more excavation is carried out and the longer the repository is kept open. Each successive disposal panel is exposed to slightly 'worse' conditions that the previous panels. This would have significance if either the total repository fuel inventory or the operational period were to be extended in the distant future. A more detailed assessment of hydrogeochemical evolution has recently been published (WR 2014-09) in which modelling of reactions in the early post-closure period illustrates a wide range of potential outcomes. Additional work is necessary to constrain the uncertainties in flow concept, matrix diffusion properties and potential chemical reactions.

1.7.3 THM evolution of the near-field rock and thermal spalling

Posiva's analysis of the THM evolution of the near-field is focussed entirely on the operational period, the generation of an EDZ and the possibility of spalling in deposition hole walls. The Performance Assessment report gives almost no consideration to post-closure THM evolution (Section 6.3). EDZ issues are covered later in this review (Part 1, Sections 4.1.2 and 4.3.1) and are not discussed further here.

PAR, Section 5.3.3, describes the results of the POSE experiments on TM behaviour, but pre-dates the final analyses. In fact, the POSE experiment was conducted in a rock mass (pegmatites and mica gneiss) that is not representative of the major rock type (veined gneiss) in the repository panels. Initial modelling predicted that spalling would occur in the rock pillar separating the two DHs. According to the MDR, the lack of observed spalling from drilling the POSE boreholes indicates (p.250) that Posiva may have assumed too conservative a value for the damage strength of the rock: they had used a value of 57% of UCS. They may also have assumed stress magnitudes and orientation that are not representative of the rock mass at this location. The report observes that the POSE findings are an indication that the understanding of site conditions is not yet complete. At the December 2013 RSC meeting, results of the Stage 3 test were shown to STUK and the conclusion drawn by Posiva that, while the thermal load on the DH produced irreversible damage in the rock, there was no thermal spalling and no new fracture development in the deposition hole walls of any significance. There was, however, a small increase in the EDZ down the borehole wall, but this was discontinuous, as it did not lead to spalling. Posiva's overall conclusion at this time was that the overall damage mechanism is not spalling: instead, they expect to see a small porosity increase in pegmatitic rocks and some fracture growth along lithological boundaries. Failure is time dependent, but continuous in nature during heating. The results seem to indicate that the rock mass at DH scale is more ductile than exhibited by the brittle behaviour at the scale of samples for rock mechanics testing. This might be related to biotite and muscovite in the gneisses, which have high compressibility perpendicular to the sheets and low shear strength and high deformability parallel to the sheets. Posiva plans a major back-analysis of all the POSE work, including detailed geological mapping linked to 3DEC and FRACOD modelling, plus more LVDT stress measurements. We consider that it would be more appropriate for Posiva, instead, to consider repeating the testing in veined gneiss at a depth and stress state relevant for the disposal rock volume.

For the PAR (p.144), produced before these recent conclusions from POSE were available, Posiva chose to take a conservative approach to the hydraulic impacts of spalling. For the Hydro-DFN flow modelling, rock damage by spalling is modelled to reach 10 cm depth in the DH walls and the damaged zone is assumed to have the same hydraulic conductivity as the EDZ. The Performance Assessment notes (p.198) that the Hydro-DFN modelling showed both EDZ and DH spalling to have relatively minor effects on flow in fractures around. Assuming a ten times higher conductivity for the damage zone and the EDZ, the initial flow rate and the flow-related transport resistance for the release pathways were not significantly affected, whereas the initial flow rate in the EDZ-path increases roughly by a factor of ten. Posiva says (p. 212) that the main conclusion from the statistical Hydro-DFN modelling is that connectivity is increased, but the effect of this is limited to DHs that are not intersected by flowing fractures, or are intersected by fractures with low flow rates per unit width and high transport resistance. The fraction of DHs having values outside these limits is not increased.

It is important to note that this is an area where Posiva accept that more data from ONKALO are needed and the latest data we saw in December 2013 indicate that thermal spalling will not occur. Posiva has a major programme of back-interpretation and modelling of POSE in place for 2014-15, which will need to be monitored closely by STUK.

Conclusion: Posiva has done sufficient work to support an interim conclusion that thermal spalling is unlikely to be a problem, but this is work-in-progress and more results will emerge through 2014 and 2015. We consider that it would be most appropriate for Posiva to consider repeating the POSE testing in veined gneiss at a depth and stress state relevant for the disposal rock volume. It is important to note that the near-field flow modelling used in the performance assessment took a more conservative approach anyway, assuming that spalling does occur. It is clear that the mechanical behaviour is critically dependent on the stress field, where more data are certainly be helpful and should be a routine part of all future demonstration tunnel and subsequent construction work. There are no indications that the near-field THM behaviour presents any kind of problem for the license application, but STUK should consider imposing requirements related to routine stress measurement and analysis schedules.

2 Site suitability

This Section addresses the matter of whether the results of the site characterisation work continue to support the suitability of the site for the repository, both today and during its future evolution.

2.1 General approach to establishing suitability of the site

The DBR presents the overall reasoning and rationale of how the performance and design requirements have been derived for a repository at Olkiluoto and explicitly addresses the legal and regulatory requirements. The approach to establishing the suitability of the site is based on VAHA, the requirements management system, which ensures that the links between safety principles and the safety concept (multi-barrier protection) and testable safety functions and performance requirements and design are systematically identified. The suitability of the site is being tested through performance targets for engineered barriers and target properties for the bedrock system.

The OSD (p.881) has a "preliminary assessment" of suitability against the YVL D.5 Suitability Factors, with the conclusion being that the site fulfils all the factors. However, it is noted that a final assessment will be made within *"subsequent repository engineering and safety assessment activities"* and it is not clear whether this means as part of the CLA or afterwards. Section 4 of YVL D.5 does not use the term "Suitability Factors", so this term is Posiva's interpretation. Considerable emphasis is put on STUK's draft wording on what the safety functions of the natural barriers 'may' consist of:

- *stable and intact rock with low groundwater flow rate around disposal canisters*
- *rock around emplacement rooms where low groundwater flow, reducing and also otherwise favourable groundwater chemistry and the retardation of dissolved substances in rock limit the mobility of radionuclides*
- *protection provided by the host rock against natural phenomena and human actions.*

OSD covers the first two of these and makes a structured argument in Section 10.9 that begins with general tectonic stability and regional stress field stability, then outlines knowledge on the nature and controls on GW flow. For the latter, the arguments presented are based on the whole panoply of data and interpretation underpinning the understanding of flow in fractures that is the core of the safety analysis and, at this level, are considered credible. Similarly, we consider the arguments on bedrock stability to be strongly based.

On the third bullet, OSD concludes that the deep flow-hydrogeochemical system displays clear evidence of the resilience of the deeper parts of the system (repository depth) to the perturbations that have occurred throughout the last glacial cycle. This argument is certainly sustainable, strongly evidence-based and credible, and is discussed in more depth later in this review.

Fulfilment of these characteristics is a matter of relative terms ("low," "favourable," etc.) rather than absolute values. Confidence in safe disposal requires that these be tied to more quantitative safety functions for bedrock suitability in terms of measurable criteria that are specified in relation to safety assessment calculations. This is discussed in Section 1.1.1.

A factor that is dealt with less satisfactorily in the Safety Case Synthesis (Posiva 2012-12) is the issue of adequate rock volume. Available rock volume has to be assessed in the context of the distribution and intensity of rock fracturing at repository depth. Initial findings in the technical galleries in ONKALO suggest that rock fracturing is more complex than previously envisaged, and the extent to which the capacity of the site is potentially affected is unclear. Quantifying confidence in the structural model (e.g. of BFZs) is difficult, but would be increased by providing scientifically based alternative models, then using the most plausible models (based on current knowledge) to explore whether and how alternative site behaviour would occur (see Section 1.2.1).

Bedrock properties that would indicate *unsuitability* of a site are not explicitly discussed. Of course, implicitly, unsuitability would be indicated by a failure to achieve the required criteria for target properties. 'Description of the Disposal System 2012' (Posiva 2012-05), states that classification of rock according to RSC will check properties indicating unsuitability of the site, *"e.g. proximity of exploitable natural resources, and abnormally high rock stresses"*, which appear incorrect, as RSC and natural resources are assessed at different scales. A full list of properties indicating unsuitability would be helpful. This issue is considered further in Section 2.3.

Conclusion: The bedrock properties are selected and defined in a way that provides confidence in safe disposal if these characteristics are met, but the requirements need to be translated into more quantified specifications, which will be included as safety functions in Posiva's VAHA system. The selection addresses regulatory requirements and is in line with international practice. There could be an issue with available rock volume.

2.1.1 Safety Functions of the Bedrock

Posiva's approach to safety functions of the bedrock as presented in the OSD is to come at them via the needs of the safety case. They define the safety functions of the geosphere (e.g. p.839) as being isolation, preservation and protection of the EBS (which could be read as 'containment') and limitation/retardation of releases. Target properties required to meet these safety functions are translated (through the levels of the VAHA) into RSC. The VAHA system is discussed later in this review.

The safety functions, taken together, cover the same general requirements for the bedrock as the suitability factors and are connected in VAHA to **target properties** for the bedrock (as defined and justified in DBR, Chapter 6), some of which are expressed more quantitatively, although generally still not in terms of measurable criteria. For example, the target property *"on the order of 1 litre/m*year"* stated for saturated flow around a deposition hole (DBR, 6.3.4.1) will not be measurable, as the deposition holes will either be open (unsaturated conditions) or filled without instrumentation. Hence there is a need to relate the safety functions to quantities that are measurable, as part of the Rock Suitability Criteria (see Part 1, Section 3 of this review).

Posiva demonstrates a comprehensive understanding of what comprise the key properties of the site. OSD does not contain any obvious gaps in this respect. In addition, the successive development of site models has enabled Posiva to identify, in a rolling fashion, data needs and topics where understanding is weaker. This has enabled successive characterisation work to focus on these issues. OSD Section 10 identifies the needs that were perceived during the period in which OSD has been assembled, culminating in a summary list of 9 topics that contain all the key information requirements for the safety case (p.839-40). There is also a lengthy description of the main issues concerning the current OSD.

Conclusion: At the highest level of VAHA, the safety functions are defined and appear comprehensive. No major characteristics of the site that are safety-related are omitted, although the emphasis on site properties providing a suitable environment for the EBS needs to be balanced by ensuring that the favourable transport and retention properties are maintained. There is an issue about whether these safety functions can be traced through to the lowest level of characterisation in VAHA. The need to quantify safety function requirements into measurable properties of the rock is discussed under RSC, in Part 1, Section 3.

2.2 Retaining the favourable properties of the site

The high level claim of the Synthesis Report (Posiva 2012-12) that favourable site properties are met and preserved so that the site fulfils its role as a natural barrier is considered to be both credible and reasonably robust. In Section 2.1 of this review it was concluded that Posiva had established the correct criteria for evaluating site suitability and that these were in line with STUK requirements.

2.2.1 Palaeohydrogeology as an indicator of stability

The palaeohydrogeological understanding discussed previously in this review (Section 1.4.6) is an especially compelling indicator of stability and consequent suitability. Evidence of how flows and compositions in the groundwater system evolved in the past is the most scientific approach to understanding how it will evolve in the future. The safety case is concerned with how the bedrock system will affect safety functions in the future. A note of caution is needed as to how 'stability' is understood: in this context does not mean 'unchanging and static'. Rather, it means that the change of the system over time is, within acceptable variability, predictable in terms of understood processes. It also means that the response of the system to episodic external perturbations is attenuated at the proposed depth location of the repository in comparison with what happens at the ground surface.

The overall concept for temporal evolution in the past is illustrated schematically in OSD, Figure 7-15. The time axis in Fig 7-15 covers only the period since the last glacial maximum. Groundwater evolution over this period is of limited value as an indicator of future evolution because meteoric water infiltration, probably uninterrupted for many tens of thousands of years, will be the dominant process after repository closure. The main safety-relevant aspects of long-term groundwater evolution will be: (a) the maximum depth and 'completeness' of dilute meteoric water flushing of the stratified brackish and saline groundwaters during a prolonged period of temperate climate, (b) the effect of permafrost on groundwaters after that prolonged period of dilute water infiltration, and (c) the maximum depth of penetration of sub-glacial melt water in a glaciation scenario. Palaeohydrogeological interpretation of the present groundwater system is more informative for (b) and (c), noting, however, that the probability of future permafrost and glacial conditions within 100 ka is rather low (Posiva 2011-04).

Palaeohydrogeological simulations based on ECPM upscaling from the base-case Hydro-DFN model (WR 2012-32, Section 13.3) significantly underestimated the infiltration of meteoric water to depth. However sensitivity studies followed by consideration of multiple realisations of the model, using reduced dispersion lengths in the inner part of the model, produced results that bracketed the hydrogeochemical data. Thus, with sufficient tuning of dispersion parameters, a degree of consistency was obtained. However, the ability to discriminate among alternative realisations or alternative model variants based on hydrogeochemical data appears to be limited.

Posiva's general approach to describing mixing as the main process of the system's evolution is appropriate, although pre-existing mixed groundwaters are inevitably poorly defined and, in reality, heterogeneous. Resolving the heterogeneity in detail is unachievable. Identifying and interpreting evidence of extreme hydrogeological conditions, e.g. glacial infiltration and temperate climate dilute water circulation and highly saline 'brine' upwelling, is a necessary objective. Posiva's interpretations of $\delta^{18}O$ versus Cl^- in OSD Figure 7-14 are key to achieving that objective. Their interpretation that the saline groundwaters (i.e. below about 300-400 m) do not contain significant amounts of glacial water can be challenged. In Posiva's conceptual model, these saline waters are 2-component mixtures between 'Shield brine' and the 'sub-glacial' component, which itself is a mixture that predates Quaternary glaciations. This is the most likely model, but these data alone cannot conclusively prove that the 'sub-glacial' reference might not contain glacial water and therefore also saline groundwater at >300 m depth. According to the statistical resolution of these mixed groundwaters using Cl^- and $\delta^{18}O$, there is evidence of a small component of the glacial end-member (Figure 6-71). Concerning the maximum depth to which glacial water (i.e. 'cold climate' water with a relatively low $\delta^{18}O$ value and probably derived from melt waters) has penetrated at any stage of the ice ages of the last 1–2 Ma, Posiva interpret this to be about 250 m depth (Figure 7-8), with vestiges of this component still detectable as shallow as 60 m (Figure 7-9). The present understanding of this process does not clarify whether this limit is controlled by duration of ice cover, hydraulic gradient, or properties of HZs, or a combination of these. Posiva's modelling of a future glaciation assumes a combination of these conditions. These are reasonable assumptions, although sensitivity to duration of ice cover should be tested.

Some additional confidence can be gained from the maximum penetration of Littorina water having been <300 m depth (OSD, Figure 7-15). In that case, the density effect of brackish seawater on hydraulic gradient has been assumed to be the driving force. Are relative densities of brackish and saline groundwaters confirmed by modelling to be the dominant factor, or is there a significant change of hydrogeological properties of bedrock at 300 m depth? It is not clear why this apparent 300 m limit for penetration of both Littorina water and glacial melt water is less than the depth of circulation, at least 800–900 m, of pre-glacial (i.e. >1 My old) meteoric water that is inferred from the sub-glacial water composition and also the compositions of pore waters in the rock matrix.

Below about 400 m, very limited mixing has occurred throughout the whole of the last glacial cycle, except perhaps in some of the more transmissive HZs. OSD suggests (p.547) that the rates of change (e.g. from ice to marine to meteoric) may have been too fast to allow impacts to develop. This indicates considerable resilience of the deep system to climate change impacts.

Modelling of the construction and operation period shows the possibility that a low percentage of deposition holes could conceivably have high inflow rates (see Figure 5-3 and Section 5.1.2 in the PAR). Similar modelling of the initial 10,000 years post-closure suggests that those locations of high inflows could also experience falls in salinity such that a low proportion (about 20) of deposition holes would become dilute. Section 5.1.2 discussed model variants that differ in relation to EDZ and damage around deposition hole. However it seems that these models assume the same conceptual DFN model. Alternative DFN models, as well as alternatives to DFN models, should both be considered. The possibility of a few deposition holes experiencing dilute water inflows after 10,000 years suggests the possibility of a much larger number of holes having dilute water after 50,000 years.

Conclusion: Posiva has demonstrated favourable and stable conditions exist at the site. Overall, there is general consistency between the palaeohydrogeological evidence and the groundwater flow and hydrochemical models for future evolution in the PAR. The totality of the OSD indicates that the favourable HCM conditions will persist far into the future, through at least the next glacial cycle (which may not occur for many tens or hundreds of thousands of years). For the shorter term evolution of groundwater flow, the main possibility is development of a more robust regional flow system, as continued isostatic rebound results in a transition where Olkiluoto evolves from being a near-shore island to entering a near-coastal continental setting.

2.2.2 Long-term mechanical stability

From the rock mechanics viewpoint the site can be characterised as stable and aseismic, consisting of gneiss of different compositions, with medium strength and deformability, intersected by large deformation zones and a low frequency fracture network and affected by average rock stress magnitudes for Precambrian shield areas. We consider the gneiss to have sufficient strength and deformability to provide protection against natural phenomena such as stress changes in the rock from shear-induced fault slip from the heating of the rock mass, future glaciations and related postglacial faulting along major fault zones and fracturing in the fracture network. However, confirmation of this statement can only be obtained from further analysis of thermal induced seismicity and related shear displacement (see Part 1, Section 1.6.2 of this review).

In addition to thermally induced strains, the heat generated by the spent fuel and groundwater flow during the first 1000–10,000 years can also cause minor changes to the strength and deformability of some parts of the fracture network, but not to such an extent that it will jeopardise the long-term integrity of the repository.

Olkiluoto is located a large distance from the present active plate boundary along the mid-Atlantic ridge to the west and the active Alpine margin to the south. Any changes of the tectonic activity at these margins that can have an influence on the Baltic Shield and Olkiluoto is not likely to happen for several tens or hundreds of millions of years. Looking to the next hundreds of thousands of years, with possible multiple ice ages, the repetition of the ice load and melting and the related down warping and uplift of the crust in the range of several thousand metres can lead to a type of fatigue process where some of the existing brittle fracture zones are activated and slip. In addition, large-magnitude intra-plate earthquakes cannot be ruled out for Precambrian shield areas like Olkiluoto. They are likely to reach the same magnitudes as earthquakes related to post-glacial faulting. Earthquake probabilities and impacts are discussed in Section 2.3.3 of this review.

Conclusion: From the mechanical viewpoint, the favourable bedrock condition at Olkiluoto will persist into the far future. Earthquake impacts are discussed separately in Section 2.3.3.

2.2.3 Geosphere FEPs affecting site stability and suitability

The geosphere FEPs that could affect site suitability and stability are considered in the safety assessment work and are listed at MDR, Table 4-6. The FEPs are introduced in Section 8 of the FEPs Report (Posiva 2012-07), where 17 geosphere *processes* are identified that could impact on *features* of the disposal system (Table 8-1). FEP couplings and interactions with the components of the disposal system are identified in Tables 8-2 and 8-3. The FEP report is essentially a catalogue that points towards the more detailed literature. For almost all the geosphere FEPs, the majority of the literature cited is 'self referencing' to Posiva (or SKB) reports or projects, indicating that the issues associated with the FEPs have been evaluated elsewhere as separate matters, rather than as part of an overall FEP evaluation process. This is to be expected and is reasonable. As a consequence, all the more significant FEPs are discussed in more depth elsewhere in the CLA documentation. Only those that are relegated and not considered in the PA are covered uniquely in the FEP report.

The report discusses uncertainties and significance for each FEP and lists interactions, but without pointing to how those interactions are considered in the safety assessment. Those that are ruled out from further consideration (e.g. methane hydrate formation; erosion of fracture minerals; salt exclusion) have been treated by 'expert judgement' (it is not clear what the process was for this) or are eliminated on the grounds of physical or chemical unreasonableness for the site conditions, or the timescales, or both. The treatment seems reasonable.

It is important to understand that there is a distinction made by Posiva about the use of FEPs in either 'Performance Assessment' (PA) or 'Radionuclide Release Scenarios' (AOS). FEPs are assigned to one or the other, or both. PA relates to modelling the evolution of the system; AOS relates to modelling the behaviour of released radionuclides as they move through the system. This distinction leads to some superficially odd-looking comments in the FEP tables in Section 4 of the Models and Data report: e.g., "sorption of radionuclides is out of the scope of PA". This only makes sense if the PA/AOS distinction is understood.

PAR, Section 4.2, identifies the 7 FEPs that could affect the host rock properties and the evolution of the geosphere part of the system. The three FEPs mentioned above (methane hydrate formation; erosion of fracture minerals; salt exclusion) have been removed from the original list of 10 FEPs identified as possibly relevant to geosphere evolution. Three of the remaining seven (on stress, shear and spalling) are linked directly to VAHA L3 target properties of the host rock, with the rest linked mainly to EBS and closure. It is not possible directly to trace what happens to these FEPs in the performance assessment. The 'housekeeping' of FEPs beyond Section 4.2 is weak, although Section 4 can be regarded as a 'hand-over point', from which point FEPs are subsequently treated in terms of their impacts on performance targets or target properties. Section 4.6 says that the FEPs are also called (in the context of this report) "processes, potential loads and other factors" i.e., impacts on the performance targets that are subsequently assessed in Sections 5-7. In fact, the term 'other factors' is never used again. The FEPs are taken up as 'loads' on the repository system. Eventually, Sections 5.9.3, 6.11.3 and 7.10.3 assert that *"All the relevant evolution FEPs ...... have been taken into account in assessing the performance of the repository system"*, but there is no formal tabulation or other 'housekeeping' presented to support this assertion.

An example of the weak FEP housekeeping can be gained from tracing 'rock creep' into the safety assessment. It is brought into the PAR as FEP No. 8.2.5, but is eventually (in Section 7.2.1) *apparently* disregarded: *"…its effects are considered to be insignificant for repository evolution compared to more rapid stress re-adjustment and reactivation or displacement of pre-existing faults"*. This presumably explains why, in the Scenarios report, Table 9-1, it is shown as *"not taken into account in the formulation of scenarios"*. However, none of the documentation explains that a decision was taken to relegate it. Similarly, stress redistribution (FEP No. 8.2.2) is shown in Table 9-1 as not accounted for in scenario formulation. Section 7.2 of the PAR has a section on glacially induced stress changes in the rock, which does not reach a conclusion about impacts, but evolves into a discussion of glacially induced faulting. The assumption must be that the only aspects of stress redistribution that are considered relevant to safety are the seismic impacts: in other words, the rock creep and stress redistribution FEPs are swept into FEP No. 8.2.3 (reactivation – displacement along existing fractures) and from there into the RS earthquake shear scenario. This is not stated specifically anywhere and FEP numbers 8.2.2 and 8.2.5 cannot be traced into the Scenarios report, which amounts to poor traceability of decisions taken in constructing the safety case.

It is nevertheless clear from Sections 5 to 7 that the most significant FEPs identified in Section 4 can be related to 'loads' that have been thoroughly evaluated and the uncertainties identified. Section 9.2 summarises the loads and the residual uncertainties and factors that are propagated into scenario generation. The principal impact on the system comes from FEPs associated with changing climate (including earthquake shear and the effect of permafrost: see also Review Topic 10, Q4), which are thoroughly evaluated.

Conclusion: The consequences of bedrock related potential future FEP's are shown to be small, not relevant, naturally counterbalanced or have been included in the safety assessment as scenarios (such as rock shear) that are dealt with by special evaluation. However, traceability is poor.

2.3 Factors that could make the site unsuitable

This Section deals with geological properties and characteristics which, if found to be present, might call into question the suitability of the site for a spent fuel repository. It also deals with the susceptibility of the site to adverse events, specifically the impacts of earthquakes, which might make the location unsuitable. YVL-D5 §412 identifies four such factors: proximity of exploitable natural resources; abnormally high rock stresses; anomalously high seismic or tectonic activity; exceptionally adverse groundwater characteristics, such as lack of reducing buffering capacity and high concentrations of substances that may impair the safety functions.

Section 10.9 of OSD covers each of these four items, making the case that the site displays none of these factors. The arguments bring together information from the main body of the OSD and make a credible case that the site has no problems with respect to 'unsuitability factors'. Apart from residual questions about the range and orientation of in situ stresses that could be encountered, there is no compelling evidence in the OSD that the site is unsuitable with respect to any of STUK's factors. The following Sections look at each of the four areas in turn.

2.3.1 Presence of exploitable natural resources

Posiva's statements on mineralisation in the OSD are rather convoluted and difficult to trace. OSD, p.883, cites WR 2010-70 and Posiva 2006-02 in support of there being no ore potential, but a search through these reports finds no discussion of the topic. WR 2010-70 mentions the sub-vertical fault set 'commonly' having tens of cm thick mineralisation of sphalerite-chalcopyrite-galena-pyrite, but this is not mentioned anywhere in the context of 'ore potential'. Posiva does not say anywhere whether this mineralisation has any potential and has not presented an actual analysis of potential. Section 11.2 of the OSD mentions the presence of indium on the site and in ONKALO and says it is 'too small' to be attractive, but gives no reference to actual data and no numbers. Nevertheless, mineral exploration on Olkiluoto island and in its immediate surroundings has not been reported and no natural resources are currently exploited close to the island. The greisen dykes associated with the late intrusion of rapakivi granite east of Olkiluoto are known for Sn-W-Mo sulphide occurrences. The closest occurrence is 12 km southeast of Olkiluoto.

Since the OSD, Posiva has addressed this issue by requesting further clarification on the inferred mineral potential of critical elements from the Geological Survey of Finland (GTK). POS-019004 describes the following factors for the metallic elements: general geological setting of the elements; their use, occurrences, production and resources in a global, Fennoscandian and Finnish perspective; indications in Olkiluoto. Based on this, Posiva restates the conclusion that none of the elements evaluated is considered exploitable in the area. In particular, spahalerite-chalcopyrite-galena, Indium and Sn-W-Mo mineralisations are spatially related to the N-S striking sub-vertical faults, which have restricted thickness compared to (for example) the SE-dipping major composite shear zones (BFZ/LDF-structures). This limits the potential volumes of the mineralised envelopes. No massive sulphide deposits have been found in Olkiluoto and the extent and detail of the geological and geophysical data would have revealed any large mineralisation. The documented occurrences of precious or 'critical' metals from the base metal sulphide veins are very rare. Considering that the volumes of In, Sn, W and Mo required for economically profitable mining are significantly lower that the volume of base metals, the potential occurrence of these critical metals is considered more significant than the occurrence of the base metals.

Extension of investigations into the less well-characterized eastern portion of Olkiluoto carries some risk that indications of exploitable minerals could be found. This seems unlikely given the lack of indications thus far from surface-based geophysics and consideration of the surface geological model. However it should be kept in mind, as moving in this direction will bring the investigations closer to the nearest rapakivi granite intrusions (Eurajoki intrusion) and associated greisen dykes.

Conclusion: The focus of the site characterization work by Posiva has been on other geoscientific factors compared to those in a resource exploration, which would focus on the distribution and grades of metals, trace metals and all accessory mineral phases. It is thus acceptable that the broader consideration of mineral potential is based on the general geological setting and known occurrences of the specific elements. The recent (post-OSD) work by Posiva has presented reasonable arguments for there being no potential. However, further assessment is recommended to quantify the potential properly. The occurrences of all observed ZnS, CuFeS2, PbS, In, Sn, W and Mo should be collected in a mineralisation summary (separate from alteration) and any known grades should be given. This should be supported by scoping modelling of actual potential that considers conservative examples of total tonnages of specific metals that would be required for economically profitable mining activities, translated into required deposit grades and sizes, specifically taking into account that the occurrence of the deposits is restricted to faults with known maximum lengths. It would be usefully illustrative if the assessment also showed how much change in metal prices in the future would be needed before the mineralisation could become potentially economically interesting.

2.3.2 Abnormally high rock stresses

There is no evidence that abnormally high stresses will be encountered in the repository volume and they have not been a problem in ONKALO construction. Posiva will need to proceed carefully with adapting design and construction methods to the stresses encountered, as illustrated by the occasions when rock falls have been stimulated by spalling procedures and the orientation of the axes of ONKALO tunnels. Rock instability with noise during scaling, loose slabs in the roof and uncontrolled block fall have been observed in the ONKALO tunnel when the tunnel azimuth changes and when the tunnel geometry changes from narrow to wider, or vice versa. During a tunnel inspection around chainage 4200 – 4420 by the SONEX expert group in May 2010, strong imprints from mechanical scaling were observed in the roof of two intersecting tunnels and, the day after the inspection, a 1.5 m^3 block fell from the roof where this was observed. The rock fall was most likely the result of a local weakness zone located in a tunnel crossing with a wider span width. However, too forceful mechanical scaling of the roof at the tunnel intersection may also have contributed. For the enhancement of tunnel stability, Posiva might consider mechanical scaling with limited hydraulic forces of the mechanical scaling equipment, in combination with manual scaling. The UOPL (Section 6.4.1) considers safety issues regarding rock falls during the operational stage.

Conclusion: There is no problem with abnormally high stresses. As Posiva is well aware, the stress regime needs to be accounted for in design and construction. As block fall might happen when tunnel geometry and azimuth is changed, and at intersection of tunnels, special design of tunnel support should be considered for these areas.

2.3.3 Probability and nature of seismicity at the site

The earthquake scenario is a central aspect of Posiva's safety evaluation, as this 'disturbance scenario' leads to the highest impacts, especially when multiple container failures are accounted for. The inclusion of the possibility of it leading to buffer erosion if shear occurs in post-glacial conditions (rather than current conditions), leads to the highest estimated peak releases. The significance attached to this scenario in Posiva's safety case is reflected in the assessment below, which is broken into several sub-sections.

Background

Information on the 'earthquake scenario' is spread across a wide range of reports. The main ones are WR 2012-08, WR 2011-08 and Posiva 2012-34) for the geological modelling and Posiva 2012-04, -08 and -09 for the way in which the geological information was used to set up consequences analysis calculations. The latter depend principally on the estimated probability of an earthquake and are dominantly concerned with the likelihood of one or more post-glacial earthquakes.

Posiva's position is summarised in the PAR (p.384), which concludes: *"The possibility of a large earthquake leading to canister failure due to secondary movements on fractures, especially at a time of ice-sheet retreat, cannot totally be excluded. It is estimated that few tens of canisters are in positions such that they could potentially fail in such an event. The average annual probability of an earthquake leading to a canister failure is estimated to be low, in the order of 10^{-7}, given that there are around 5 zones that could host such an earthquake. Therefore, during the first glacial cycle, the probability of occurrence of such an earthquake is low".*

Posiva has analysed two earthquake events leading to canister shear in two scenarios, RS1 and RS2, in which rock shear and canister failure occur at 40,000 years (during the present, temperate period) and at 155,000 years, during a period of ice-sheet retreat. The Synthesis Report summarises the outcome as follows: *"The highest peak normalised release rates from the geosphere are, in both cases, more than two orders of magnitude below the regulatory geo-bio flux constraint. This implies that more than one hundred canisters would have to fail simultaneously before the regulatory geo-bio flux constraint would be exceeded, even without taking into account the low probability that this event would actually happen. This exceeds the few tens of canisters estimated to be in critical positions that are vulnerable to failure in the event of a large earthquake".*

Consequently, two important issues considered in this review are (a) the probability of occurrence, near enough to the repository, of one or more earthquakes of large enough magnitude to cause shear on a fracture and (b) the number of containers that could be affected by such an event. Posiva's position is that the probability is very low and the 'random' number of poorly located DHs is, in any case, very low and would be minimized actively by adequate application of the RSC criteria for DH location.

The outcome of this review includes concerns about: Posiva's magnitude (M), frequency (F) and fault location estimates (both during current and PG stress conditions; where EQs could occur with respect to the repository location; the likelihood of propagation of EQ shear into the relatively shallow region where the repository is located; whether Posiva has gathered and used sufficient data (e.g. LIDAR, GPS). There are also suggestions of a possibility that distributed displacements of large magnitude could occur 1 or 2 km from a M7+ EQ on a distant BFZ.

Recent evaluations of EQs in stable continental regions (e.g. Klose and Seebers[1]), supported by much broader statistical studies reported by Cloos[2] indicate that M<5.5 EQs have a low probability of causing BFZ displacements in the upper 1 km of crust that contains the repository, so an assumption of any associated 'target fracture' fracture displacements for small events thus seems conservative. In order to arrive at events within the 5 km radius around Olkiluoto that are of sufficient magnitude to be of concern, an assumption has to be made of full-length surface rupture, which appears to be even more conservative and requires earthquake magnitudes that are approaching 6 to 6.5. These are the largest (M_{max}) that are expected for this region of Fennoscandia. A further observation is that large (M7+) PG EQs will be restricted to long, pre-existing BFZs, the nearest being >10 km away from the repository, so analysis of target fracture displacement for such big events needs to take this into account. An additional factor that should be considered is whether any/all of the BFZs in the Olkiluoto area are capable faults: it would be conservative to assume that they could all reactivate.

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[1] C.D Klose & L. Seeber (2007). Shallow seismicity in stable continental regions. Seismological Research Letters, 78(5), 554-562.

[2] M. Cloos (2009). The Nature of Tectonic Hazards. In: Connor, C. B., Chapman, N. A. and Connor, L. J. (eds.). Volcanic and Tectonic Hazard Assessment for Nuclear Facilities. Cambridge University Press, Cambridge. 24-73.

STUK seismology expert review

STUK's March 2014 EQ workshop considered whether the rock mechanics approach to induced displacements used by Posiva (using 3DEC) is adequate for M>6 EQs. With the 3DEC approach, fault rupture is initiated at a pre-defined hypocentre (by a programmed reduction of the faults shear strength) and programmed to propagate outwards radially across the fault plane with a specified velocity (MDR, p.255). Both the fault and target fracture displacements calculated are considered (p.269) to be conservative, despite the assumption of elastic deformation of the target fracture with the maximum displacement at the centre of the fracture. The reviewers considered the methodology generally acceptable and supported. A suggestion is that a seismological approach, using probabilistic fault displacement hazard analysis (PFDHA) would be more conventional for large events. Conversely, rock mechanics may remain the best approach for M<6.

Considering the possibility of a large EQ in the current temperate climate state and tectonic regime, the following conclusions can be drawn:

- There are BFZs at the repository site (5 km radius zone) that are capable of hosting M5-6 EQs, based on their size (although their depth is unknown – which is a critical matter in any analysis, to account properly for their potentials – and it is not clear about how Posiva calculated M_{max}).
- There is a low likelihood that most BFZs could host a M6.5 EQ within the Olkiluoto site: the highest estimated probability being about 40% for BFZ214 – the rest are <20%, generally very much less. This would only happen if they were subject to full-length surface rupture.
- The EC's SHARE (Seismic Hazard Harmonisation in Europe) project produced a weighted average value for M_{max} for this area of 6.68.
- Posiva's estimates of large magnitude event F at the repository site (5 km radius zone) are the most conservative of those evaluated by the reviewers. The annual probability of M5+ in the 'circle' is c.10^{-6} to 10^{-7}, depending on approach. This means that, in the next 1000 years, P is thus about 0.001, which could justify an impact analysis for this early period.

The review raised the issue of distributed faulting. Significant fault/fracture displacement is known to occur many km away from large M seismogenic faults in some geological environments (Petersen et al.[3]). The outward limit for such displacement from seismogenic faults seems to be c.12-20 km. Displacements considerably greater than 5 cm have been observed in some environments (for M>6). Reviewer McCalpin calculates that no BFZ in the 'circle' would have distributed displacements >5cm at a distance greater than tens of metres from the source fault (i.e. such displacements would lie within the 'respect zone' of a BFZ), even with full length surface rupture, and the probability of occurrence is anyway limited: c.8%. However, nearby Class 2 BFZs *could* lead to greater displacements and Class 1 BFZ 15 km away could have the same impact (but with M7.74, which is >M_{max} for region). The probability of such a large Class 1 event affecting the repository needs to look at a larger area and works out at about 10^{-7}/year, which is similar to the P of M>5 within the 'circle' BFZs.

There are many questions about distributed faulting. Are there any known observations of distributed displacements associated with large PGFs in this geological environment? Is it a appropriate to use Petersen's model in high-strength Proterozoic basement rocks? Would triggered faulting on small BFZs (e.g., km length) be a more likely response to M7+ on a nearby (10+ km away) major fault than displacement on small fractures (e.g. 75 m radius 'critical fractures')? Triggered faulting dominates beyond about 2 km from the primary fault (Petersen et al., 2011).

For post-glacial faulting (PGF), the conclusions that can be drawn from Posiva's material are that this occurs on large, pre-existing BFZs, rather than on the small BFZs within the 'circle'. In identifying such major structures it is important also to consider the possibility of concealed 'blind' faults beneath the site. It is generally accepted that the Olkiluoto region recovered from LGM loads during the early Holocene so no further PGF is likely until after the next glaciation. The workshop considered the most likely location for a future large M7+ PGF to be the Aranda rift, whose closest structure is >15 km N of the Olkiluoto site. A M7+ event here could induce >5cm displacements at the site, with a P =

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[3] M. D. Petersen, T. E. Dawson, R. Chen, T. Cao, C. J. Wills, D. P. Schwartz & A. D. Frankel (2011). Fault Displacement Hazard for Strike-Slip Faults. Bulletin of the Seismological Society of America, 101, 805–825. doi: 10.1785/0120100035

0.001, using Petersen et al. probabilistic approach. Importantly, reviewers have suggested that there will be a higher frequency of PGF than estimated by Posiva (varied estimates: c. x10 - x20). This is a key parameter in the safety assessment.

It is notable that Posiva does not look at other probabilities affecting PGF, for example the probability that a glaciation occurs at all (e.g., the 2003 European Commission BIOCLIM project[4] estimated it could take until 200 ka – 0.5 Ma:) and that there is thick (enough) ice cover at the site to impact strain suppression and stress recovery.

Posiva's safety assessment does not use information on EQ magnitudes. Also, it does not use the probabilities of >5 cm displacements in different parts of the repository: it simply assumes that such displacements can only occur on critical fractures (which are taken as >75 m radius: it is difficult to trace where this number comes from) and will occur on all of them in the repository in the event of *any* EQ M>5 within the 'circle'. It then uses the stochastic DFN model to estimate the number of deposition holes that could be affected by undetected (and hence unavoided) critical fractures (there are 35 or 78 for different avoidance criteria). The assessment assumes that all canisters located on critical fractures will fail but, when the assessment looks at multiple EQs over the 8 glacial cycles modelled in the next 1 Ma, it is not clear whether all these fail at the first EQ. The results are presented as EQ probability-weighted releases normalised to the STUK radionuclide-specific regulatory constraints. The two cases (RS1 and RS2) have EQs that occur at 40 ka (current temperate) and 155 ka (post glacial). Posiva 2012-08 says that the choice of the 40 ka timing is "absolutely arbitrary".

The peak releases for both single-can failure and EQ-probability-weighted, multi-can failures are the same and lie about two orders of magnitude below the regulatory constraint (Posiva 2012-09, Figure 11-8). For the RS-DIL scenario, where sub-glacial dilute water can erode the buffer faster in sheared deposition holes, this margin falls to only a factor of 10 (Posiva 2012-09, Figure 11-12). So the PA results are sensitive to EQ probability and scale linearly with it. Consequently, uncertainties of P of factors of 10 to 100 could push the releases up, towards or above the regulatory constraint.

There are several questions about the calculation of EQ probability. It is built up in a stepwise fashion. First, the annual probability of a >M5 EQ in the 'circle' area is split into the annual probability per fault in that area (~ 2–5 × 10^{-8}). It is then assumed that 5 BFZs are capable faults (so P ~ 1–2.5 × 10^{-7}). Posiva then assumes 3 glacial retreats per glacial cycle (each of 120,000 year) and the EQ P for a single glacial cycle is taken as 1–2.5 × 10^{-7} × 120,000 / 3 (i.e., 0.005 to 0.01). Posiva then multiplies by 24 (for 8 cycles out to 1 Ma) and multiplies this probability by the number of canisters in critical locations and by the single canister release value from the RS1 scenario (which is certainly conservative) and assumes that all canisters that could fail, do fail (although this can only happen once, it is assumed to happen repeatedly) to get the numbers quoted in the previous paragraph. Posiva conservatively models all critically located canisters to fail repeatedly every time there is an EQ. This is clearly physically unreal, but presumably each peak of expectation value in their dose v. time plots for repeated deglaciations over 1 Ma can be regarded singly as a correct value for an EQ event occurring at any of the given times.

Posiva responded to an RAI to clarify the structure of the multiple container failure and repeated glacial cycle calculations in August 2014 (POS-0188311). The RAI response says (p.21-22):

An average rate of occurrence of large earthquakes throughout a glacial cycle is proposed, used to derive the average number of earthquakes occurring during the cycle. It is then, however, assumed that these earthquakes in fact occur during periods of glacial retreat. A zero probability is assigned to the occurrence of earthquakes at other times.

… the assumption is made that average rate of occurrence of earthquakes throughout an entire glacial cycle is equal to that inferred from the relatively short-term historical records of the Olkiluoto region (between around 1.2 × 10^{-7} *and 2.4 ×* 10^{-7} *per year; see the response to Request # 1). Assuming three periods of glacial retreat per 120,000 year glacial cycle, the average number of large earthquakes in any one of these periods is between around = 0.0048 and = 0.0096 (i.e. between 1.2 ×* 10^{-7} *× 120,000 / 3 and 2.4 ×* 10^{-7} *× 120,000 / 3).*

The division of a glacial cycle into 3 'deglaciation' periods of 40,000 years has no geological basis, be-

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[4] EU 5th Framework Project BIOCLIM, 2000–2003: Modelling Sequential BIOsphere Systems under CLIMate Change for Radioactive Waste Disposal.

cause deglaciation takes place over a few thousand years, during which time (if the Weichselian is representative) there is a high probability of EQs, so with 3 glacial retreats per 120,000 years, perhaps only a total of about 15,000 to 30,000 years lies within periods of ice retreat. It seems that Posiva considers it conservative to use a long retreat period because the number of EQs calculated to occur in a deglaciation is then larger and there is some parallel assumption that the 'EQ potential' across a full glacial cycle is focused into one of these periods.

A fundamental question remains of whether the use of the present-day EQ frequency values across a total glacial cycle is appropriate. Although the *average* value across a whole glacial cycle may be the same (see discussion below), STUK's seismology experts certainly agree that it must be significantly higher during ice retreat periods. The RAI response says (p.22):

However, tentative arguments are presented.. that suggest that the rates inferred from historical records (in particular the rates proposed by Fenton et al, 2006) may, in fact, be more representative of the post-glacial phase than they are of the present day. This tentatively suggests that our assumption is conservative, assuming present-day rates are lower than those in the postglacial phase.

…

Assuming that the postglacial faults observed in Finnish and Swedish Lapland cover the full spectrum of large earthquakes for the last deglacial phase (which is a fair assumption, as it is improbable that faults that could host M6+ or M7+ earthquakes would have not been undetected until now, or at least the number of such faults should be quite low), it can be inferred that approximately 20 large earthquakes took place within the deglacial phase.

STUK's seismology experts would disagree with this. There is continually growing LIDAR and other evidence of large fault displacements in central (not only northern) Sweden (e.g. Jakobsson et al.[5]) and it is particularly surprising that Posiva makes no mention of the evidence immediately offshore Olkiluoto itself. For example, STUK expert Bungum, in Appendix 6 of Hora and Jensen[6] estimates several hundred large events in Lapland, with the value depending on the assumed M_{max} value used. His areal frequency value within a 5 km radius of Forsmark is about 20 times greater than SKB's and the same would most likely apply to Olkiluoto.

Posiva's (thus, too low) value of 20 large EQs is then equated with Posiva's scaling of the Fenton et al.[7] F-M relationship for historical SCR EQs and used to speculate that Fenton's data are actually more appropriate for PG conditions than for the present day. These arguments are, as Posiva states, speculative.

STUK expert McCalpin's review brought together STUK expert NORSAR's estimate of PG activity frequency (a factor of 20 times greater than today) and his own estimates. McCalpin observes:

I have assumed that the total hazard in the next 170 ka results from glacial loading suppressing earthquakes from ridge-push stresses, and unloading releasing those stored stresses until they were all released. After releasing the stored stresses in a 2 ka Deglacial, the following Interglacial only experiences infrequent ridge-push (tectonic) earthquakes. This scenario represents a zero-sum game; the (potential) earthquakes suppressed during the Glacial are exactly released during the deglacial, but no more. There are no "extra" earthquakes and no "extra" seismic moment release. Therefore, the total seismic hazard in the next 170 ka would be equal to the present (interglacial) hazard rate times 170 ka.

In the 43 ka of Glacial time the activity rate will drop to much lower than at present (as low a zero), and in the 6 ka of Deglacial time the activity rate will be as much as 8 times higher than today's. But the total seismic activity over the 170 ka would be a constant.

The only thing that would change the above conclusion would be if the glacial loading/unloading process did more than simply suppress and later release horizontal ridge-push stresses to cause earthquakes. In other words, does the loading/unloading process create additional earthquakes beyond those released by the "stored" ridge-push

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[5] M. Jakobsson, S. Björck, M. O'Regan, T. Flodén, S. L. Greenwood, H. Swärd, A. Lif, L. Ampel, H. Koyi & A. Skelton (2014). Major earthquake at the Pleistocene-Holocene transition in Lake Vättern, southern Sweden. Geology, 42, 379-382. doi: 10.1130/G35499.1,

[6] S. Hora & M. Jensen (2005). Expert panel elicitation of seismicity following glaciation in Sweden. SSI Rapport 2005:20, 119 pp.

[7] C. Fenton, J. Adams & S. Halchuk (2006). Seismic hazards assessment for radioactive waste disposal sites in regions of low seismic activity. Geotechnical and Geological Engineering, 24, 579–592.

strain energy? If this is true, then the sum of earthquakes that would be generated in the next 170 ka will be greater than merely the tectonic (Interglacial) rate times 170 ka.

The implication here is that using present-day frequency data as an average for a full glacial cycle, as Posiva has done, *is an appropriate approach*. As noted above, the hazard is focused into the short glacial retreat periods, when frequency is higher, by a factor of 8 to 20. It remains a problem that Posiva continues to use numerical approaches that rather tend to obscure the geological and seismological characteristics.

This raises the fundamental issue of whether Posiva's estimates of P in the current tectonic regime are conservative or not: a value of 2.4×10^{-7} per year has been assumed by Posiva. STUK's experts concluded that, for present day and future temperate conditions, the M-F curve developed by Posiva (Figures 2-10 and 2-11, Posiva 2012-34) was conservative in the way that it blends F values from historically high and low seismicity areas around the site. It is noted that the curve is based only on low M EQs (no data above about M4.5) so the projection to large-M is inevitably conjectural. However, the accepted Gutenberg-Richter 'b' value to use in such circumstances is 1, whereas Posiva have used a more conservative value of 0.77. Estimates made by STUK's consultant McCalpin, based on other approaches, produce lower F values. The assumption that these two zones would persist for 100 ka is difficult to justify, although this factor does not significantly affect the conclusions.

In the RAI response, Posiva arrives at a more pessimistic value of F for M5+ earthquakes in the 20 km radius around Olkiluoto, of 3.3×10^{-5}/a. The approach is less sophisticated than the independent analysis made by McCalpin in which he looked at Posiva 2012-34 (Saari's) approach, the SHARE results and his own independent assessment of the most appropriate 'a' and 'b' coefficients for the Gutenberg-Richter relationship. He concluded that: *"For M6.5 and higher, Saari's coefficients predict more earthquakes than any of the other relationships, even my higher coefficients. Saari's coefficients also predict more earthquakes than my lower coefficients down to M4.5, and more earthquakes at all magnitudes than the SHARE coefficients. Thus, it appears that Saari's coefficients are the most conservative of the group from the standpoint of seismic activity".*

McCalpin also notes (p.35) that the approach to frequency values used by Saari *"…does provide the most conservative assessment of M>6 seismic activity rates around Olkiluto during interglacial periods such as today"*. In Appendix 1B of its RAI response, Posiva appears to have taken a further step closer to conservatism by using the worldwide SRC data of Fenton et al.

It is important then to note, that for deglaciation periods, STUK's reviewers agree that P will be up to 10 – 20 times higher than the average values discussed above.

So, how conservative is the overall EQ scenario of Posiva? The assumption that all N_{crit} canisters would fail in a single EQ seems highly conservative and, apart from EQ frequency, the analysis is deterministic and does not incorporate several other probabilities that would give a lower P-weighted impact. The probability of a M5 EQ propagating upwards into the shallow crust where the repository is located is low (perhaps about 10%) so only M6+ within the 'circle' are likely to be 'effective' and they have diminishing P. This points to conservatisms that could balance the possible lack of conservatism in PG values of P.

In response to the 2014 RAI, Posiva provided information on the impacts of an early EQ, occurring 200 years after closure. This supplements the existing analyses of EQs at 40,000 and 150,000 years. Posiva notes:

It is acknowledged that, at times as early as a few hundred years, saturation of the repository near field may be incomplete and repository-generated heat may affect the performance of the repository barriers and hence the release and transport of radionuclides if such early canister failure were to occur. These effects would, however, require considerable effort to quantify reliably and are not taken into account in the present calculations.

In acknowledging that there might be some combined thermal and EQ shear impacts, Posiva has not specifically identified combined EQ and thermal shear of target fractures. At the time when this review was being completed, parallel work by SSM was producing an initial evaluation of an alternative approach (particle flow modelling) to estimating shear displacements on target fractures and fracture zones within the repository, caused by large EQs and thermal strains. Initial results suggest that significant displacements (cm scale, exceeding the canister shear limit) occur on target fractures and fracture zones. Neither thermal strain nor induced EQs of M<3 alone can generate shear displacements that exceed the suggested limit of 5 cm. However, the superposition of thermal strain and an induced EQ along any of the major fracture zones will generate shear displacement exceeding the canister shear limit. The SSM work suggests that an EQ on a nearby BFZ that would *not* cause canister shear under 'normal' (after the thermal period) conditions, *could* cause shear if it occurred while the rock is significantly heated. So, an early EQ such as the 200-year illustration calculated by Posiva, is more likely to cause shears than a similar EQ occurring later in the temperate or post-glacial period. Posiva will likely be unaware of this work as it is currently unpublished.

For the 200 year EQ scenario, Posiva calculates a peak dose that arises from 90-Sr and is around 1 mSv/a, then uses the regulations to justify applying a probability to the deterministic single can release value, which seems appropriate (the March 2014 EQ workshop record notes that *"Posiva would be entirely justified in treating this probabilistically"*).

The value used by Posiva for the number of canisters that fail (100) does appear to be suitably conservative, even taking into account the possibility raised by the SSM work that an early 'thermal EQ' could lead to a higher susceptibility of target fractures to shear. First, the number is set a factor of 3 to 4 higher than the calculated number of susceptible deposition holes. Second, as Posiva asserts, it appears unlikely that all potentially susceptible target fractures in the repository would shear and also unlikely that all shear events would lead to total failure of the canister.

Nevertheless, on the first point, another new SSM study[8] indicates that, using an independent model and comparing it to the same approach to target fractures as used by Posiva, SKB may have underestimated the number of susceptible deposition holes by a factor of 2.5 to 14, a difference that cannot currently be totally accounted for and thus needs further exploration. The report points out that the positions identified using the independent approach include a significant proportion at the plug end of deposition tunnels, which would likely be identified more readily as they also intersect access tunnels.

Even taking this work into account, the Posiva value of 100 failed canisters still appears adequately conservative, but the whole critical (susceptible) fracture and thermal shear topic is an area that certainly justifies continued study.

Whether there could be an EQ of sufficient magnitude to cause target fracture shears in this early period is a further matter. The March 2014 EQ workshop noted that the SHARE regional M_{max} value (6.5 to 7.1 with weighted average of 6.68), together with the size of the local BFZs, limits the possible M to values similar to those evaluated by Fälth and Hökmark, which show small displacements (as do the estimates of McCalpin). Only a M7+ could cause shear failures.

In addition, of Posiva's RAI response (p.8, on larger magnitude earthquakes and consideration of a larger area around Olkiluoto) matches closely with the conclusions of the STUK seismology reviewers with respect to temperate period conditions. While some of the larger BFZs discussed at STUK's EQ workshop are big enough to host M7+ events, the SHARE data and STUK's seismologists' reports suggest that this would only be likely under post-glacial conditions.

There are other activities that appear important for Posiva's future work:

- A conventional PSHA for the facility (operational and post-closure), which presumably will be required by STUK for the operational license for both the surface and underground facilities. Given the above discussion about validity of the rock mechanics approach, a seismic hazard analysis should include a PFDHA for higher magnitude EQs.
- Neither Posiva nor SKB has formally responded to or rebutted Morner's interpretations of large, late EQs in central Sweden. For completeness, it would seem important to have their views on what has become a running challenge on the record.

Posiva is certainly planning further work on EQs and in December 2013 outlined ongoing work that will be published in WR 2013-64 on the stability of LDZs during a glacial cycle. In addition, new work on the stability of deformation zones during a glacial cycle was published at the time of completion

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[8] J. Geier (2014). Independent evaluation of the number of critical canister positions in the KBS-3 repository at Forsmark. SSM Technical Note 2014:44.

of this CRR and has not been reviewed (WR 2013-37). The results of the ongoing LIDAR surveying to locate PGFs are going to be an essential component of further evaluation of the EQ issue.

STUK expert review conclusions on conservatism of Posiva EQ scenario

The two principle EQ parameters that influence how the safety consequences of EQs have been calculated are:

1. **Frequency:** which is used directly to provide a probabilistic weight to the multi-canister releases. Any underestimation of F scales directly onto the calculated releases.
2. **Magnitude:** although the value of M is not used in safety assessment, the value of n_{crit} is central to the multi-canister release calculations, and this derives from the value of critical fracture radius, which in turn relates to the largest magnitude EQ and its possible deterministic BFZ location with respect to distance from the repository.

STUK's March 2014 EQ workshop identified a number of conservatisms in Posiva's work and a number of non-conservative assumptions. Separately, in response to the subsequent RAI, Posiva also assembled some possible conservatisms, but did not integrate or quantify their impacts.

The **conservatisms** identified by STUK's experts are:

- frequency estimates of M>5 EQs under 'normal' temperate conditions;
- assumption that BFZs would rupture completely across their whole length;
- assumption that all containers in critical positions would fail (i.e. the actual estimates of critical fracture displacements, which are calculated by Posiva and STUK's expert to be small for anything other than a nearby M7 EQ, are not used at all);
- assumption of cycling glacial conditions after 50,000 years, rather than a prolonged interglacial;
- using the Weichselian as a model, which Lagerbäck & Sundh suggest might be unique among Quaternary glaciations in having led to major PG faulting;
- the suggestion by Steffen et al.[9] that there may be only one or two M7+ events per deglaciation even for a major ice-sheet, which would impact the F value for PG EQs.

The **non-conservatisms** that STUK's experts identified are:

- frequency estimates of all large PG EQs with M>5;
- the size and consequently the number of critical fractures for M7+ PG EQs close to the repository;
- the possible location for a M7+ PG EQ being only about 1 to 2 km away, beneath the E-Bay (where there are indications of such movement c.9000 years BP);

Uncertain factors that might be either conservative or non-conservative include:

- the geometry of BFZs at EQ nucleation depths beneath and around the site;
- the probability calculation methods used by Posiva for multiple glaciations;
- the application of a PFDHA approach as a probabilistic front-end to the deterministic 3DEC rock mechanical calculations of fracture displacement.

Understanding how all of these factors might balance out requires quantitative analysis, but the general feeling of the experts was that Posiva's safety case incorporated a margin of safety that would not be significantly challenged by the balance of these factors. No single factor appears to be sufficiently dominant in the balance to be highly challenging. Nevertheless, it is clear that further work is required in several areas.

In March 2014, Posiva presented an impressive forward programme of work on rock stress, strain monitoring, glacial evaluation and seismology that includes:

- POST (parameterisation of structures), including a project to characterise a large BFZ and monitor it whilst inducing slip
- PGSdyn: LIDAR survey evaluation with the Geological Survey (for Olkiluoto and S. Finland)

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[9] R. Steffen, P. Wu, H. Steffen and D.W. Eaton (2014). The effect of earth rheology and ice-sheet size on fault slip and magnitude of postglacial earthquakes. Earth and Planetary Science Letters, 388, 71–80.

- Attenuation of ground motion at depth: observations within ONKALO at different depths over a 6 month period.
- Possibility that a large EQ on BFZ214 could trigger movement on smaller BFZs (this seems to match one of our own suggestions, below).
- Stability of BFZs during a full glacial cycle: early results show shallow dipping zones (<60 degrees) are unstable in the upper 200 m and stable below 500 m, with implications for the EQ nucleation depth issue discussed above.

In addition, we suggest further requirements for Posiva to address, with the central point being 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 phase PSHA. A seismologically informed approach is needed that integrates the following:

- knowledge about how EQs initiate and propagate in the shallow and mid-crust in this SCR geological environment;
- deterministic studies of specific BFZ behaviour scenarios in and around the site, using the latest lineament data and deep geophysical profiling of BFZ geometry;
- observational evidence from LIDAR studies;
- strain budget modelling based on GPS data, EQ fault-plane solutions and in situ stress measurements;
- 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;
- rock mechanical analysis building on the 3DEC approach and novel techniques such as SSM's particle flow modelling could help elaborate the concept of critical fracture size and the N_{crit} parameter, and these developments should be kept under review by both Posiva and STUK.

This degree of integration will require planning that incorporates Posiva's already impressive future work programme (e.g. the 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.

A specific study that is required in the near future is the evaluation of an EQ on one of the E-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 PG 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 any further development of the RSC, hence its suggested early delivery.

Conclusion: There are uncertainties associated with several aspects of the Posiva EQ analysis that will take some years to resolve satisfactorily. However, the safety case is adequate for the construction license. More R&D on the EQ scenario is envisaged by Posiva and should be a commitment. More information and evaluation of an alternative, seismologically based approach will be needed for the OLA; evidence for the possibility of distributed displacements should be pursued (e.g., do they occur in this geological environment and would they give rise to different N_{crit} values and numbers of failures than in the 3DEC modelling?); a PSHA is needed anyway for the OLA and should also include a PFDHA for higher magnitude EQs and the possibility of there being smaller critical fracture radii (and thus more critical fractures) for a M7+ EQ. The specific conclusions and recommendations made by STUK's experts are given above.

2.3.4 Adverse hydrochemical conditions and the presence of methane

The deep groundwaters in the disposal volume are expected to meet the target property requirements of Posiva and to display no adverse characteristics (see Section 1.4.3). Nevertheless, there are a few topics where uncertainties and anomalous values of certain parameters need to be understood better.

The evolution of salinity through an extended period (many tens of thousands of years) of temperate climate and dilute water infiltration potential could dilute groundwaters at repository depth to such an extent that the target property value for cation concentrations to preserve the buffer against chemical erosion might eventually be violated (see

Section 1.6.1). Whilst more work needs to be done to model this variant scenario and to understand the potential impacts of a very long temperate period on groundwater movements and salinity evolution, water-rock reactions are expected to mineralise diluted waters to the extent that, with high probability, will satisfy the target property requirement. Posiva's modelling of hydrogeochemical evolution underpins this conclusion and is reasonably robust, although various simplifications and uncertainties are involved and modelling of the extended temperate period has yet to be reported.

Dissolved gases data have been affected by sampling difficulties, especially depressurisation and outgassing. Therefore gas concentrations are likely to be minima with 'tens of per cent potential inaccuracy' (OSD, p.620). Methane and higher hydrocarbon contents therefore probably have *in situ* concentrations higher than reported values, which are already remarkably high. Posiva suggests that sites in the Fennoscandian Shield where oxidising conditions have affected the crystalline bedrock in the geological past (e.g., evidenced by hematite staining or Fe-oxide in fractures) tend to have lower deep methane contents (e.g., Forsmark, Hästholmen; OSD, p.621). Olkiluoto gneisses do not have such evidence of oxidation. If correct, this hypothesis has implications other than just high CH_4, for example stronger reducing capacity of bedrock, buffering to attenuate dissolved oxygen, and also perhaps reduction of SO_4. More geochemical investigation is needed to test this hypothesis. An issue not explored in the current review is whether methane levels in the groundwaters could constitute any form of operational safety concern for the ONKALO and repository excavations. Posiva should have adequate monitoring of the underground atmosphere to detect and mitigate any gas build-ups.

Anomalously high sulphide contents have been found in a few groundwater samples. These constitute an adverse groundwater property although it is evident that these anomalies are transient and localised. The Description of the Disposal System (Posiva 2012-05) should refer to work elsewhere that fully evaluates such deviations outside target properties and shows that they do not compromise the suitability of the site.

Conclusion: As concluded in Section 1.4.3, although there are several areas of continuing uncertainty, some anomalous values and a need for continued and improved interpretation, overall, none of the reliable data indicate any significant breaches of the performance targets. Posiva needs to carry out or report modelling work to show that there is a high probability that the bedrock will buffer the TDS to acceptable levels even during an extended period of temperate climate. The operational safety implications of high methane concentrations in the groundwaters need to be borne in mind.

2.3.5 Development of adverse conditions during glacial periods

During glacial cycling, the main issues are changes in flow and hydrochemistry. Under glacial conditions, all of the perturbations take place in the upper 500 or so metres. Flow rates through the repository volume during the retreat of an ice sheet increase by factors of 4 to 7. The PAR summarises the overall position on flow perturbations through the full glacial cycle as follows (p.384): *"The groundwater flow related target properties are expected to be fulfilled over the considered time frame for most deposition holes. The fraction of the canister positions with a flow rate above* 10^{-3} $m^3/(m{\cdot}a)$ *remains low (about 10% of all the potential canister positions with no inflow criteria applied) during the temperate period. There is an increase to 20% during ice-sheet retreat, when the ice margin is located close to the site. During the permafrost period, the groundwater flow is reduced. During the high flow conditions related to the ice-sheet retreat, when the repository is still under the ice sheet (mobile ice sheet 10 years), there is a significant increase in potential deposition hole locations having a transport resistance in the range of* $3{\cdot}10^4$ *to* 10^6 *a/m, but transport resistances below* 10^4 *a/m remain exceptional."*

Chemical perturbations principally concern salinity, i.e. TDS content (effectively, avoiding dilute waters). The stability of the deeper saline waters in notable: as the PAR observes (p.309): *"Hydrogeological variations during former glacial periods have not been able to develop sufficiently high gradients to dilute the saline groundwater volume to fresh water"*. The PAR flow modelling estimates that relatively high salinities could occur under certain conditions due to an upwards bulge of deep saline groundwater ahead of the advancing ice sheet. In the case of a mobile ice sheet, there is no major change in the salinity at repository level as the ice margin moves quite fast. However, if the ice margin remains over the site, the maximum salinity in the reference volume rises to about 30 g/l and the minimum salinity also decreases to a few grams per litre during a period of 1000 years. This is close to violating L3-ROC-15 (max. 35 g/l, though this target property has been set cautiously low), but Posiva argues that a static ice front for a long period is unlikely, using the value of 1000 years that has been interpreted for behaviour during the Weichselian retreat (although not at Olkiluoto). The numbers of DHs that will be affected by dilute waters during glacial cycles is calculated by the Hydro-DFN model (PAR, p.304), and it is concluded that the number is small. The results are critically dependent on and highly sensitive to the matrix diffusion penetration depth, which, if small, will result in more DHs being affected. Reducing the penetration depth into rock blocks from total penetration to 0.1 m has a factor of up to around 100 impact on DH numbers that are affected. The most realistic case, according to Posiva, is that the whole rock matrix is available for diffusion. Under prolonged temperate climate conditions, modelling indicates that dilute water penetration would affect more DHs than during a glaciation (PAR, p.304). However Posiva argues that the extent of groundwater dilution in general will be moderated due to water-rock reaction, pre-existing saline water and by diffusive exchange with porewaters in the rock matrix (PAR, p.310).

Conclusion: The topic is dealt with in the PAR and the resulting impacts are shown to be limited, with the target properties expected to continue to be met.

2.4 The selected disposal location and depth

It is important to note that the CLA documentation does not contain an integrated justification for the choice of disposal depth. The DBR explains the basis for having a depth at around -400 m but only says that "…rock properties are in general considered to be favourable…" without citing any data to justify this. Remoteness from impacts of glaciation and permafrost (and from potential human intrusion) is the rationale for going deep, whilst increasing salinity and CH_4 (as potential reductant of SO_4 to HS^-) are the geochemical factors in favour of not going deeper. The DBR says that *"it is not evident"* that fracture frequency continues to decrease below 400 and that groundwater chemistry is favourable below 300 m. Posiva 2012-22, p 79, mentions that one argument for not going deeper is that there are *"uncertainties in the harmfulness of the salty groundwater to bentonite"*. This is a reasonable justification for the selected depth. There is quite a high degree of uncertainty about both the gradient of increasing salinity beneath repository depth and also about the possibilities for upconing of this deeper saline water during the construction and operational phase. Nevertheless, for the chosen depth, the risks of dramatic upconing such that bentonite stability would be compromised are low.

The chosen disposal depth is approximately at the interface between interpreted Depth Zone 3 and Depth Zone 4 of the Hydro-DFN model. WR 2012-42 suggests that this leads to heightened sensitivity to choices regarding model truncation thresholds. Posiva should clarify whether the depth zones are well founded and, if so, explain why the repository has not been moved slightly deeper into the apparently better rock in Depth Zone 4.

All the information provided by Posiva is of a qualitative nature and there is no integrated justification of choice of disposal depth. For example, the state of stress at repository level and deeper has not been discussed with respect to repository location and depth. Clearly, there are many other factors involved in choice of depth, including environmental impacts of excavation, construction safety and costs. While the selected depth is technically acceptable with respect to the TCHM properties of the rock/groundwater system, it would be useful for STUK to see how these other factors were weighted in reaching a decision on depth.

2.4.1 Hydrochemical conditions and the choice of depth

There are 27 water samples obtained from OL-KR boreholes from the interval 400–450 m, which could be considered to represent proposed disposal depth. This number of water samples is just sufficient to make a well-based judgement about geochemical favourability if the samples and analyses are evaluated to be reliable.

Redox data (Eh values) throughout the OL-KR water samples are more scattered than they are expected to be, with a wide range of Eh values from strongly negative (reducing) to +250 mV (oxidising). The discrepant (i.e. positive and low negative) Eh values are probably measurements that have been perturbed by atmospheric oxygen ingress. There are 20 measurements of Eh in groundwaters between 400–450 m depth. Of these, one qualified value is +68 mV, and the other 19 values are between -90 and -300 mV. These Eh data are just adequate for giving confidence that groundwater is reducing at disposal depth and elsewhere in the system, though the spread of values is greater than is consistent with the expected redox equilibrium (OSD, Fig. 7-39). The reviewers consider that the deep groundwater redox condition is reducing everywhere – but additional quality control and evaluation of the redox data plus continued measurements and monitoring are needed to improve the level of confidence.

Salinity in samples from the 400-450 m depth interval ranges from 9500 to 23300 mg/l TDS and 5860 to 14500 mg/l chloride, with a high variability of salinity around disposal depth. However, this range is well within the acceptable range of target properties. The variation poses the question of whether there is evidence of either dilute water infiltration with drawdown to ONKALO or saline water upconing (see Section 1.7.2). Monitoring during construction will be needed to understand this variability.

Conclusion: Conditions at disposal depth are geochemically favourable with respect to measured salinity and sulphide. While there are some problems with measured redox values, the reviewers consider that the deep groundwater redox condition is reducing everywhere. Consequently, the selected disposal depth is acceptable from a geochemical perspective.

2.4.2 Permafrost penetration to depth

Section 4.1 of the PAR (p. 101) notes that *"…the possibility of permafrost formation has been taken into account primarily in the selection of the depth of the repository…"* No permafrost is expected to occur until after 50,000 years. Section 7.3 cites Hartikainen (2006) to say that permafrost will not reach repository depth. A subsequent report (WR 2012-34) says that a period of at least 30,000 years, with an extremely dry climate and without ice sheet, vegetation, soil or snow cover, would be necessary for permafrost to reach repository depth. The PAR (Section 4.1) states that: *"From the knowledge of the LGC, these conditions are very unlikely to persist for such long periods at Olkiluoto in particular and Finland in general."* The low probability of this 'dry glacial cycle' seems a reasonable conclusion to draw, based on the results shown in WR 2012-34, although Posiva notes that they plan more work on this. As discussed in Section 1.6.1, we consider that current evidence indicates that permafrost probably did not penetrate deep in glaciated areas of Fennoscandia during the Weichselian and that Posiva presents reasonable evidence that deep penetration is highly unlikely to arise.

Conclusion: The depth implications of permafrost evolution are considered and analysed with modelling and convincing explanations, but there is no integration of this analysis into a discussion of optimum disposal depth.

2.4.3 Human intrusion as a factor in selection of depth

The Synthesis Report (p.174) describes the DS(G) Deep Well Disturbance Scenario, where a deep (> 300 m) well is drilled at, or in the vicinity of, the site and used for extracting household water, watering animals and irrigation purposes. The well intersects a water-conducting feature deep in the geosphere and the water drawn from the well has passed through the repository. Posiva says that this is 'unlikely' but, given the increasing use of deep heat exchange wells, even for individual domestic purposes, it may not be so unlikely. The DS(F) scenario calculations are stylized and multiply consequences by an "indicative annual probability" of intrusion. The probabilities are in the Biosphere Assessment report, which has not been reviewed. The human intruder dose assessment report (WR 2012-23) appears to calculate doses, but is not referred to at all in the PAR or the Synthesis Report. There seems to be some confusion and lack of traceability here.

In any case, this scenario does not seem to have been used in terms of setting an appropriate repository depth. Posiva simply asserts (Synthesis Report, p.229) that: *"The location of the repository, at a depth of about 400 to 450 m below ground, will provide isolation from the surface environment and protection against inadvertent intrusion"*. The expectation is, in any case, quite low, as the relevant Posiva Safety Function simply says "…. limit the possibility of human intrusion", not exclude it.

Conclusion: Intrusion does not seem to have been used other than in a conceptual sense when considering repository depth. There is no quantitative discussion of depths and types of intrusion or the circumstance under which they might occur (or likelihoods). This is not an issue of any significance. Intrusion by drilling can never be excluded. Over very long times, it has a high probability. However, the whole conceptual basis of deep geological disposal is that depth equates with isolation. No reasonably achievable depth for construction/operation provides complete protection anyway. STUK can accept that the spirit of the deep disposal concept is being properly adhered to by Posiva by locating the repository at >400 m depth. This should not be an issue in the CLA.

2.4.4 Sufficient volumes of rock between LDFs

Posiva's brittle deformation model as summarized in the OSD is scientifically credible, but represents just one possible interpretation of the available data. Alternative models have not been developed to assess the effects of geological interpretation uncertainty. Posiva has taken a "minimalistic" approach to defining brittle deformation zones (BDZs). BDZs are included only if they can be correlated among multiple boreholes. BJZs (joint zones) are given comparatively little attention compared to BFZs (brittle fault zones), leaving open the question of whether all BJZs of possible significance for the layout have been identified. Speculative BFZs and possible extensions of BFZ are not included. As a consequence of this "minimalistic" approach, Posiva's BDZ model may lead to overestimation of available space for a given repository footprint. The results of prediction-outcome studies so far indicate that more fracture zones may be encountered than predicted by the model, so the question of "adequate volume" will depend on how the "extra" fracture zones (presumably mainly smaller-scale brittle deformation zones) are treated.

Posiva 2012-21 addresses the major layout determining features (LDFs) and the respect distances assigned to them, which are a strong control on available volume of rock at repository depth. The report acknowledges that this is 'work in progress', but provides a clear enough statement of approach and results to give a picture of constraints and uncertainties. Unlike SKB, Posiva's LDFs and their respect distances (and volumes) are based on avoiding two possibilities: the possibility of a fault hosting a post-glacial earthquake (the only one used by SKB) and the possibility that a high transmissivity fault zone could cause significant future flow/hydrochemical perturbations. This is considered a sensible approach. For the former, faults >3 km in length are automatically LDZs as they could host a $>M_W 5$ earthquake. For the latter, faults with $T > 10^{-6}$ m^2/s and lengths of several hundreds of metres are automatically LDZs. Other zones, with lower T, have been included on the basis of expert judgement, but Posiva does not explain what criteria were used or whether this was a rigorous use of expert judgement – consequently a challenge could be that they 'miss' some potential LDZs unless they can be more explicit about their assumptions. Once the LDZs have been identified, the rest of the report only looks at these faults and goes on to calculate Influence Zone sizes. Only the thickness of the main core zone has been included, even if there are several zones with denser fracturing, transmissivity and low P-wave velocities, which affects the applicability of the scaling laws and the asymmetry of the influence zones, and hence the understanding of the faulting processes. The sequential approach for doing this is logical and seems to make the best use of the fracture intensity and hydraulic data available. Some of the fracture evaluation on either side of faults seems to have been done using borehole core photos, rather than the core itself.

Figure 4-10 of Posiva 2012-21 shows damage zone (Influence Zone, IZ) thickness as a function of fault length. The Olkiluoto LDZs have smaller IZs than would be predicted based on scaling laws using global datasets (from Scholz, 2002). The thickness variations of the influence zones have been attributed to the radial growth of the fault, with larger influence zone thicknesses in the fault core, where displacements have been the largest. However, an alternative reason might be that the zone thicknesses vary due to the intersection of the fault zone with other fault zones, or due to changes in the fault geometries (curvature).

The use of the Scholz scaling law is correctly understood by Posiva to have high associated uncertainty, especially when applied to BFZs for which the extent of the feature along strike or dip is not well constrained. The proposed use of this scaling law – only for features that lack more direct observations – is appropriate for the purpose of estimating the available space. Posiva is clear that using scaling law estimates of IZ would be more conservative for the safety case. This is supported by the estimates of *"rock volumes affected by deformation* *zones"* (as derived independently from fracture data analysed in conjunction with Geo-DFN modelling), which are smaller than the deterministic IZs and those constrained by scaling laws.

An important finding of the RSC testing reported in the RSC 2012 report also addresses the width of IZs at the 'large fracture' scale, rather than LDF scale. The IZs of some larger BFZs that were measured were wider than modelled at the site scale (e.g. RSC report p. 120, where the local DSM v1 widens the zones beyond the scaled values derived from the site scale model and p.192, where the measured values after excavation were wider than estimated from PH data, and also asymmetric).

The least convincing aspect of LDF treatment is the derivation of IZ thickness using hydraulic data (Section 4.4.2). The plots of transmissivity (from PFL data) against distance from fault are over-interpreted to give IZs of around 10-15 m. The data are too patchy to draw conclusions. However, the HTU data available for some of the LDZs give a much clearer indication of a c.15 m IZ. The value is thus probably reasonable. Nevertheless, the possibility that some faults have high transmissivity splays some tens of metres away ought to be taken into account in setting respect distance. For example HZ20 hanging wall and HZ099 both have high T fractures some 30–35 m from the fault core.

Results on different ways of estimating IZ thickness are tabulated for each of the identified LDZs. They are variable between each borehole intersection of an LDZ. For example, HZ20A varies from about 5 to 60 m; HZ099 varies from about 17 to 77 m. It is interesting to compare these with the conservative values that the Scholz scaling approach would give. Depending on what fault length actually is (not properly discussed in this report), they could be about 40–60 m, so the results seem reasonable in terms of an average value, but do depend on assumptions about LDZ length, based on their connectivity relation to adjacent faults. However, respect volumes then seem to be set that use the variable values (i.e. they vary along the lengths of the LDZs), which is certainly not conservative.

Posiva does not seem to recognize that estimates of influence zone thicknesses based on boreholes and tunnels that penetrate a BFZ at one or a few points are likely to be biased downward, in comparison to influence zone thicknesses that would be determined from surface traces (due to the fact that secondary features such as splay faults are less likely to be identified as associated structures from a limited exposure along a tunnel or borehole, as well as the likelihood of missing the widest parts of an influence zone). This bias will tend to reduce the conservativeness of the respect volumes, rather than to reduce estimates of available space. However, since Posiva's overall approach to defining respect volumes is conservative, this bias in estimating influence-zone thickness can be accepted. If Posiva finds a need to reduce the conservativeness of LDF respect volumes during the construction phase, owing to insufficient space, the consequences of this bias might become more consequential, so this needs to be monitored.

Conclusion: The IZ results for each LDZ (which is the key concern for determining respect volume and thus available rock volume at disposal depth) are a reasonable basis for the current CLA, but there are significant uncertainties that can only really be addressed by more observations from boreholes drilled during construction. It is hard to get a feeling about how conservative or non-conservative the mapped respect volumes are, without going into considerable depth on the data for each feature. The key Figure 5-1 does not have a scale and is not sufficiently detailed to work out the exact size of the mapped IZs for each feature and how these vary along length. Consequently, we do not know what the sensitivity of useable repository volume is to IZ size for some of the key LDZs. For example, if a uniform conservative IZ was applied to each LDZ, based on scaling, it might significantly affect useable volume and Posiva does not discuss this, although it is presumably central to viability.

2.5 Basis for the bedrock performance targets

The performance targets and their limits for the bedrock properties are stated in VAHA Levels 3 and 5. The targets are L3 and they feed down into the RSC, which are L4 and L5. A central aspect of the whole Performance Assessment is strongly based upon exploring how TCHM properties of the rock affect system behaviour, whether performance can deviate from the targets and on scenarios that look into disturbances that can lead to parameter values moving outside the targets.

2.5.1 Defining and meeting the performance targets

In the DBR, Posiva uses the term "target properties" rather than "performance targets" for the properties that are defined based on the safety functions. As explained on p. 59 this is because once the site has been chosen, the host rock's properties must be regarded simply as given. This is a reasonable distinction, provided the site selection process was thorough and comprehensive and provided good confidence that the known properties of shortlisted sites would meet isolation and containment requirements when subject to further investigation. The target properties for the bedrock in DBR Section 6.3 are based on a mix of research and expert judgement. Reasonable scientific arguments are given for each of the target properties. These arguments are generally of good quality but some targets are vague, with some defined clearly and quantitatively, others in semi-quantitative terms and others only vaguely (e.g. 'low' and 'limited'). This indicates that these target properties are not strongly based on a thorough scientific analysis of their importance for the safety case, but more on some level of expert judgement. The vagueness of the requirement for "limited" flow into deposition tunnels is recognized in the RSC report (p. 209). The lack of clear, quantitative criteria on all target properties should be regarded as a deficiency in the CLA.

For example, Section 6.3.4.3 sets a design requirement for inflow of groundwater to deposition tunnels to ensure performance of the backfill. The primary concerns are piping and erosion in the early post-closure phases. The target is 'shall be limited'. In the RSC report, a criterion of <0.25 l/min inflow from a single fracture has been established for acceptance of a deposition tunnel. The Design Requirement and the RSC criterion should be consistent. In view of the potential importance of degradation of the backfill by piping and/or erosion, and for consistency with the way that design requirements for deposition holes are set, there should be a quantitative design requirement for deposition tunnels. In discussion of 'loads to be taken into account' in the Design Basis report, the experimental background to the RSC criterion is mentioned, indicating backfill tolerance to inflows between 0.1–0.5 l/min.

In respect of these unquantified targets, a specific issue is whether Posiva has adequately explained how attainment of target properties will be assessed in cases where the specified properties are not directly observable. For the **hydrogeological target properties** enumerated in DBR Section 6.3.4, the explanations are partly given in the paragraphs titled, "Loads to be taken into account." These explanations can be summarized as follows:

- Low flow rate around deposition holes: Posiva suggests (p.70) that this target property can be assessed by measuring inflow rates while the holes are open, and then scaling the observed flow rates *"according to the expected gradients in the expected [saturated] conditions after repository closure."* Problems with this approach include that: (1) the highly heterogeneous hydraulic gradients during the open repository period need to be understood, but a clear plan for measuring these gradients has not yet been presented; (2) it does not take into account changes in transmissivity of near-field fractures due to e.g. shear dilation caused by small shear movements caused by thermally-induced stress after closure; and (3) it does not account for flow-path switching which can occur in sparse fracture (or sparse channel) networks in response to changes in the direction of hydraulic gradients. Results of Hydro-DFN modelling of open vs. post-closure flow rates (WR 2012-48, Figures 4-1, 4-2, and 4-13) indicate that, although this conceptual model predicts a positive correlation between the two flow rates, the scatter is nearly of the same magnitude as the trend. Thus, examination of the results of Posiva's models for this issue leads to an impression that simply scaling open-hole flow rates is of limited reliability for assuring that this target property will be fulfilled.
- Sufficient transport resistance: Posiva explains (p.71) that this transport resistance is to be estimated from DFN models. This approach is well explained in Posiva's transport modelling strategy report. The main weakness is that the evaluation of transport resistance relies on a single conceptual model (although parametric variations are considered). Supporting arguments based on alternative approaches (whether numerical models or other lines of evidence) should therefore be presented as part of the safety case.
- Limited flow to protect backfill: This concerns the total inflow to each deposition tunnel during

the construction period, which can be observed directly. Posiva discusses reasonable methods that will be used to control inflows during the construction period (avoiding hydrogeological zones, grouting etc.).

- Favourable retention properties: Posiva notes (p.72–73) that retention depends on the chemical conditions, mineralogy and properties such as alteration of the host rock and fracture surfaces. Sorption parameters have been estimated based on these factors while porosity and matrix diffusivity have been measured on a laboratory scale and discussed as part of the OSD. Posiva concludes that *"the degree of variation [of retention properties] is such that it is not meaningful to consider this characteristic further in the criteria adopted in locating the deposition holes."* This is a reasonable approach in view of the complex spatial variability of the controlling parameters along flow paths, which are largely unknown, and considering the potential future variation in hydrogeochemical conditions.

In summary, the major concerns are that a methodology for predicting post-closure flow rates to DHs is not adequately presented (apart from the results of WR 2012-48, which suggest that the reliability of predicting these from open-repository conditions is limited), and the methodology for predicting transport resistance relies on a single (DFN) conceptual model, which is analysed in terms of a small set of variants.

With respect to **geochemical target properties**, the rationale for the target property of anoxic groundwater at repository depth is set out in Posiva 2012-03 (Sections 6.3.1.1 and 6.3.3.1). There are two interlinked requirements: absence of dissolved O_2 (DO) as a corrodant of copper and chemically-reducing conditions to minimise rate of spent fuel dissolution and solubilities of radionuclides that have redox-sensitive speciation, i.e. U, Tc, Se and C. Whilst the requirement for DO is 'nil', which implies analyses of DO that are within analytical precision of zero, the definition of reducing conditions is not set out. A target redox measurement (or interpreted value) is needed so that measurements are assessed objectively. That target could be justified, for example, by reference to the Eh-pH speciation 'predominance' diagrams for U, along with commentary on the adequacy of this for Tc, Se and C speciation and solubility. Considering the pH target range of 6-10, Eh below the corresponding range of about +100 mV to -100 mV should ensure that all U stays as U^{IV}. Thus, for consideration of U, the definition of reducing conditions could be 'below -100 mV Eh' with a margin for confidence. A thorough discussion of this issue and of the tolerance for DO measurements is missing from Posiva's documentation.

The rationale for conditions to minimise corrosion, i.e. high enough pH and low [Cl^-], is set out in Section 6.3.1.2. Quantified target ranges for pH and [Cl^-], i.e. in which corrosion is known to be minimal, are pH >4 and [Cl^-] <2 M. Understanding of relevant processes is referenced to SKB TR-10-67, which is an update of Posiva 2002-01. Although the explanations and quantification of corrosion processes are authoritative, there is no explanation of these pH and Cl^- thresholds for the safety function. In addition, differing targets are given, e.g., for pH (VAHA L3-ROC-11, L3-ROC-16 and L3-ROC-30). The principles involved are qualitative justifications for 'high enough' pH and 'low enough' salinity, but it is not clear how rigorously these thresholds should be enforced. This is most pertinent for Cl^-, because it is at least plausible that [Cl^-] could rise above 2 M (i.e. >71,000 mg/L) at some time in the future.

The roles in corrosion of other solutes, i.e. NO_3^-, NO_2^-, NH_4^+, acetate and especially HS^-, are also explained, but the use of the term 'limited' in the target property statement avoids quantitative targets for concentrations of these species. This is especially significant for HS^-. SKB's 'SR-Site' assessment has a similarly unquantified safety function indicator criterion of 'low' for HS^-. The same comments concerning lack of quantified targets apply to Posiva's requirements for organic C, H_2, S_{tot} and CH_4.

The rationale for 4 mM being the lower limit for charge equivalent of cations, $\Sigma q[M^{q+}]$, in order to mitigate possibilities of buffer and backfill erosion is referred to SKB Technical Report TR-09-34 and TR-10-47. Experiments reported quantitatively justify the 4 mM lower limit to prevent erosion of a bentonite that has at least 20% Ca^{2+} occupancy of the exchange sites. Therefore, compliance of the system with this target property requires also that the buffer and backfill will both maintain bentonite compositions with >20% exchangeable Ca^{2+}. It is also noted that Posiva consider that 'available experimental data suggest that bentonite colloids are not stable at concentrations higher than that set by the target property' (WR 2014-09, p.8); the origin and significance of this assertion should be clarified. The general applicability of this target property, which is based on limited experimentation, should be assessed for the full range of potential bentonite materials and hydrochemical conditions, e.g. pH, ionic strength, SiO_2, K^+, etc..

The rationale for the salinity maximum (35 g/l TDS, or transiently 70 g/l) to preserve bentonite swelling pressure is also referenced to SKB TR-10-47. Bentonite in backfill is particularly vulnerable because of its lower compaction. The target is based on experiments with bentonites. SKB assigns a salinity maximum of 100 g/l TDS (= 1.7M NaCl), so it appears that Posiva's target is conservative and perhaps over-cautious. However the specific or general validity of the conclusions from experiments has not been reviewed, so no conclusive comment can be made about the robustness of the 35/70 g/l maxima used by Posiva.

The limitation of acceptable pH range for buffer and backfill stability is based on thermodynamic stability of bentonite and therefore depends also on other relevant solutes, SiO_2, Ca^{2+} (as Posiva state) and also Na^+, Mg^{2+}, K^+ and Al. The particular concern is alkaline dissolution and alteration. However long-term stability in normal pH conditions also needs to be assured. Posiva's rationale in Posiva 2012-03 is a statement of consensus opinion. The target of 'limited' for K^+ and Fe_{tot} concentrations, also for buffer and backfill stability, does not allow for a simple objective assessment. Acceptable concentrations that assure bentonite stability could be bounded using thermodynamic modelling, though composition-dependent free energy data for montmorillonite are rather uncertain in relation to potential alteration products.

The rationale for chemical conditions to be reducing to minimise spent fuel dissolution and radionuclide solubilities lacks definition of 'reducing'. Referring to the discussion above concerning thermodynamic stability of UO_2 and U^{IV}, a maximum redox value (Eh) of -100 mV would seem to be conservative. A further rationalisation should refer to the effect of redox on the kinetics of UO_2 dissolution and also to redox effects on other redox-sensitive radionuclides e.g. Tc, Se and C. Those considerations are not discussed in Posiva 2012-03.

Acceptable concentrations for colloids and organic C in groundwaters around future deposition hole locations are not defined. There are no specific conclusions in the literature relating to these target properties, and it is unclear how rigorous targets should be estimated since colloid-facilitated radionuclide transport depends on physical and hydraulic factors also.

Various properties promote matrix diffusion and sorption of radionuclides in host rock, as acknowledged in Posiva 2012-03: chemical environment, interconnected porosity, diffusivity and mineral surface characteristics. For these target properties, Posiva should indicate what conditions and properties might be unacceptable or deficient in relation to retention and retardation. Although Posiva have developed a rather sophisticated conceptual model for transport and retardation that involves four classes of fracture and wall rock textures (Posiva 2011-02), it is not clear how this translates into an objective target for the safety function.

The same unquantified target of 'limited' is given for the other reactants involved in biogeochemical reduction of sulphate to sulphide: organic matter (DOC), H_2, CH_4, total S (i.e. predominantly SO_4). A meaning for 'limited' needs to be discussed in the context of what would be 'actionable' concentrations and how these can be based on the specific effect on corrosion.

Target properties of groundwater compositions 'to prevent montmorillonite dissolution' (Section 6.3.2.3) and for buffer/backfill stability (Section 6.3.2.4) are subjective and unquantified, and evaluation of these targets would need expert judgement. The way that these targets are going to be used in practice is not described.

Conclusions: There are shortcomings with respect to the weak definition and measurability of several target properties. This is discussed in more detail in Section 3.2, on RSC, where most of the key hydrogeological properties will be measured. In terms of geochemical target properties, the values for baseline hydrochemical conditions (i.e. initial state) do not presently exceed the tolerances (even the qualitative ones) stated by Posiva. However, Posiva needs to provide a protocol and guidelines by which they will assure their assessment in a defensible way. Explanations are needed of both the scientific basis and of how expert judgement will ensure that target properties and design requirements will assure the safety functions of the bedrock and lead to quantitative tolerance levels, above which a safety function would be impaired.

2.5.2 Use of complementary considerations to support performance targets

There are two potential roles of complementary considerations (CC): (a) to support the definition of performance target and act as indicators that they are met and (b) to support forecasts of long-term system behaviour in the safety case, including estimates of releases of radioactivity.

Section 9 of the Synthesis Report describes how CCs have been used to back-up the confidence in geological disposal and in the site, but most of the information provided is derived directly from the site characterisation work and is included as part of the OSD. The only specific reference is to the natural analogue work at Palmottu, where penetration of oxidising glacial meltwaters into the site was buffered by the host rock after only a hundred metres depth, which Posiva says is supporting evidence indicating the suitability of the crystalline host rock for a repository. In the CCR there are other examples that are not brought forward into the final argumentation: e.g., the evidence for permafrost development producing relatively small salinity increases in underlying groundwaters (p.66). Little or no use is made in the main safety case of other CC information: e.g. the Greenland Analogue Project is scarcely mentioned in the CC report (with no results described) and not at all in the Synthesis Report. Thus, the CCs have not been used to define performance targets. Apart from the introductory material about the Posiva approach to the safety case, targets are not mentioned in the CC report.

Quantitative comparisons of CCs with PA results are made in Section 9 of the Synthesis Report and Section 13 of the PAR. The following statement is possibly one of the most compelling results of the safety assessment: *"Thus, the fact that the activity flux from the repository, summed over all radionuclides, is less than the natural Ra-226 flux indicates that the activity flux from the repository is no more radiologically toxic than the natural flux, based on a measure of toxicity (the dose conversion factor for the hypothetical wells) that is relevant to the site".* There is a similarly powerful statement about C-14: *"…to put this peak annual release rate in perspective, it is almost an order of magnitude less than the annual uptake of natural atmospheric C-14 by a forest ecosystem over the repository footprint".* Posiva has not updated the calculated fluxes with current geochemical data, as the concentration data appear to be from 2003, before ONKALO was excavated, combined with more up-to-date flow data. Presumably, additional and more distributed data on elemental and radionuclide concentrations are now available for the site and it would be useful to update these flux data before the next license round.

This type of direct comparison with information from the natural environment is ideal for use when direct observations are not possible, as in the case of estimated releases. The data are in Section 11 of the CCR, but the presentation is rather weak, with the effect that information is spread around in an apparently random fashion. In addition, the CCR makes no comparison with repository releases. It is frustrating that both the direct impacts of natural radioactivity and the comparisons with repository doses have been completely separated from this material, so that sections of the CCR often finish without making any comment on utility.

Conclusion: Complementary considerations have not been used to define performance targets, but this is not a problem. The CCs support are mainly useful in supporting the safety case and are not a good mechanism for setting targets. They appear strongly in support of the quantitative flux and release concentration results. Where the CCs are used as strong support for the safety case, as in the flux and concentration comparisons, the results are compelling. Given their significance and that release fluxes are incorporated into the regulations, it would be useful for STUK to ask Posiva whether up-to-date geochemical data from ONKALO groundwaters would modify the results presented.

3 Rock classification system

The rock suitability criteria (RSC) are the key indicators of whether a disposal tunnel or deposition hole location can be accepted for use and are thus at the heart of practical decision-making during construction. Posiva started the development of a rock classification system in the late 1990s (Posiva 2000-15), which led to the development of the Host Rock Classification, Phases 1, 2 and 3 (WR 2003-04, 2005-07 and Posiva TKS 2009), which later became the RSC programme for layout determining feature and preliminary criteria for tunnel location and deposition holes (Posiva WR 2009-29). Over the period 2010 to 2012 the development of the tunnel-scale and deposition hole-scale criteria is referred to as RSC-II.

The 2012 RSC report makes the strong statement (p.99) with respect to the RSC that *"…its efficient implementation will necessitate its seamless integration with design, construction and research activities"*. The RSC implementation testing to date has not been 'seamlessly integrated' with construction, as Posiva acknowledges that tests were omitted or incomplete owing to the tightness of the ONKALO construction work. This Section assesses the RSC methodology development and the actual criteria proposed.

3.1 The RSC methodology

This section considers the structure, development and testing of methodology, Posiva's approach to improving it and how adaptations to repository design might to cope with changing ground conditions might make use of the RSC.

3.1.1 Structure, development and testing of the methodology

The RSC project represents 'work-in-progress'. Posiva has made good progress on developing criteria and testing approaches at the tunnel and deposition hole (DH) scale, but testing in the Demonstration Tunnels has had to be fitted in around construction schedules. The work is good, but it has not been possible to structure the sequences of activities properly in all cases. Section 6 of the RSC report is at a high level and there is insufficient information on procedures. Consequently the tests used for methodology development are rather patchy and pragmatic, and it would be difficult to repeat some of them on a regular basis (e.g. RSC p.126 and 131). Nevertheless they have been extremely useful. Posiva acknowledges that RSC is an on-going programme that is going to require more development and testing. For example, it is already clear that some of the RSC-II criteria (such as tunnel inflow) need to be amended to make them practical and meaningful, and this will need testing. Posiva does not present plans in the RSC report for how they plan to move forward. The conclusions say that work in DT1 and 2 will be completed and that demonstration will continue in 'adjacent areas', but does not explain the nature, scale or timing of this work – or its aims.

The RSC methodology appears to be sufficient to ensure that volumes of bedrock with favourable properties are correctly identified *eventually, provided early indicators of unsuitability are treated with caution*, but its practicality needs much more testing work. There will need to be many more tests at both tunnel and DH scale before the system can be deployed with confidence. The information provided by tunnel PHs is a particular problem at the moment, and does not yet constitute a confident basis for making excavation decisions. For example, the initial tests in access tunnel pilot hole 10 (e.g., p.39) would have led to the tunnel being condemned on the basis of PH data, when subsequent excavation showed much more of it to be acceptable. It is also recognised (p.71) that PHs cannot identify tunnel-cutting features, which are a key indicator of disposal tunnel suitability (e.g., p.137). The exploration for hydraulic features in the DT pilot holes also failed to identify half of those found in the excavations (p.132). The points at which STUK would become involved in evaluating the RSC decision-making points (RSC, Fig. 7-2) clearly need consideration.

Description and 'diagnosis' of semi-horizontal fractures (i.e., those that do not intercept deposition tunnels but which are perhaps the largest threat to deposition holes) presents a particular detection problem. Posiva found that the large fracture criterion (L5-ROC-64) in areas where horizontal and sub-horizontal fractures prevail has a large effect on the host rock volume considered suitable for canister emplacement. Canister locations could be discarded unnecessarily due to lack of data about the true fracture length and characteristics. Posiva sees the need for additional work to improve the characterisation of the geometry and orientation of shallow dipping fractures and set of fractures. Also, Posiva has to consider situations where the tip of a fracture or a brittle fracture zone with any orientation terminates in the host rock a short distance away from the periphery of the deposition tunnel or deposition hole. In this respect, geophysical methods need much more evaluation. Posiva intends that work will continue with *mise-à-la-masse* measurements between boreholes and seismic investigations, including down-hole seismics. There is a need for development of a borehole radar system for detection of discontinuities of all scales that is tuned to work satisfactorily in the migmatitic gneisses. Overall, better conceptual models of the occurrence of brittle faults and fractures would aid in estimating the lengths and significances of fractures with unknown sizes.

A practical method still needs to be demonstrated for routine measurement of inflows to DHs, along with a well-defined protocol for when these flows should be measured, and how they should be interpreted. The Hydro-DFN modelling approach demonstrated in WR 2012-48 shows promise as a means of testing and developing a rationale for specific protocols. Detection and monitoring of inflows, especially where these are diffuse or where the provenance is not easily attributed to single fractures, is problematic because underestimation of inflow rates has significant safety case consequences. Monitoring and analysis of ventilation air humidity and water content is needed to check the component of water balance that is not accounted for by the weirs and local collectors described in WR 2014-17. In addition, Posiva has not tested the hydrochemical RSCs in its demonstration work.

There are no quantitative RSC criteria for water compositions. The chemical components and parameters of interest in RSC will be those in the safety functions and target properties, i.e. pH, redox, sulphide and other corrodants, etc. Targets for many of these, e.g. sulphide etc are qualitative (e.g. 'low') so RSC criteria will presumably also be only qualitative. Because the hydrochemical conditions apply to large volumes of rock, the hydrochemical RSC are possibly only needed at the repository and panel scale and do not need frequent measurements at the tunnel or deposition hole scale (apart from the 'lack of grout' criterion). There is a clear link here to the broader monitoring programme, where the L5 chemical RSC can be addressed by routine monitoring schedules, rather than requiring 'RSC-specific' measurement work (see Part 2, Section 4.6, of this review). Enhanced sulphide contents in some groundwater samples could be due to transient perturbations caused by borehole activities having stimulated microbial activity and the fast reduction of sulphate. A similar process could cause unexpectedly high sulphide concentrations in groundwaters around tunnels and deposition holes. Testing for this should be one of the main objectives of analyses of sampled inflows as part of the RSC procedures, but it is not clear what is planned in this direction. The many practical issues of the reliability of samples obtained from inflows and seepages question whether such monitoring for sulphide as part of RSC procedures would be sufficiently meaningful as a decision-making basis. The time factor also needs to be considered. A part of the central tunnels will remain open for several years (SER, Fig. 7-3), which may induce upconing of more saline waters in some parts of the disposal rock volume.

The step-by-step application of the methodology has not been properly tested yet. The tight ONKALO construction schedule prevented this in the DTs. The sequential approach is clear but seems overly complicated. Posiva recognises the need for streamlining (p. 209). At present, it is not clear that each classification step of the RSC II methodology can and will be completed prior to the start of each construction step, in a production environment. More work is needed to reach that point of practicability, although the overall approach has good prospects of achieving that goal. Also, some larger-scale aspects have not been tested yet and there is no plan of how the RSCs will be applied at panel scale. For example, it would seem sensible to excavate multiple tunnels (or even a whole panel) before any DHs are located, as the tunnel-to-tunnel data will provide considerably improved confidence in the fracture DSMs. This effect was evident in the staged tests in DT1 and DT2. Another aspect that is not really tested is the use of the panel central tunnel at the initiation of the RSC application to a new panel. The short central tunnel in the demo area did not provide much support to characterisation of the DTs. Posiva might want to keep options open about the practicalities of deployment, as they expect more experience will keep this constantly updated. Posiva needs to be allowed flexibility in this critical and complex area, but they should provide detailed plans and objectives for their RSC development programme. The RSC development and testing plan is missing.

Conclusion: Posiva has done good work on the RSC development and testing that is adequate for the CLA, but this area will require considerably more work. The methodology is logical and would be expected to achieve the objective of identifying suitable rock volumes. There are clearly emerging problems in deploying it (e.g. the value of both tunnel and DH pilot hole data) and also a risk that ‘good’ rock could be wrongly classified as unsuitable in the earlier activities in the RSC sequence. The opposite problem could arise, but will be resolved at the excavation stage. Continued RSC development should be the primary focus of Posiva’s site-related R&D efforts during the construction stage. However, no detailed research plans for further development of RSC are presented by Posiva (e.g. in YJH-2012). The importance of the RSC means that this needs to be followed up by STUK, and translated into requirements. A related question is whether the RSC will need to change fundamentally if Posiva moves to KBS3-H.

3.1.2 Improving the methodology

The updating from RSC I to RSC II, and the demonstration of the RSC II methodology as documented in the RSC report, show that Posiva has the technical capability to make improvements in the methodology as knowledge is gained, at least in a research setting. Whether improvements can be made within the more difficult time constraints of a production environment is not clear. Posiva’s ongoing RSC demonstration work should help to establish whether they are developing organisational capacity in this area.

Some optimisation of the EFPC criterion may be possible through further development of methods for discriminating among FPI fractures to determine which are most likely to be very large fractures, by means of geological and geophysical characterisation from tunnels. Experience and information gained from tunnels can be expected to be useful in this regard. The results of PH investigations and modelling indicate that characterisation based on PH observations will be less useful for this purpose and this is a significant matter for Posiva to resolve, as there is currently no apparent alternative to using PHs. Efforts to optimize the EFPC criterion based on geological and geophysical characterisation would tend to lead to less conservatism for long-term safety, since there would be an increased chance of misidentifying an FPI fracture as small when, in fact, it is large enough to host significant shear displacement. However, the current criteria are highly conservative, so the marginal effect on safety might be small.

From calculations based on the Hydro-DFN approach in support of RSC (WR 2012-48, p.153), an implementation of the basic FPC leads to poor utilisation of just 61%, even with an adaptive design approach. The authors state that a utilisation factor of at least 74% is required to accommodate the planned fuel inventory. A variation on the FPC in which only FPI fractures larger than 75 m radius are avoided leads to an acceptable utilisation rate of 83%. Whether such fractures can be reliably identified underground remains to be demonstrated, but the results of WR 2012-48 suggest that development of a less conservative version of the EFPC is necessary to fit all of the spent fuel into the currently designated space.

If a less conservative version of the EFPC criterion leads to better utilisation of the rock in the central part of Olkiluoto, resulting in a smaller repository footprint and avoiding the need to expand into the relatively uncharacterised rock under eastern Olkiluoto, the net result might be positive for long-term safety.

RSC describes 8 cycles of application in experimental deposition holes in the 2 Demonstration

Tunnels between May 2010 and November 2012. These 'cycles' are a mixture of progressive refinements of the classification criteria and evaluations of the impact on overall utilisation of available tunnel length (utilisation ratio, %). The important objective at this stage is to assess the effectiveness and practicability of the RSC in terms of locating DHs and optimising use of rock volume (i.e. not being overly conservative). This objective is not clearly achieved yet, nor is progress towards it clearly evaluated. 8 cycles of refinement in just over 2 years of intensive work indicates clearly that there is more yet to be done.

Conclusion: Posiva has the technical capability to improve the methodology as construction proceeds, but STUK will need to be convinced that this takes a sufficiently high priority over construction drivers. Experience in the initial phase of construction will inevitably lead to improvements in the RSC procedures and specific problems, such as the poor utility of PH data, need early resolution. The basic procedures and parameters have to be refined and consistent from the very first deposition holes and the traceability of decisions has to be 100% reliable right from the first deposition hole. Posiva have not yet given an outline of how they expect the RSC procedures to be implemented and improved at that stage.

3.1.3 Adapting repository design to ground conditions using the RSC

The RSC report (p.18) says that *"In case of non-compliance, the system design – or ultimately the whole disposal concept – has to be modified until a technically feasible and long-term safety system can be demonstrated. The development of the disposal system can, therefore, be considered as a continuous iteration between performance assessment, evaluation of safety and design basis."*

In principle, Posiva appears intent on adapting design to the conditions found – this is a *sine qua non* of the whole project and Posiva would certainly expect themselves to have to do this. In the Demonstration area they have already had to do it, even for the purposes of demonstration tests. The lengths of the DT tunnels were changed to provide sufficient DH locations and to avoid nugatory excavation in poor rock. This is analogous to the decisions that would be taken routinely in qualifying every disposal panel/tunnel. However, there is no description of procedures with hold-points that will be used in practice. Indeed, the tight ONKALO timetable seems to have precluded them from having any hold-points in the demo work. At the December 2013 RSC workshop, Posiva was asked about how management decisions based on RSC measurements would be taken. STUK was told that the RSC programme only leads to recommendations to decision-makers and that there is no current documentation on how RSC findings would be weighted in operational decisions on layout, excavation go/no-go, time scheduling etc. The possibility of a 'Master Document' to capture these key points was mentioned by Posiva. Section 2.4 of the UOPL describes a process known as the *Management of the Disposal Concept* that is used to guide design requirements. The new process must interface closely with the deployment of RSC and presumably should be monitored by STUK, at least over the initial period, to see how decisions are made and what controls them. The same section also notes that some issues have changed during the excavation of ONKALO (e.g. permitted depth of the EDZ being less in the lower parts of the ONKALO) and this raises the question of whether Posiva has a Change Control system in place as part of VAHA which ensures that any changes and the reasons are formally documented – again, a procedure that STUK should inspect in the future. Also, STUK should inspect how Posiva integrates the RSC results into planning, design and construction of the repository.

The LDF report discusses plans for adjusting the classification of rock volumes in response to increased characterisation of the influence zones associated with BDZs. Posiva will have a strong incentive to make such modifications, because the scaling relationship used to predict influence zone thicknesses is likely to lead to larger respect volumes than thicknesses estimated from tunnels. The procedures for modifying respect volumes are fairly clear, but there are no clear decision hold-points within this procedure. This could be an important area for regulatory involvement.

Conclusion: Posiva has experience of adaptation but has no published procedure for its use in the real repository, or any description of hold points. Improving interaction between the RSC team and the design and construction teams should be one goal and STUK should establish a requirement that this be developed. This seems critical for STUK, as the inspection of how and why operational decisions are taken that affect the long-term performance of the repository is critical. Section 2.1.4, below, makes suggestions for STUK requirements in this respect. Although procedures are said to exist, STUK would need to incorporate them into a formal inspection programme. The issue of formal 'change control' in VAHA will be important to track.

3.1.4 Suggested requirements with respect to RSC programme development

Following the December 2013 workshop on RSC, the following were proposed as a list of possible requirements that STUK could place on Posiva to ensure that the RSC development would lead to a practical methodology to determined acceptable disposal locations that could be incorporated into STUKs inspection programme.

1. To present a clear plan and procedures for the construction and operational management decision-making steps, 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.
2. Prior to licensing, Posiva should provide STUK with a construction plan that clarifies issues such as how many deposition tunnels are to be constructed at one time and should explain whether such decisions will affect the quality of RSC interpretations.
3. To develop, test and update 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. In particular, the Manual should address situations where tests fail or are inconclusive, or require support by new or additional work.
4. To design and present a routine programme of hydrogeological testing and monitoring work that will be used once panel construction begins and 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. This should be designed to enhance the fracture or channel network models that underpin various aspects of the safety case and should utilise state-of-the-art testing techniques and instrumentation.
5. To present a report on DH inflow measurement tests.
6. To resolve the uncertainties surrounding the derivation and proposed measurement approaches and application of a tunnel inflow criterion in the RSC. This needs to be done before or immediately after licensing, even though it is recognised that it may be further updated in the early stages of construction.
7. To provide STUK with a documented version of the Panel Calculator that can be evaluated and used as a basis for inspection. After testing and potentially further developing the Panel Calculator, Posiva should provide a sequence of variables (and their orders and magnitudes of variation) that will be used, according to which the results of the panel calculator will be used. Such variables include, e.g., DFN fracture set parameters and suggested variations in the tunnel orientations.

3.2 The RSC criteria

This section considers the way in which the criteria are formulated, how they relate to the target properties and the practicalities of measuring the relevant parameters and using them to make layout and spatial utility decisions.

3.2.1 Appropriateness of the criteria

Posiva acknowledges that the RSC-II criteria are *"not the only solution"* to meeting target properties and they are their *"best current understanding of how the target properties could be met"*. This transitory situation is acceptable, provided a credible development programme is in place. The RSC-II have recognised shortcomings, but appear to be a suitable working basis *at present* for bedrock classification, with the proviso that they need considerably more testing and will no doubt develop and be adapted during construction work.

At the December 2013 RSC workshop, it became clear that there could be gaps in the RSC: e.g., it was not clear whether thermal rock properties will be included in the RSC before construction begins (e.g., to measure and incorporate the lithological variability in thermal properties into decisions on precise DH locations). Also, whether lithological mapping of tunnel floors and DHs will be carried out routinely and used to estimate DH-scale thermal responses before a DH is located/accepted, and whether the TERO probe will be used routinely in DH testing and qualification. There might be a need for a Level 4 requirement that specifies design modifications with respect to the subordinate rocks in the tunnels (pegmatites, amphibolites).

The RSC report does not go into detail on hydrochemical monitoring methods for 'geochemical stability' (p.76). Posiva has stated that these are under development and will be reported in the next RSC update. Presumably, water samples will be collected by the same or similar equipment as used for measuring inflow rates, which are still primitive. They are likely to be reliable quantitatively only for point or linear inflows and will underestimate diffused seepages. Equipment that could be systematically and reliably deployed has not yet been described. The selected parameters are pH, Cl^- and total cations concentrations, but the values of these parameters are almost certainly going to be within the target ranges. It is thus important to know where and how often measurements will be made and with what intention, in terms of the volume of rock intended to be classified as 'chemically acceptable' (panel scale or smaller). The only possible deviations will occur due to grout influence, saline upconing or dilute water penetration as technical/introduced water.

Sulphide (HS^-) is missing from the stated criteria, but is a directly relevant parameter for canister corrosion and should not be omitted. However, it is easily perturbed during sampling to transient high values due to biogeochemical activity (the relevance of which is not fully understood) or to low values (due to oxidation of sulphide by air). A consistent monitoring procedure needs to be developed. Sulphate (SO_4) concentration should also be monitored because it would be a source for HS^- by biogeochemical reduction, and also because it is rather variable at repository depth and therefore localised data are needed. Occasional sampling for microbial analyses, e.g. at inflows that can be more reliably sampled, should be included, and also DOC, CH_4, and ammonium NH_4.

Hydrogeological modelling (WR 2012-32, WR 2012-42 and WR 2012-48) results indicate that the correlation of flow rates between open-repository and post-closure conditions is not strong enough to assure that post-closure target limits of inflow will be met for all canister positions that are accepted based on open-repository measurements. Therefore Posiva will either need to strengthen the criteria, or else show that safety functions will be maintained with less stringent limits. In other respects the observable hydrogeological and structural geological criteria can generally be regarded as appropriate, justified, and sufficiently extensive for bedrock classification.

Conclusion: With the exception of thermal and some geochemical properties, the RSC-II criteria appear suitable, adequate and workable in principle for the present stage of the project, provided that both STUK and Posiva keep this development work on a tight pathway with clear interim and final objectives. There are no major problems with Posiva's approach that would affect licensing or delay the process, but the RSC application system will need to be further clarified and developed from now through into the initial stages of construction. Posiva will need to give confidence that they have an adequate programme and plan for the critical transition from RSC research to RSC application during construction.

3.2.2 Connection to bedrock target properties

The link to target properties for the bedrock is expressed in the VAHA levels. The targets are L3 and they feed down into the RSC, which are both Level 4 Design Requirements and Level 5 Design Specifications. Posiva has difficulties explaining the VAHA definitions and levels and Chapter 3 of the RSC report is difficult to understand.

The key question is whether the quantitative acceptance values of the RSC are valid. Avoidance of 'large' brittle fractures (the earthquake shear criterion) appears valid and, from a purely mechanical viewpoint, appears conservative. The issue of whether fractures could propagate into the DHs (by thermal or EQ strains) is still at the research level and it seems improbable that it could lead to a practical RSC. The existing chemical RSC for the rock at repository level are straightforward and valid with respect to desired target properties, but they are incomplete and they have not yet been demonstrated (see previous Section 3.2.1). The absence of L5 RSC for S, N, K, DOC, methane etc., means that the L3-ROC-12, 13 and 17 target properties appear unconnected to the RSC. However, a problem arises with the inflow RSCs, which is discussed below in Section 2.2.3. Apart from the measurements issues identified below, the key point is whether: (a) the inflows are representative of the actual inflows that will occur after backfilling and during repository resaturation and the start of thermal loading and (b) as discussed by Posiva, whether the tunnel inflow value is meaningful with respect to backfill erosion. Posiva says it is considering redefining the tunnel inflow RSC and the current value of 0.25 l/min has appeared without traceable documentation.

On point (a), Section 1.3.4 of this review raises the possibility that connectivity in the DHs may not be modelled correctly by the Hydro-DFN. The possibility that flow in the network of open channels seen after excavation could be redistributed during the 'recovery' period, such that seemingly dry holes had higher flow channels redirected to them, seems open. This possibility is mentioned in the Design Basis report (e.g., p.70): *"Therefore the groundwater flows to each deposition hole needs to be ascertained during excavation to ensure that this requirement is met. However, for evaluation of acceptable flow rates in saturated conditions the flow rates to open deposition holes must be scaled down according to the expected gradients in the conditions after the repository closure."* It is not clear if and how this 'scaling down' has been done in the CLA documentation.

As discussed in Part 2, Section 3.1 of this review, the selected DH inflow value of 0.1 l/min does not appear conservative if tunnels are left open for many months (significant buffer erosion may occur). It is based on a limited set of experiments and there is no information on why the specific value was selected, or of any attempt to do the kind of scaling mentioned above. At the December 2013 RSC workshop, Posiva accepted this criticism, so should provide information that leads STUK back through the complete document trail that gave rise to the quantitative tunnel and DH inflow requirements.

Stochastic modelling is not incorporated into the RSC. Posiva has not applied a strong stochastic approach to characterisation of the host rock, with the exception of the DFN, so any decision on suitability of the host rock based on probabilistic methods can be questioned. Posiva should outline its proposed schedule of both Geo- and Hydro-DFN model updating and explain how and when the DFN will be utilised in future decision-making – for example, the extent to which it might be used (or not) to inform construction decisions at panel and tunnel scales. This explanation should clarify whether Posiva intends to use existing or future data on fractures and BFZs/LDFs to test FPI predictions that have been made previously using the DFN to support estimates of available space in the repository.

Conclusion: The connection to target properties is clear for mechanical RSCs and the stated chemical RSCs, but these are incomplete, leaving some target properties unconnected to L5 RSC. The connection is not clear for the tunnel and DH inflow criteria and thermal properties. Posiva needs to provide more information on these matters.

3.2.3 Practicality of the criteria

We identify practical problems with some of the criteria. As discussed above, Posiva acknowledges that the tunnel inflow criterion (0.25 l/min to a specific feature) is both poorly defined (e.g. how many wet features are 'allowed' in a tunnel?) and may not have real meaning with respect to backfill erosion (e.g., RSC, p.183 and p.198). At the December 2013 RSC workshop, Posiva confirmed that it will be applied 'at the time of backfilling' the tunnel and that there may eventually be a 'full tunnel inflow' criterion. In addition, there is not a validated method of measuring tunnel inflows – only some rough tests using bottles, plates and tissues. Appendix A of the PAR discusses the inflow cases used for assessing backfill performance. Total tunnel inflows of >5 l/min are regarded as 'wet' (with a probability, derived from the DFN modelling, of having a total inflow > 1 l/min of about 40%), with 0.5 l/min being regarded as 'typical'. The latter values would be observed if there are one or two 10 – 20 m sections with a few fractures with inflows of 0.1 l/min, plus some additional small point inflows. Measuring small water inflows is also made difficult by the effects of ventilation on water at the rock surface (evaporation). The use of tunnel PHs was discussed in December 2013 and there is development work underway on the use of single PHs for a full 300 m tunnel (instead of several holes) and on the feasibility of flow measurements in upward-inclined pilot holes. Ensuring that the PH stays inside the 3.5 x

4.4 m tunnel section for 300 m will be a slow and demanding task. The lack of head measurements around the demonstration tunnels is a missed opportunity to understand the flow field in conditions representative of the deposition volume.

Similar problems arise for the critical measurements of inflows to the DHs. As observed at RSC p.186: *"….inflow measurements proved more difficult than anticipated…. development of the methodology was still in progress at the time of writing…"*. In December 2013, Posiva said that DH inflow tests would be done in the DH pilot hole (to decide whether to excavate the DH), on first construction of the DH and immediately before use of the DH. The new 'PFL-Lite' probe has been developed for use in entire 8 m length of the DHs. The PAR says that: *"…results suggest that in the order of 50 % more inflows above the 0.1 L / min limit would be obtained if inflows to deposition holes were calculated assuming the tunnels and holes to be progressively excavated, tunnel by tunnel compared with calculations with the whole repository open"*. The same presumably applies to actual measurements as well as model results.

At the June 2013 expert meeting, Posiva said that higher inflow rates impaired the effective emplacement of buffer and backfill and were important with respect to the potential for piping erosion of buffer and backfill, and the linkage between inflow rate and Q_{eff} of the deposition hole. In December 2013, Posiva said that the 0.1 l/min criterion is not a clear indicator of long-term flow rates at DHs, or the local transport resistance. They expressed a desire to be able to characterise connectivities, which they consider a better indicator of long-term flow. They are also assessing the use of injection tests in the DH pilot holes to generate flow data. While this work certainly addresses the key problems and could lead to an improved DH inflow criterion, the difficulty is that there is not currently any documented information for the CLA.

The dilute water buffer erosion scenario (sub-ice-sheet) shows that applying the DH inflow requirement has no significant impact on performance. DBR, Section 6.4.5.1, says that the main rationale (design requirement = L4) leading to L5-ROC-62 (deposition hole inflow) is to protect the buffer in the saturation period. It is important to consider how this matches with the concept of saturating the buffer quickly to develop its full specification properties. It is acknowledged that reduction of the early post-closure period buffer erosion potential is the key driver for this criterion. After this period, and given the acknowledged change in inflow rates during pre-closure repository operations from a variety of factors, it is not clear what is the basis for Posiva's assumption that measured inflows/ Q_{eff} in deposition holes will not change over thousands, to 100,000 years following repository closure. Modelling results presented by SKB and SSM show that loading from each of bentonite swelling, thermal loading from the waste and excess groundwater pressure from glaciation will generate joint and fracture slip, causing aperture changes and modifications of the initial flow field.

At this time, Posiva has only one 'wet' deposition hole on which to base their inflow modelling, where they made repeated measurements over a period of 3 days. It will be important to clarify where the timing of a measurement would fit into the tunnel and hole excavation and completion time schedule. Posiva acknowledge that this is a dynamic parameter that could change with time of measurement and relationship to surrounding excavation and water management procedure. It will clearly require additional experience in constructing deposition tunnels and holes and making measurements. Posiva is much more confident that there will be no problem in identifying FPI fractures in drill-and-blast conditions. Posiva also stated that they would request STUK approval of their measurement methodology and the time for making this measurement. This would be an item for STUK inspection during construction.

A further topic for inspection will be the codes that have been developed for making suitability estimates. The RSC report describes three codes that have been developed and sequentially replaced each other, culminating in 'Panel Calculator' (see p.174). No doubt this code will be further developed and tested. At some stage, STUK will need to verify or audit the code if it is to be used routinely for decision-making during operations. As noted previously, this tool should also be made available for independent calculations to support inspections by STUK.

Posiva uses three suitability classes (suitable, possibly suitable and not suitable) at the three scales of repository, tunnel and deposition hole. Possibly suitable refers to a situation where additional investigations and excavation would be needed to confirm suitability. There is no need for additional classes and it seems the three classes function well in the repetitive process of performing suitability classifications following the specified levels of the target properties.

Rejection of DHs could create a space problem for Posiva. Section 4.5 of the System Description report (Posiva 2012-05) notes that the inflow RSC will be combined with an engineering (or technical) approval process to ensure that the requirements for the hole geometry and declination are met. Figure 4-5b gives an example of modelled inflows from the DFN modelling, but its implications and limitations are not discussed. There is no discussion of uncertainty about available space and the decision process, although this might be in the suggested 'Master Document'. YJH-2012 'Future Plans' report promises (p.204) that Posiva will produce a report on RSC where *"…the functionality of the criteria will be assessed and the entire classification criteria will be finalised and submitted for approval so that it can be implemented in the construction work"*. A 2017 update of RSC is suggested as a possibility.

For the chemical RSC, Posiva might consider selective rather than routine monitoring, because samples of very small volumes of inflows are likely to be so perturbed by aeration, drilling/blasting and other introduced materials that data will have to be assessed for reliability every time. This could cause unnecessary and unexpected problems, delays or inconsistencies. Careful consideration is needed of what is practicable and meaningful for long-term safety. In parallel, it would be advisable to monitor for general environmental contaminants that might affect operational safety, e.g. fluoride, arsenic, radon. At a broader scale, Posiva will need to consider the potential hydrochemical impact of the extended open time (c.100 years) of the repository with respect to possible upward migration of more saline waters caused by continued pumping of the progressively extending volume of the openings.

Conclusion: Whilst we acknowledge that the RSC are a continuing project, Posiva needs to provide more information about measurement procedures and a logical plan for further testing and development during construction. This could be in either the RSC Working Manual (said to be available in early 2014) or in a 'Master Document', which was under consideration at the time of the December 2013 meeting. It should present a detailed programme of RSC methodology updating and deployment activities that covers the transition period from RSC research (i.e. up to and including the DT3 and DT4 work) to the measurements that will precede the initial construction of the first panel spine tunnel and the first deposition tunnels. STUK will need this to plan its inspection activities. STUK should also ask what plans Posiva has to ensure that a sufficient number of trained geoscientists and geotechnical staff will be available for deployment during construction, to manage the day-to-day requirements of RSC measurement and interpretation. At present, one team is available and Posiva is likely to require strength-in-depth once work begins.

(In August 2014, Posiva delivered an incomplete draft of the RSC Working Manual, which addresses some of the questions above, whilst leaving open questions such as the stages at which STUK would be involved, managing possible central and deposition tunnel realignments and the impact of extended open times. This draft Manual had not been fully reviewed when this CRR was finalised).

3.2.4 Using the RSC to accept/ reject disposal locations

There is little practical experience in this area. The utilisation ratio values that have been determined for Demonstration tunnels 1 and 2 using the RSC are remarkably low. Unexpected conditions have been encountered in at least one of these tunnels and those seem to account in part for the low utilisation. Two issues arise: (i) if these conditions were not predicted by the geological model, then it suggests that there will be more 'unexpected' conditions as construction proceeds; (ii) if the low utilisation ratio were to be typical of the repository volume, then utilisation would be surprisingly low.

The RSC report describes the situation, both for the first work on the access tunnel and for the final work on DH positions in DT1, where one hole (No.8) proved acceptable even though drilled in a 'non-acceptable' location. The main DT work produced different results in terms of %suitability for each tunnel. From suitability classification Tests 2 to 7, DT1 went down in suitability: 62%, 56% and 40%, while DT2 went up: 35%, 44%, 64% and 70%. It is difficult to see how this has come about, because the report does not present a summary of the changes and the reasons for them. Considering that different RSC were used as the project progresses and that the model length of both tunnels changed, interpretation is difficult. One problem is that the RSC testing has shown that the properties of large brittle fracture zones are quite variable along their length and on either side of their cores, with the extent of IZs, the nature of core minerals, the geometry etc., being hard to predict (especially from PHs). Consequently, the increasing detail that is gained as the sequence of tests proceeds gives different conclusions. In fact the DSMs that were developed are surprisingly consistent and give some confidence that the sequential approach works.

Posiva's joint project with SKB on large fractures found that deposition tunnel PHs are not much use for detecting and characterising TCFs (RSC, p.71) and concluded that they can be missed or, alternatively, given an over-pessimistic classification. On p.137 it says: 'It is therefore difficult to identify large fractures from a pilot hole drillcore; the uncertainties of the method used here to select the possibly large fractures from the pilot hole data still need to be quantified'. There is evidently a basic problem about the distinguishing information for fracture extent that can be inferred from PHs. Fracture extent is the most significant property with regard to DH location. Nevertheless, experience in ONKALO access tunnel suggests that PH observations of brittle fracture zones are 'quite reliable' for existence and location (p138). The uncertainties arise in orientation and influence zone width.

Robust conclusions about locating deposition holes and about likely utilisation ratio in a deposition tunnel will probably only be made after construction of the deposition tunnel or even at the time of drilling the deposition holes. That may lead to difficult decisions about locating deposition holes because money will have already been spent on the tunnel. That would be acceptable for long-term safety as long as a pessimistic/conservative interpretation of RSC is consistently used. The use of plugs inside the deposition tunnels to isolate possible sections containing LDFs or/and their respect volumes might need to be considered.

Conclusion: The final decisions on use of space are only made after the final excavation step in RSC application, when the most information is available, so the likelihood of using poor rock that was originally shown as acceptable is extremely low. Posiva faces the opposite problem – of possibly rejecting good rock (RSC, p.209, states that Posiva will need more work on how to deal with such conservatism). The main problem is that the PH data for both fracturing and flow seem to be generally misleading. For at least one DH-RSC (presence of grout), the criterion cannot, in any case, be tested until a DH has been constructed (a test only in PH for a DH would not be sufficient), so this is a 'last moment' decision factor.

3.3 Ground Types

The division of the rock mass into Ground Types (GTs) is required for rock support and grouting in the repository. The designs of tunnel geometry, span widths and orientation of the tunnels and underground chambers are dependent on the stress/rock strength ratio as well as the orientation of the stresses with respect to the magnitude and orientation of the virgin stress field. The RSC methodology and criteria are used to guide the design of the repository and its panels, tunnels and deposition holes. According to Posiva (SER, p.67), GTs should consider two topics of the RSC:

- performance targets, considering rock properties of relevance for long-term safety of the barriers and their respective safety functions;
- engineering targets, regarding constructability and operational safety.

Posiva defines the different GTs in SER, Chapter 4. The concept of GTs and their application to deep geological repositories was made first in the site engineering reports for Forsmark and Laxemar in 2009 (SKB R-08-83 and SKB R-08-88). In SKB's GT approach, the key parameters in the design work are specified, with ranges of values within acceptable limits, acknowledging that uncertainty and spatial variability also exist for these values, e.g., the stress data. This approach arose because SKB does not have equivalent access to the underground rock mass as ONKALO, where rock characterization underground has been in operation for a long time.

SER Section 4.1 mentions that the GTs should be developed in an iterative manner. This is the first time GTs have been presented by Posiva and it is somewhat late in the development of the design process for the repository. In addition, the different support system for the individual GTs has not been modelled and determined, despite the fact that

Posiva has known the parameters that are included in the GTs – namely the properties of intact rock, the fractures and the rock mass. For the present development of the GTs, the hydrological and hydrogeological conditions of the rock mass and the need for grouting are not included in the methodology.

Posiva admits that the stress field has a major influence on the rock mechanics and stability of the underground openings. At this stage of the development of the methodology and parameters to be included in the GTs, Posiva has omitted the stresses with the motivation that the stress field at the site is rather constant. In defining the stress field for the repository level, Posiva has estimated different stress domains above and below the major brittle deformation zone BFZ020. SER Section 4.2 claims that, in the further development of GTs and the design of support system, it is likely that a factor will be introduced to relate the tunnel orientation with respect to the orientation of the maximum principal stress. Before this can be done and included in the definition of different GTs, Posiva will need to have a better grip on the reorientation of the stress field adjacent to BFZs. The issue of the extent to which the stress field is reoriented and the stress magnitudes change in the vicinity of BFZs will appear already in the development of the first panel, close to the central area, where BFZ045b intersects the six deposition tunnels, as shown in SER Figure 8-3.

3.3.1 Ground type key parameters

The classification of the rock mass into different GTs starts with the description of the most significant geological characteristics and structures, followed by geotechnical parameters. The selected parameters and their values are extracted from Posiva reports on site geology, the OSD, rock mechanics modelling reports and the compilation of data in the SER; altogether more than 20 parameters are presented for the definition of the different GTs. However, it is not clear that the selected parameters are necessarily the most relevant to characterize the different GTs. This can only be known when Posiva identifies which analytical, mathematical and numerical methods will be used to design the rock support. Therefore, there is little value in commenting on the selection of individual parameters and their selected values at this stage, until Posiva provides more information.

SER Section 1.2.4 mentions the possibility that the calculated values of the parameters entering the rock mass properties using the Hoek and Brown failure criterion might be too high. Posiva should establish with Professor Evert Hoek whether he or his colleagues have experience or knowledge of applying the failure criterion to design work of tunnels and underground openings in migmatitic gneisses, such as found in Olkiluoto. For the moment there is a need to build confidence that the failure criterion for migmatitic rocks is conservative.

3.3.2 Ground type classes

At this stage, Posiva has suggested that the rock mass at Olkiluoto can be described by four different GTs (SER Tables 4-3 and 4-4). GT1 and GT2 are defined as massive or moderately fractured rock, respectively. GT3 characterises BFZs extending typically less then 3 km and GT4 characterises significant brittle deformation zones, which are determined as LDFs. The present number and type of GTs is very coarse and Posiva needs to develop several additional sub-sets of the four GTs to characterise better the intermediate rock masses between the existing fractures. Posiva needs to consider whether the different support systems related to the GTs should be included in the GT protocol or should be presented as a separate document. Also, the different characteristic features of the groundwater leakage can be incorporated into the existing and future GTs or be developed as a separate sub-set of hydrology ground types, HGTs.

The GT1 class (massive or sparsely fractured rock mass) has been given a GSI value higher than 71, based on experience from drilling and blasting in ONKALO. Posiva introduces an additional empirical factor to the existing empirical Q system, called Excavation Support Ratio, ESR. For underground nuclear constructions the ESR factor has been given the value 0.8. The final Q-value to be used for rock support is obtained by multiplying ERS by Q to express safety considerations. Assuming the stress term SFR=5 and the groundwater term J_w=1, the Q-diagram in Figure 4-1 indicates no need for shotcrete and a bolt spacing of about 2.5 m. There is a strong need for Posiva to develop and apply a new, physically-based modelling tool for the support system. Modern, distinct element methods are able to build synthetic rock masses where migmatite foliation and banding of neosomes and leucosomes can be simulated, and different reinforcements included. The reasoning regarding modelling the rock support is equally applied to the rock mass of GT3 and GT4 rock mass.

The GTs are based only on the strength and fracture characteristics of the rock and the classification is coarse. Almost all the disposal panel volume (apart from significant BFZs) is expected to lie in GT1 and GT2: mostly in GT1, which requires no support for 5 m tunnels. SER p.79 says that, in fact, the GSI definition of GT2 is difficult to justify, with GT2 and GT3 being artificially separated, and later that the boundary between GT3 and GT4 is "without solid justification". Nevertheless, it is proposed to use the GTs to make support decisions. There is no evidence that a back-fitting exercise has been carried out to assess how the many support decisions that have already been taken in ONKALO relate to fitting of the rock into GTs. A concern that emerges from the SER is that Posiva already has considerable knowledge on rock characteristics and their variability from ONKALO (and elsewhere) and it is hard to see them getting significantly more information that would enable them to refine the GTs much further.

Posiva needs to explain whether, in future, they will include thermal properties (conductivity, anisotropy) in the GT definitions as well, or whether these will go into the RSC, or be treated as a separate matter. This is an area where there is a clear distinction between rock types, when the current GTs simply lump the rock types together, because they have similar GSIs (E, UCS etc., although there are comparatively few data on the PGR, compared to the gneisses).

As noted above, the properties that define the GTs are not the same as those that define the RSC. Also, the GTs and RSC have different purposes – engineering design for GTs and safety for RSC. But both of them converge immediately onto the same point: making routine decisions on DT length/geometry and DH locations. It will be important for STUK to see how Posiva manages these two inputs to decisions and whether the same, or different, groups will be 'in charge' of developing and assigning the GTs and the RSC. The few words provided on SER p.67 about the interface between RSC and GTs are not informative about Posiva's plans.

This SER will be the first of a 'living series'. The next SER will focus on the first emplacement panel. It would be useful for STUK to know when this SER is planned to appear – presumably, well before any excavation work begins, if it is to be used for design. SER Section 8 would certainly need to be more detailed for panel design before excavation. At present, there is no indication of how much depth and detail the SER should present to the designers – surely more than is given in Section 8? This reinforces the need for Posiva to provide more information on its management decision procedures for construction.

Conclusion: Although Posiva intends to use GTs in future for making critical operational decisions, it is difficult to see how the current GTs will be of much practical use. STUK should establish if and how Posiva will develop the GTs into more sensitive sub-sets that can be used practically: Posiva expects that GTs could need revision between future versions of the SER. However, it is not clear that significantly more information would enable them to refine the GTs much further. At present, the issue of definition and use of GTs appears to be at an unsatisfactory level for moving to construction in the disposal rock volume.

4 Long-term effects of construction activities

4.1 Effects on long-term bedrock stability and groundwater flow

A requirement is set by YVL D.5, 508a: *"….rock construction methods shall be used that limit disturbances in the rock surrounding the emplacement rooms to a level as low as reasonably achievable"*. The DBR, Section 6.4.2, requires that construction should *"keep thermally and mechanically induced damage to the host rock sufficiently low"*. Damage would include fracturing (including reactivation), formation of an EDZ and spalling. These effects would potentially increase groundwater flow and reduce transport resistance. There is no explanation of what is meant by 'sufficiently low'. The PAR, Section 5.1, considers these issues briefly, but only in a short-term context, discussing effects on groundwater inflows and compositions, water evaporation due to ventilation and introduction of foreign materials. Effects of construction on long-term bedrock stability and groundwater flow are implied to be negligible in the PAR, and are treated as being significant only in the relatively shorter-term excavation and operational phase. Description of the Disposal System (Posiva 2012-05) provides a good description of all potential disturbances: construction and operation, tunnel backfill and plug, closure components, which are described in terms of 'initial state'. Disturbances due to construction are briefly covered in Section 4.3.2: hydraulic, hydrochemical, mechanical, thermal, rock damage and foreign materials.

4.1.1 Long-term mechanical and thermal loads

The most important long-term mechanical loads on the repository rock volume are caused by the future glaciation cycles. Posiva has studied the mechanical loading from an ice sheet corresponding to the Weichselian glaciation (WR 2011-13; WR 2012-08). These studies are the most advanced in modelling the field of rock stress generated by ice loading and melting of an ice sheet. The main uncertainties are related to the estimation of magnitude and orientation of the regional stress field in the upper crust of the Fennoscandian area and surroundings and the uncertainty in the pore pressure in the crust during the glaciation cycle. The ice load suppresses tectonic seismicity whilst it is present and, combined with removal of overburden stresses at the end of a glaciation, the resultant stress release has produced large magnitude earthquakes. This issue is discussed in detail in Part 1, Section 2.3.3 of this review.

The heat generated by the spent fuel causes long-term thermal loading of the repository rock volume. Thermal expansion of the rock mass around the repository will generate a compressive thermal stress field at repository level and a tensile stress at the ground surface. The thermal stresses will be superimposed on the virgin stress field in the crust. This new stress field could exceed the strength of some existing faults and fractures and generate slip which can cause enhanced and new paths for the groundwater flow around the repository. Posiva has not considered and modelled these thermally induced fault/fracture slip. Of particular importance for the long-term safety is potential slip on layout determining features (LDF) with a trace length > 3 km, as discussed in Posiva 2012-21(p. 41) in terms of average fault core thickness and the surface area of the deformation zones. Posiva shows that the damage zone width and fault length are correlated with fault surface area, which suggests that Posiva will need to apply different thermal conductivity to the core and damage zones in future thermal calculations of far-field host rock response.

Conclusion: These impacts are discussed elsewhere in this report: Sections 1.6.2, 1.7.3 and 2.3.3.

4.1.2 Formation and impact of an EDZ

Posiva has performed a series of investigations on the formation of an excavation-disturbed zone (EDZ) and published a series of technical reports (WR 2008-66 and WR 2010-27). The critical issue from the perspective of performance assessment is whether the EDZ is continuous along disposal tunnels, thus providing a higher transmissivity pathway for groundwater flow and radionuclide transport.

Posiva accepts that blasting will always produce an EDZ with some transmissive fracturing, and looked closely at whether this is continuous. Posiva is less assertive about the possibility of EDZ continuity than is SKB, saying only that "damage is probably not continuous". The conclusion used in the safety case, before the results of the latest experiments were available, is that this is not continuous, even in the tunnel floor, where the EDZ is most strongly developed. OSD Section 9.4.2 concludes that the EDZ does not exist as a continuous layer, but instead consists of patches of reduced rock quality and increased fracturing and porosity. The thickness and extent of the EDZ are greater beneath the floor than behind the walls of the tunnel. In the tunnel wall there are only a few locations where the estimated EDZ has a thickness greater than 24 cm and the EDZ itself is only locally developed. It is suggested that the data indicate the presence of fractures with enhanced transmissivities (10^{-12} to 10^{-8} m^2/sec) within perhaps 20–30 cm of the tunnel floor. The expectation that EDZ hydraulic conductivity can be kept below 10^{-8} m/s is mentioned in connection with the performance target for hydraulic conductivity of the backfill (DBR, p.120). The hydrogeological calculations presented in WR 2012-32 and 42 consider an adequate range of EDZ-related hydraulic effects on the repository near-field rock. The results of a sensitivity case presented as Appendix H, WR 2012-42, show a significant sensitivity to the calculation grid, which, while a matter of concern in terms of quantitative accuracy, is unlikely to affect the main results.

Drill and blast breaks the rock in the vicinity of the shot holes by compression and shear (2 to 3 radii) and by tension (tens to hundreds of cm). The cracks caused by compression and shear can be indicated by GPR, but it is not possible to identify cracks perpendicular to the measuring surface with GPR, especially as they are masked by the parallel near-surface cracks. Since the Safety Case documentation was issued, GPR and other data have been produced from ONKALO that suggest that a continuous EDZ could exist. During 2012 and 2013 Posiva performed a geo-electric investigation in the floor of the rock mechanics niche of ONKALO. Electrical measurements were conducted between a large numbers of electrodes drilled into the floor. Tomographic analysis of the large number of measurements has clearly demonstrated that the EDZ is continuous in the floor of a drill and blast tunnel. Results of the geo-electric investigation and the positive outcome of using the road-header equipment for reducing the EDZ and evening the floor are not mentioned in the SER. The positive outcome of the test might provide an independent test method by which GPR measurements can be calibrated as a tool for use in all deposition tunnels.

As noted above, the PAR uses the original interpretation of a discontinuous EDZ in the disposal tunnel floors as a basic understanding (p.140), but uses three alternative models in the groundwater flow modelling (discontinuous, as in Posiva's basic understanding; continuous 0.4 m thick; no EDZ). Posiva regards the last two cases to be non-physical bounding cases, because the continuity of the EDZ with respect to hydraulic properties has not been observed. Posiva has carried out a comprehensive analysis of the potential impacts on flow under various variant conditions, indicating little significant impact on number of suitable deposition holes. However, the PAR describes the impact of the EDZ on inflows to the deposition only in qualitative terms (e.g. *"The increased connectivity provided by the EDZ has the effect that there would be some, although very limited, inflow in nearly all the deposition holes"*; and *"In general, the different assumptions on the continuity and hydraulic properties of the EDZ affect inflows only in the potential deposition holes that would in the case of no EDZ have an inflow less than approximately 1 mL/min"*). Neither statement gives confidence that the design requirement inflow could not be exceeded in many holes and the numbers are hard to interpret from PAR, Fig 5-4 (where all realisations appear the same, at higher flows), especially for the last statement. Section 1.3.4 of this review considered Posiva's evaluation of the equivalence of impacts of spalling (and an EDZ) on hydraulic behaviour. As a potentially positive aspect of the EDZ, Posiva claims that the increase of specific surface might give better sorption than intact rock, but this would have to be proved to be of value in a safety case.

An issue not assessed is the possibility that a continuous EDZ could progressively transport eroded tunnel backfill material away, over a long period causing subsidence of backfill, the opening of a crown-space void and possible roof block fall and ravelling of the rock.

A coarse estimate of the extent of the EDZ can be made when the completed drilling and blasting plan is known. There is a theoretical possibility to adjust the drill and blast plan in a way that creates breaks in the EDZ at the walls and roof. In the floor, this is probably not possible for drill and blast.

Conclusion: The issue of EDZ continuity seems unresolved at present. Posiva intends to continue work on hydraulic evaluation and it is likely that more data will come from the Demo area work. The cautious approach is to assume that a continuous tunnel-floor EDZ exists and factor this into safety-related calculation cases (as is done by Posiva). For the RSC and tunnel characterisation schedules that Posiva will be developing, it would seem appropriate for STUK to have a license requirement that calibrated GPR testing for EDZ is carried out in all tunnels, at least for the initial work in the first panel, until the issue is better understood. Given the caveat from this review on the validity of the Hydro-DFN representation of connectivity, the hydraulic impacts of both EDZ and spalling damage in the DH volume seem to have been incorporated adequately into the Performance Assessment, but this is an area of ongoing study and new data will arise even over the next 12 months. The incorporation of the impacts has been done in a conservative fashion, which can be considered appropriate for the CLA.

4.2 Effects on hydrogeochemical properties, processes and stability

The main issues of concern with respect to hydrochemistry are the disturbance of the groundwater flow field by pumping (leading to redistribution of waters of different composition), the disturbance of redox conditions and reactions (especially by biogeochemical processes) and the introduction of foreign materials such as grouts, nitrates from blasting and organic matter. DBR, Section 6.4.2.4, requires that the use of foreign materials in underground openings shall be controlled and regulated. The effects on hydrogeochemistry are covered in Description of the Disposal System (Posiva 2012-05; Section 8.4.3), in which the potential short-term disturbances are well summarised and an inventory of chemical components that would be introduced in foreign materials is provided.

4.2.1 Redistribution of waters of different composition

There has been much discussion about whether ONKALO or repository construction and operation would lead to upconing of saline waters into the disposal zone. The main PA concern is with the impact on the swelling of the tunnel backfill.

Salinity contours at disposal depth shown in OSD Figs 7-27 and 28 are based on baseline data and thus are not affected by ONKALO, assuming that Posiva has not added any post-ONKALO measurements to the baseline data set. The highest values at 420 m depth are to the north of and directly below where ONKALO is now located, with a pronounced dome in the 35 g/litre contour below the ONKALO location. For comparison, the palaeohydrogeological modelling of the brine interface under natural evolution conditions does not produce ‘natural’ doming over the 8000 years modelled (OSD, p.577 and Fig. 6-76). OSD speculates (p.644) that increased salinities monitored in OL-KR9 since 2009 may be due to saline water upwelling (upconing) after HZ20B was intersected by ONKALO. Upconing has certainly occurred as a result of pumping in the Infiltration Experiment (Section 7.6). This issue is covered in more detail in Sections 1.4.4 and 1.7.2 of this review, where it is noted that the detailed modelling shows the implications for critical parameters to be minor. However, STUK should consider that all of the THC impacts get progressively worse the more excavation is carried out and the longer the repository is kept open. Each successive disposal panel is exposed to slightly worse conditions that the previous panels.

Conclusion: The OSD makes the case, largely via modelling, but also based on limited monitoring since ONKALO began, that saline upconing caused by the repository is both understood and of little significance. First, the natural distribution of salinity appears to be non-dynamic, even with respect to major climate-driven perturbations. There is a broad mixing zone between deeper saline waters and shallower meteoric waters that spans the disposal depth. Second, it is acknowledged by Posiva that upconing will be patchy and controlled by transmissive features and that, if the repository remains open long enough, salinities will increase. Posiva asserts that this can be mitigated by operational procedures, including grouting transmissive zones. This is acceptable provided Posiva can continue to show that salinity will remain below design limits and the effect will diminish or reverse once natural hydraulic gradients are re-established. Posiva has made an adequate analysis of the long-term hydrogeochemical disturbances to the groundwater system caused by ONKALO and repository construction.

4.2.2 Foreign materials introduced into the repository

Hydrochemical data in the annual monitoring reports contain the evidence to analyse and assess the disturbances due to ONKALO at least over the short timescale for which it has existed. The latest hydrogeochemical monitoring report is for 2010 (WR 2011-44). These annual reports on monitoring are of a high standard and analyse the data adequately. However data for the last 3 years is likely to be important for understanding whether disturbances due to ONKALO are becoming evident.

Posiva's plans for selecting, monitoring, controlling and removing foreign materials are discussed in Part 2, Section 4.6.4 of this review. Foreign materials are estimated in WR 2011-32 and have been updated from previous estimates, using data from the practical experience of ONKALO. Results are dependent on the removal efficiencies assumed. The mineral materials introduced as impurities in the backfill clay (e.g. pyrite, carbonates, titanium oxide etc) constitute by far the largest amount (totalling over 100,000 tonnes) of foreign material. Foreign materials are discussed mainly in terms of impacts on redox and pH and in terms of EBS performance. Although their potential impact on radionuclide solubility and sorption is acknowledged in the PAR, e.g., p.107, where iron, sulphate, ammonium, nitrites, nitrates and organics are highlighted, no analysis of these impacts is reported.

Conclusion: The latest 2011 monitoring analysis represents a credible evaluation of foreign materials, a topic that Posiva seems to be keeping under proper observation. The PAR does not evaluate the specific impacts on radionuclide behaviour.

4.2.3 Impact of gases produced by repository materials

The PAR shows that the highest calculated releases of C-14 from the repository to the environment occur when considering the possibility of gas-mediated release. Radionuclide-bearing gas releases are averaged over 1000 years, although gas generation and pathway opening and closing (breakthrough pressure) are clearly shorter-term effects that would presumably lead to short pulse releases. Posiva presents pulse release data that indicate that exposures are not significantly higher. The peak annual release rate, averaged over 1000 years, is only around a factor of four below the regulatory geo-bio flux constraint. If the C-14 dose via gas is the main early risk, then the groundwater pathway is secondary.

Conclusion: The gas pathway through the geosphere is not well presented. Hydrogen movement and modelling (as a transporter of methane) in the fracture network is not described, nor is it discussed whether the gas pathway through the EBS and the rock is the same as the water pathway.

4.3 Preserving critical rock characteristics during construction

Mitigation of construction impacts principally concerns ensuring that excavation techniques are deployed that are of sufficiently low-impact that the rock mass adjacent to tunnel and deposition hole walls and floors retains its required target properties. This principally concerns mitigation of the negative impacts of and EDZ. The KBS-3V concept was developed to place the canister well below the tunnel EDZ.

4.3.1 EDZ mitigation

DBR, Section 6.4, states that Posiva will use smooth and careful blasting of the underground tunnels and chambers to reduce rock damage and minimize the dimension of EDZ. In the UOPL (p.70), Posiva describes how the thickness of the EDZ can be controlled to some extent by the design of the blasting technique, separation and placement of blasting holes and the amount of explosives used for each run. The standards applied to blasting for tunnel floor excavation are increased by one level from Class 3 to 2 in the InfraRYL 2010 standard between access and deposition tunnels, for example. To be in accordance with YVL D.5, 508a: *"such rock construc-*

tion methods shall be used that limit disturbances in the rock surrounding the emplacement rooms to a level as low as reasonably achievable", they should, arguably, have been increased to Class 1. The same applies to the VAHA Specifications below. They also note that the use of reaming in shafts and DHs is intended to reduce the EDZ in the walls. The L5 Design Specification in VAHA includes blasting and reaming methods selected to meet specified targets and standards. The approach taken by Posiva appears to be advanced, in terms of controlled excavation methodologies in hard rock environments.

It is possible that the techniques being evaluated by Posiva (and SKB) to produce a deposition tunnel floor that is smooth and level enough for DH operations would to some extent mitigate the possibility of the continuous EDZ in this region. Posiva has evaluated the use of a road header to smooth the tunnel floor after blasting as part of a normal tunnel excavation process and, in the DTs, this seems to have been successful and the results are impressive. SKB is studying rock sawing where, in advance of blasting, a horizontal fracture is wire sawed in the face of the tunnel where the tunnel floor is to be located. The UOPL says that this is expected to result in a more even floor and *"could be the method eventually employed by Posiva"*. This situation will evolve as Posiva gets more experience with the simple technique of using the road header, although the results are likely to be rock-type and fracture density specific. The different EDZ studies performed by Posiva are described in Section 5.2.3 of the SER, but none of the geo-electric investigations in the rock mechanics niche, or the successful excavation of the tunnel floor with a road-header in one of the demonstration tunnels, is mentioned in the report.

The EDZ appears to be up to 30 cm thick on GPR profiles in the ONKALO rock mechanics niche, so levelling the floor will not entirely remove it and the road header may induce some damage of its own. The GPR data that are presented in the UOPL (Figure 5-9) are difficult to interpret and not well explained. Posiva notes that, in 'reality', and in particular during the excavation process, EDZ conductivity is hard to measure, so they propose that its depth is used as a representative feature. Here, it would be valuable if Posiva can use its geoelectrical testing method to calibrate the GPR approach to depth measurement. A problem is that Posiva is confirming one geophysical method with another geophysical method, when the need is to relate the outputs to water flow in the rock. The testing needs to be related to the construction method and performed for each of the drilling and blasting operations to be applied in the repository. However, if depth is not representative of continuity, then this could be a problem for controlling EDZ as excavation proceeds. This really needs more practical experience to test the approach and Posiva should commit to carrying out more work in this area as construction proceeds.

Neither Posiva nor SKB has followed the technical development or reported on the possibilities of using a tunnel boring machine (TBM) to construct the deposition tunnels for the KBS-3V concept. TBM methods result in less rock damage and a smaller EDZ (e.g., as tested many years ago at Äspö HRL, by SKB, and at Grimsel, by Nagra). Over recent years there has been major technical improvements of TBM technology, including developments where the machines can turn in a much smaller radius and are thus more flexible. There are also new developments of rock reinforcement and grouting while drilling, new tool developments with longer lifetimes of individual cutters, stronger driving machines with larger capacity etc. Today, TBM is a realistic alternative to drill and blast for both the main and the deposition tunnels and Posiva should undertake feasibility studies on the introduction of TBM technology. The lower compressive and tensile strength of the inhomogeneous gneisses might be more favourable for TBM than the strong and hard and brittle meta-granite at Forsmark. In practice, the strongest components of an inhomogeneous rock define the degree of success to be achieved with a TBM.

An EDZ could also be an issue in the DHs. Based on using reaming for DH construction, Posiva assumes (UOPL, p.75) that the EDZ is not a critical issue in the production of deposition holes, from the long-term safety point of view. Posiva notes that it intends to study the EDZs of the test deposition holes to confirm the matter.

EDZ is also an issue with respect to plugs. The Closure Production Line report (Posiva 2012-19) makes no mention of how plug notch designs and construction techniques, or the choice of seal locations, will address the issue of an EDZ. For the plugs emplaced at the end of disposal tunnels, which only have a design life of about 100 years, this seems less relevant. The Mechanical Plugs that are emplaced largely for closure operational purposes have a design life of only 50 to 100 years (p.34), but the Hydraulic Plugs to isolate major conductive faults and isolate spaces backfilled with different materials, are expected to provide *"service over long times"*… which are not specified. The UOPL (Section 5.4.4) says that the openings for Deposition Tunnel plugs will be constructed by a combination of wire sawing and blasting, which will help to reduce the EDZ. The depth of the EDZ caused by diamond sawing is only a few millimetres.

Conclusion: It is not clear that the techniques being tested would mitigate the EDZ and further testing will be required as construction proceeds. It should be noted that the safety assessment calculations for the CLA present conclusions regarding the EDZ that can generally be accepted as credible, based on its stylized treatment in hydrogeological models and consideration of a range of EDZ properties that encompasses the reasonable range of possibilities (fully connected, intermittently connected, and poorly connected). Testing both for EDZ evaluation and optimisation of operational construction procedures should run in parallel and STUK should ensure that Posiva continues its EDZ studies in parallel with excavation technique development work. Posiva should carry out a TBM feasibility study, as this is a means of ensuring the highest quality excavations and minimising the scale of the EDZ. Notches are part of the plug design concept and could be constructed to minimise EDZ and flow around plugs in the rock. For deposition tunnels, Posiva has a plan for recess construction that should assist with EDZ mitigation. The EDZ seems to be of little importance here, given the limited design life of the plugs and the fact that at least those in the deeper parts of the repository are not central to containment and the safety case.

4.4 Long-term safety impacts of layout decisions and construction planning

The CLA documentation contains little information on repository layout aspects. The current layout is defined in several reports, with the key references being Posiva 2012-69 and WR 2012-50, both in Finnish only, combined with the thermal dimensioning report (Posiva 2012-56). The outcome is outlined in the Disposal System report (Posiva 2012-05), but there is no explanation of how adaptation will be undertaken as the project proceeds. Layout is only based on one model of LDFs and their IZs. The impacts of uncertainties on LDF geometry and IZ width have not so far been taken into account in estimating useable volume.

4.4.1 Using future characterisation data

The UOPL report (Section 3) briefly discusses how the progressive design work of the disposal facility during operations will utilise the results of characterisation work. The approach to general layout planning will be described in more detail in the Design of the Disposal Facility 2012 report (Saanio et al., 2013), which was not available at the time of this review. Similarly, Underground Openings Line Demonstrations Stage 1, 2012 (Posiva Report 2012-33) was also not available. The UOPL say that the design process includes quality actions - requirements that the design has to fulfil in order to be classified as a qualified design, which are derived mainly from legislation. STUK inspection personnel will need to be familiar with the legislation and the concept of qualified design and track this as it relates to Posiva's QA system. Section 3.1 introduces undefined activities/terms that are closely related to this: quality actions, method statement, quality notes etc. Section 3.2.3 introduces a quality 'control programme' and how it is recorded, which will need inspecting by STUK, but the description is insufficient to form the basis of a plan.

Conclusion: The UOPL provides confidence that Posiva does have procedures in place to incorporate site data into the progressive design and that these are part of its quality system. The information is sparse, however, and this is an area that STUK will need to focus on soon after licensing, as it will be a major topic for inspection.

4.4.2 Adapting design to evolving TCHM impacts of an expanding repository

Posiva sets a design life for the tunnels of 100 years (UOPL, p.31), which is shorter than the potential operational life, which could extend to 120 years. Presumably, Posiva countenances some refurbishment of operational area tunnels during the life of the repository. It is also noted (p.50) that optimisation of the use of excavated space will be one of the methods used (along with tunnel design and grouting procedures) to control the inflow of water into the repository during operations. This suggests that openings will not be excavated until needed and that the hydraulic interactions between planned openings will be taken into account in the design work. It is not explained how this will be done, but it will be a factor for STUK inspection during construction work.

Conclusion: Whilst Posiva has a VAHA requirement (LI-STH-48) to prevent problems by careful excavation and support, it is not possible to determine how the evolving TCHM impacts of the gradually expanding disposal facility will be taken into account in the system engineering and layout planning. There is no specific information about how Posiva would adjust the geometry of the underground openings if the anticipated stresses or measured in-situ stresses threaten to compromise the bedrock stability.

4.4.3 Grouting methodology

Grouting design has evolved as ONKALO has been developed (UOPL, Figure 5-2). Section 5.2.2 explains the techniques and the equipment used for grouting. In the deeper parts of ONKALO (below 300 m) the use of normal cement is not allowed for grouting, due to its potential impact on bentonite (note: the UOPL sometimes says 300 m and sometimes 290 m: e.g., p.67). Low-pH cements are being developed for grouting inflows to tunnels. Colloidal silica grouting development work is also underway. It had been thought that only colloidal silica would be used at disposal depths, but low-pH cements are necessary for wider, water-conductive fracture zones because colloidal silica has too small a small particle size and too low strength. These requirements on control of where and when grouting can be used are included in the L5 Design Specifications (e.g., L5-ROC-15 to 17 and L5-ROC-46 to 49 and several others). WR 2012-84 describes the testing of the colloidal silica grout in relatively tight rock and a conductive feature. The results were inconclusive, the equipment requires further testing and the drilling of grout holes caused some difficulties. This cannot yet be regarded as a mature technology.

In general, grouting methodology for ‘novel’ materials appears not to be uniformly tested and mature, although testing is still in hand and it is acknowledged (UOPL, p.67) that choice of grouting machinery has not yet been made. The UOPL cites experience of using low-pH and colloidal silica grouts that indicate how and when they can be used and the performance that might be expected. For example, mainly low-pH cementitious grouts were used during the penetration of the major conductive feature HZ20 and gave *“at least as good a performance as so-called standard cementitious grouts”* (p.64). The importance of grouting to the overall chemical characteristics of the rock mass is indicated by Figure 5-6, from which it can be inferred that hundreds of cubic metres of grout have already been injected into the upper parts of the access tunnels of the repository.

Conclusion: This is an important topic and Posiva understands well its relevance to overall repository performance. The balance between achieving good hydraulic conditions to enable operations and high quality EBS emplacement and the need to minimize cementitious grout use is being addressed through the use of materials that are currently still under test. Results for both low-pH grouts so far appear good; those for colloidal silica are not so good, so the methodology will need further work before it can meet design requirements and VAHA specifications. STUK should expect to see more demonstration and testing as work progresses and expect to see further development of grouting machinery. The methodology is thus not fully mature, but is at an appropriate level for the CLA.