Repository Layout, Adaption to the Characteristics of Crystalline Site and Input to the Safety Case, the Finnish Example – 14545

Heini Laine*, Ismo Aaltonen**, Nuria Marcos*, Timo Saanio*, Pirjo Hellä*, and Annika Hagros*
* Saanio & Riekkola Oy, Finland
** Posiva Oy, Finland

ABSTRACT

Posiva Oy is responsible for the disposal of spent nuclear fuel produced by its owners, the nuclear power companies Teollisuuden Voima Oyj (TVO) and Fortum Power and Heat, in Finland and has recently submitted a construction licence application (CLA) to the Finnish government for a geological disposal facility for spent nuclear fuel (repository) at the Olkiluoto site. The CLA is supported by a safety case, TURVA-2012, which is based on site investigations on a very detailed level as well as on the repository design (KBS-3V) developed to a mature level, reflecting the stage of the programme developing from the R&D stage towards the operational phase. In the TURVA-2012 safety case, the repository layout is used for many purposes and it has been developed taking into account the site properties in addition to other constraints. The repository system is developed based on a set of requirements and their systematic application in the safety case and design. These requirements also guide the actual operation. Regarding the host rock, rock suitability classification (RSC) is used to guide the layout adaptation and the positioning of the deposition tunnels and holes. The repository layout has now been adapted for the Olkiluoto site. It is concluded that as long as the layout is adapted to site-specific layout determining features, defined by RSC, the needed flexibility for further layout optimisation can be allowed while keeping the long-term safety impacts low.

INTRODUCTION

Posiva Oy submitted a construction licence application (CLA) for a geological disposal facility for spent nuclear fuel to the Finnish government at the end of 2012. The repository site, Olkiluoto Island, is located in southwestern Finland at the coast of Baltic Sea (Fig. 1) and it has been extensively studied since the early 1980s. The construction of the underground research facility ONKALO started in 2004 at the site. The CLA is supported by a post-closure safety case (TURVA-2012) assessing the long-term safety of the facility. The report portfolio for the TURVA-2012 safety case is presented in Fig. 2. This paper focusses on showing how the extensive site knowledge has been used in the layout adaptation at the Olkiluoto site and how the layout is then used in the safety case.

Fig. 1. Location of Olkiluoto Island (Figure: Posiva Oy).

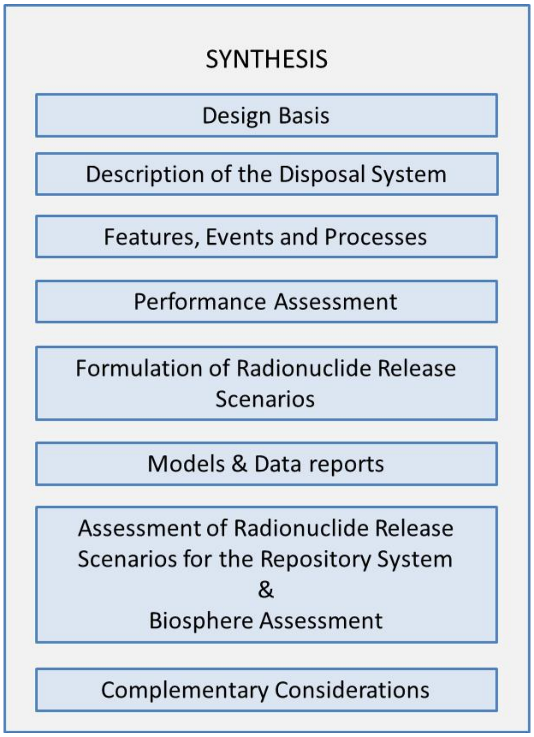

Fig. 2. Simplified illustration of the main reports of the TURVA-2012 safety case portfolio; modified from Posiva [1]. The safety case process and results are collectively presented in the Synthesis report.

DESIGN MATURITY

Posiva’s repository is based on the KBS-3 method [2]. The current reference design, KBS-3V, is based on a multi-barrier principle where copper-iron canisters containing spent nuclear fuel are emplaced individually in vertical deposition holes, surrounded by a bentonite buffer (Fig. 3) [see e.g. 1]. Deposition holes are located in deposition tunnels which are to be backfilled and plugged. The repository is planned to be constructed at the depth of 400 to 450 m in crystalline bedrock at Olkiluoto [1]. The design of the repository system (along with the layout) is at the mature level required for the CLA and has evolved in a step-wise fashion incorporating new knowledge of the Olkiluoto site [3], improved understanding of the interactions between the engineered barrier system (EBS) and the geosphere during evolution and updates in the spent nuclear fuel inventory. The current inventory of spent nuclear fuel accounted for in the safety case is 9000 tU [1].

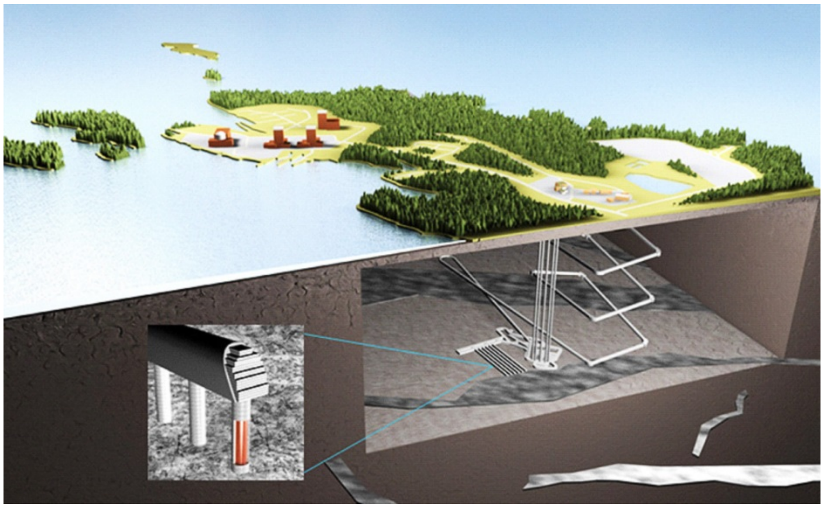

Fig. 3. Schematic presentation of the KBS-3V design at Olkiluoto. Index figure shows close up of backfilled deposition tunnel and deposition holes with copper canisters. Connections to the surface are via access tunnel (ramp) and shafts. (Figure: Posiva Oy)

OLKILUOTO SITE

The main rock types at the Olkiluoto site are high-grade gneisses that vary in texture (migmatitic gneisses, tonalitic-granodioritic-granitic gneisses, mica gneisses, quartz gneisses, and mafic gneisses) [4]. In addition, igneous rocks are found that include pegmatite granite and some occasional mafic dykes [4]. As described e.g. in [3], the metamorphic supracrustal rocks have been subjected to a polyphase ductile deformation producing thrust-related folding, shearing, strong migmatisation and pervasive foliation. Brittle deformation has then produced distinctive zones, mainly SE dipping thrust-faults. In addition, NE-SW striking strike-slip faults are also common. Imprints of multiple stages of hydrothermal alteration are seen in the Olkiluoto bedrock, which are estimated to have taken place at temperatures from slightly over 300 °C down to 50 °C [5]. During site investigations, extensive effort has been placed upon determining the fault zones and hydrogeological structures and their spatial connections as on how these will constrain the rock volumes to be used for disposal. According to site investigations [3], groundwater flow is concentrated within hydrogeological zones (HZ) that generally follow the geological structural orientation, but do not fully coincide with the geological brittle fault zones (BFZs) of the geological model (Fig. 4).

Groundwater flow, although to lesser extent, takes also place along a network of sparsely connected fractures between the hydraulically active deformation zones. These fractures have lower transmissivities than the hydrogeological zones. These fractures outside the deformation zones are modelled using a discrete fracture network (DFN) model, which currently defines four hydraulic domains in the Olkiluoto bedrock. The definition of the domains is based on similarities in their fracture orientations and intensities [3]. The knowledge on well conductive fractures and on fractures with large extent is important due to their effect on the potential locations of the deposition holes.

Other relevant site properties include the salinity of the groundwater and the in situ stresses, which both increase with depth and thereby affect the depth levels suitable for disposal. At the depth of 400 m, the salinity of the groundwater, in terms of TDS (total dissolved solids), is approximately 10−20 g/L, whereas at the depth of 600 m it is about 30 g/L, on average [3].

In the Olkiluoto region, the major principal stress is the maximum horizontal stress. The magnitudes of the horizontal stress components (σ_h and σ_H) demonstrate high variation but relatively well-defined trends, the maximum horizontal stress being some 25 MPa at the depth of 400 m, on average. The strength properties of the Olkiluoto rocks do not, however, show any large-scale spatial variation [3]. Due to a relatively low strength/stress ratio, the suitability of the depths below 500 m for disposal is questionable [6].

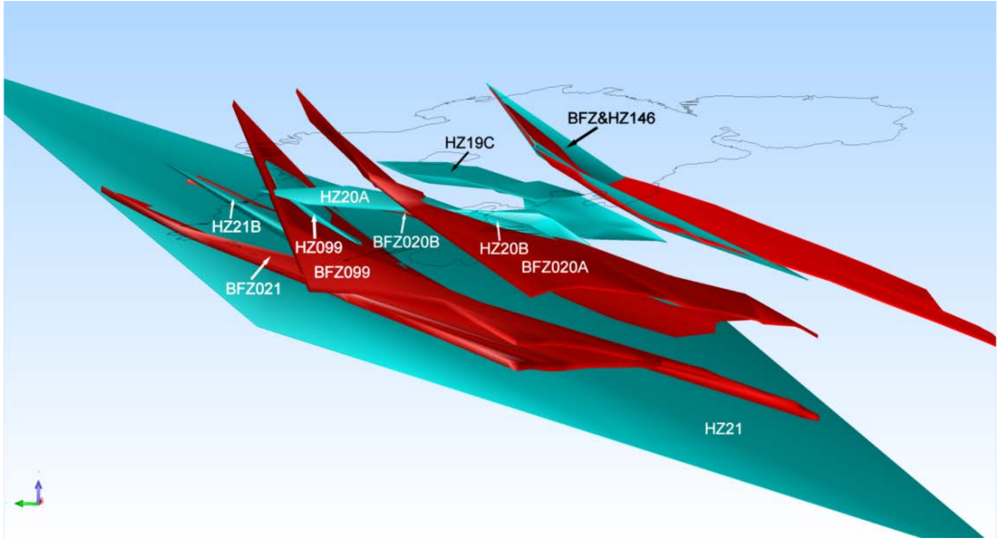

Fig. 4. Main Brittle Fault Zones (BFZ) in red and Hydrogeological Zones (HZ) in blue (outline of the Olkiluoto Island is shown in the figure, oblique view towards northeast) [7].

SAFETY FUNCTIONS, REQUIREMENTS AND ROCK SUITABILITY CLASSIFICATION

Rock Suitability Classification (RSC) is part of the requirement system developed for the geosphere. Certain safety functions, which define the roles of each barrier, establish the long-term safety of the repository system. The safety functions of the host rock are [1]:

- to isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface;

- to provide favourable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers; and
- to limit the transport and retard the migration of harmful substances that could be released from the repository.

Performance requirements consist of performance targets for EBS components and target properties for the host rock that are formulated such a way that the safety functions are fulfilled. For the host rock, target properties are set up in the requirement system, and based on these, more detailed design requirements and design specifications are derived including the actual RSC criteria. These performance requirements are defined based on the existing knowledge of the expected conditions in the repository host rock, EBS and its performance and experience from the earlier assessments.

SITE INFORMATION IN LAYOUT ADAPTATION

The layout for the repository is adapted to the site based on classification criteria related to the geological, hydrogeological, hydrogeochemical and rock mechanical properties of the site, engineering constraints [18] and the requirements set by the safety functions of the EBS [1,7] and host rock [8]. The layout adaptation also aims at limiting the disturbances to the host rock surrounding the repository. In practice this means accounting for, e.g., geological features, such as fault zones, and the heat output from the spent fuel canisters. The latter is accounted for in tunnel and canister spacing in order to ensure low enough buffer temperature (below 100°C) and thereby to avoid thermal alteration of smectite [1]. Demonstrating the suitability of the site to host a geologic repository in support for the CLA has been one of Posiva's key tasks during the past few years [3]. The first RSC criteria were developed during the Host Rock Classification project [9,6]. The work was then continued within the RSC Criteria programme, and interim results were published in 2009 [10] and further as a RSC system and the RSC criteria were reported for the CLA in 2012 [8].

The RSC system is applied at several scales [8]: repository scale, panel scale, deposition tunnel scale and deposition hole scale (cf. Figs. 3 and 6 for components discussed). The criteria for the repository scale, which considers large-scale characteristics of the rock mass, are intended to guide the selection of suitable rock volumes for the repository panels. Major deformation zones, classified as Layout Determining Features (LDFs), are identified based on site investigations and geological and hydrogeological modelling (Fig. 5) [11]. LDFs are fault zones which are potentially mechanically unstable in the current stress field or in anticipated future stress fields or hydrogeological zones that act as potential main groundwater flow paths and are thus important for the transport of radionuclides and the chemical stability of the repository. Around the LDFs, influence zones have been defined and these are to be avoided when locating the panels. An influence zone is *"a volume of rock around a deformation zone (fault) that has a higher fracture density than the rock mass outside the influence zone and also has a higher hydraulic conductivity and is more likely to exhibit alteration. This term is used, as it includes additional features to what is commonly termed a damage zone or perhaps a transition zone in structural geology"* [8]. On the basis of the repository-scale criteria [8], several options for adapting the layout have been proposed [3]. In Fig. 6, the selected layout for the latest safety analyses [7] is presented, showing also the LDFs. In addition to the LDFs, the local stress field and the orientation of the main fracture sets are accounted for when determining the tunnel orientation [3,12].

In addition to the repository-scale criteria, Posiva has developed more detailed criteria at the scale of the panel, deposition tunnel and deposition hole [8]. These include more detailed criteria needed to assure favourable properties in the near field.

The layout has evolved iteratively, starting from the first generic layouts [13], during the site investigations and RSC programme in order to allow increasingly better adaptation to the Olkiluoto site [14].

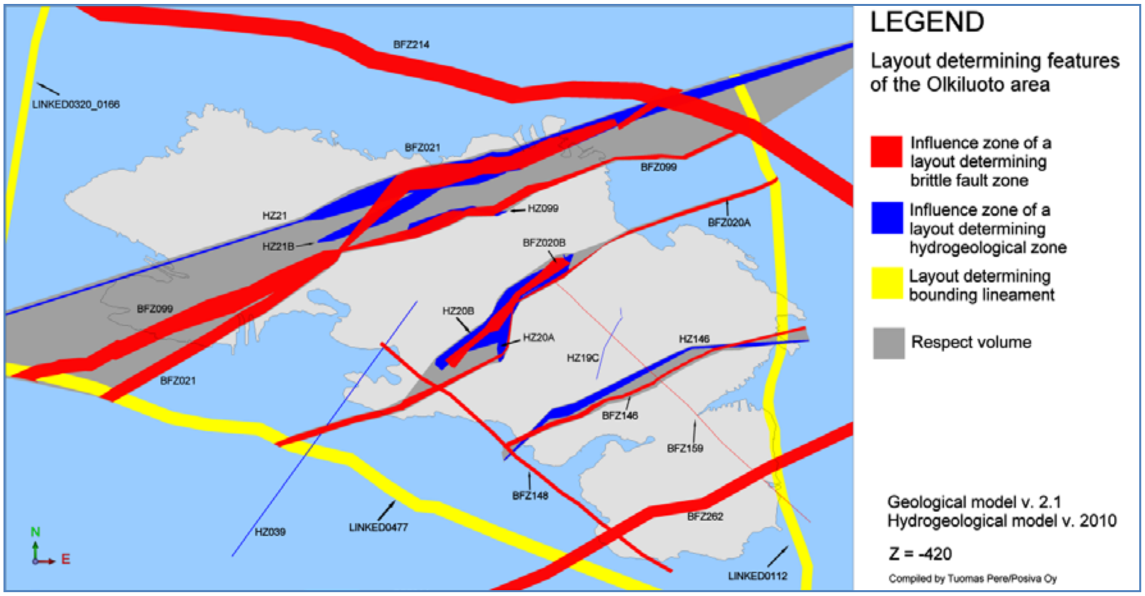

Fig. 5. The layout determining features for the Olkiluoto area at a depth of -420 m [8].

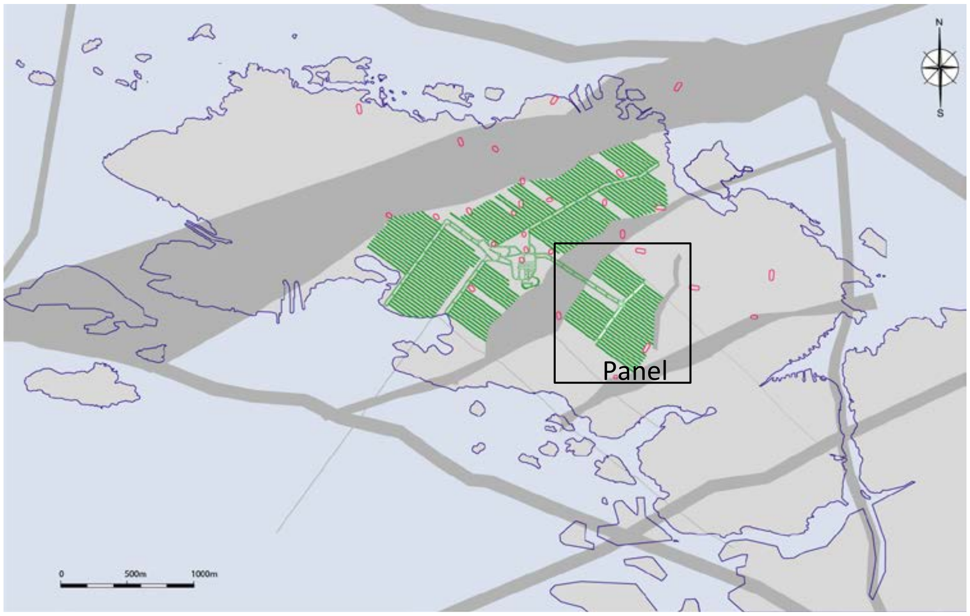

Fig. 6. Layout adaption for a repository hosting 9000 tU of spent nuclear fuel used in Posiva's safety case TURVA-2012, dark grey areas are not suitable for deposition tunnels according to the RSC criteria, as they are intersected by LDFs and their respect volumes, i.e. the volumes surrounding LDFs not allowed for deposition tunnels. Red ovals denote respect distances to drillholes [14].

USING LAYOUT IN THE SAFETY CASE

The repository layout is essential initial information needed for the safety case at the current maturity of Posiva's project. The layout is used as input data in e.g. [15]:

- modelling the thermal evolution of the repository system;
- modelling the mechanical stability of the repository system (estimation of the number of deposition holes with potential for canister failure by shear load [16]);
- groundwater flow modelling;
- geochemical modelling; and
- estimating the material amounts to be emplaced in the disposal facility (cf. cement-clay interaction).

The result of these analyses form a large part of the information utilized in the performance assessment [17], which in Posiva's safety case evaluates the fulfillment of the performance targets and target properties of the EBS and host rock during the "expected evolution" of the repository system and also in the radionuclide release, retention and transport analyses [18,19,20], which assess the potential radionuclide releases to the geosphere and surface environment and their radiological consequences.

The layout and its use in various modelling tasks are discussed in the models and data report produced for the safety case [15]. As mentioned above, there have been several layout options designed for the repository to be constructed at Olkiluoto. The one selected for the safety case (Fig. 6), is only one option presented by Saanio et al. [14]. Also, the work done prior to extending the layout to 9000 tU in 2010, has been included in the safety case [15].

Thermal evolution of the repository is modelled to show that the temperature will stay below the required 100°C [cf. 17]. Below this limit it is considered that the buffer will not be subjected to any thermally induced alteration [e.g. 1]. Thermal modelling is iteratively considered both as input information to layout planning as well as then subsequently as a means of ensuring the performance of the system. Layout information is utilized in the most recent thermal modelling by Ikonen and Raiko [21]. Mechanical stability modelling uses the layout to estimate the potential number of the canisters that could fail due to shear load induced by a potential earthquake in the future. Such failures are possible in case a large fracture intersecting a deposition hole remains undetected even though such deposition holes are avoided by applying the RSC criteria. Such estimates are based on a DFN models presenting all fractures [22].

Hydrogeological evolution of the geosphere is one of the most fundamental aspects to be understood in order to produce relevant data to be used in the safety assessment. Hydrogeological modelling includes relevant site data; in addition to the information of the layout it includes the geometrical model of the hydrogeological zones, description of the sparsely fractured rock (either by an equivalent porous medium (EPM) model or DFN model, operation schedules as well as relevant rock properties (EDZ, transport and thermal properties). The key models for the hydrogeological evolution are presented in detail by Löfman and Karvonen [23] and Hartley et al. [16,22,25].

The main outputs of the modelling utilized in the safety case are the estimates on groundwater flow rates, flow paths with flow and transport properties along these flow paths, salinity distribution in the geosphere and around the repository (Figs. 7 and 8). This output is essential information that is incorporated in further analysis, supporting primarily the assessment of the geochemical evolution, assessments of the performance of the buffer, backfill and closure, assessment of the copper corrosion by sulphide and radionuclide release and transport analysis [17,18]. Based on the modelling [23], it is expected that in the longer term, salinity, chloride concentration and total charge equivalent of cations all will decrease very slowly, due to the infiltration of meteoric water as presented in the time shots in Fig. 7.

To show the complexity of the system and how each step on the way affects the next one in the safety case, it is further noted that the results obtained as output from the modelling of the geochemical evolution of the geosphere support further assessment of the geochemical evolution of the EBS including various modes of canister corrosion. One of the most essential uses of the information on the geochemical evolution of the groundwater is the determination of the solubility, speciation and retention parameters for the radionuclide release and transport analysis [see e.g. 15 and references therein].

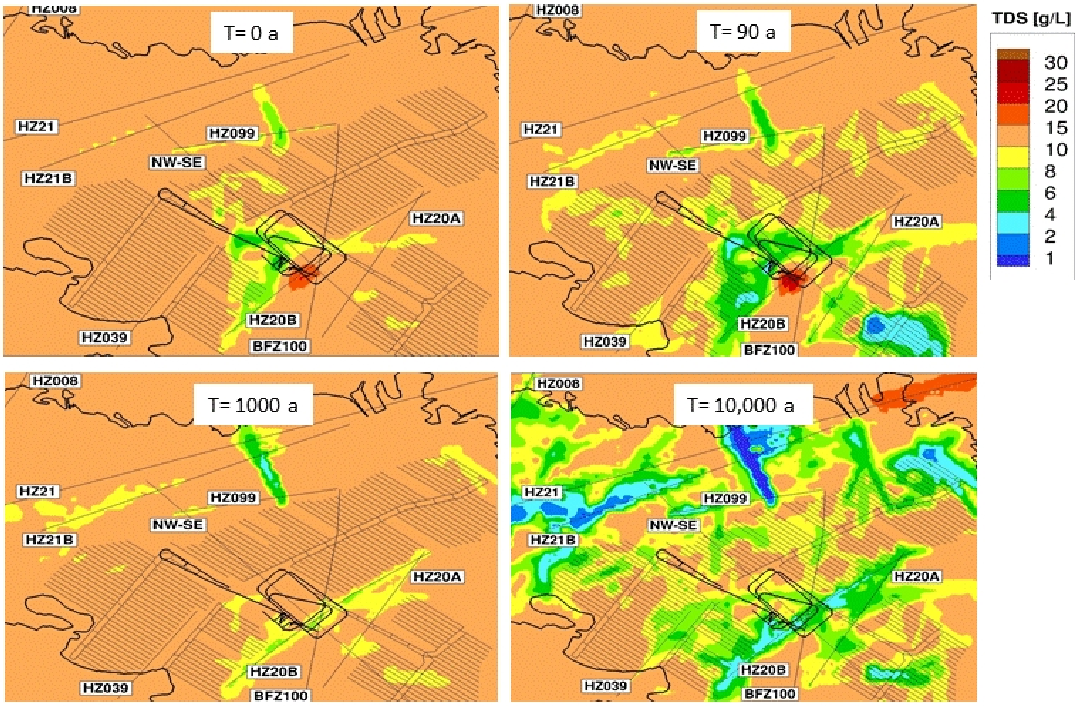

Fig. 7. Geosphere salinity evolution during 10,000 years [23].

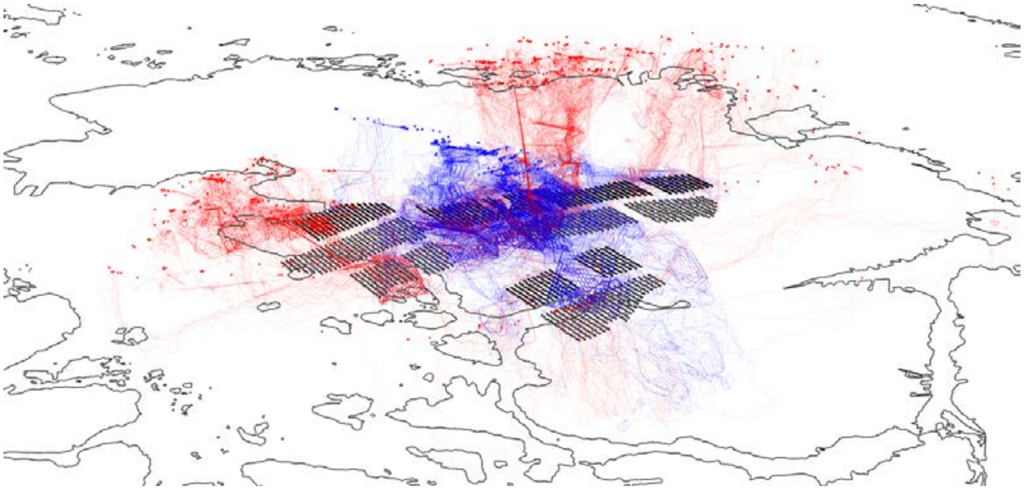

Fig. 8. Recharge pathlines (blue) and discharge pathlines (red) for the base case model at 2000 AD [22].

LAYOUT FLEXIBILITY AND IMPLICATIONS TO SAFETY CASE FINDINGS

As discussed above, several layout adaptations of the repository have been produced for a repository [14,12]. As described in the models and data report [15], most of the modelling in the TURVA-2012 safety case has been based on a selected layout adaptation for 9000 tU, but part of the modelling has been based on the 5500 tU layout (for details see Appendix H in [15]). However, the final layout for the repository can be adjusted in the future taking into account the findings of the continued site characterisation and possible other constraints (e.g. land use restrictions). At the moment, the start of the operation at Olkiluoto is foreseen to commence around 2020 according to Posiva Oy. The RSC at the repository scale (the deposition tunnels and holes are located so that LDFs are avoided) provides a tool to locate the repository in a way that the findings of the safety case are not sensitive to details of the layout [15].

CONCLUSIONS

The more mature the disposal programme, the better the site and EBS data that are incorporated into the repository layout. Detailed site characterisation produces data that are essential in order to design viable layouts for a real site. This requires development of criteria that comply with the requirements set for the system performance. During the period leading to the submittal of the CLA, several iterations of the layout have been carried out based on increasing information on site properties, developments in the RSC and updates in the inventory of the spent fuel to be disposed of at the site. It can be concluded that the layout needs to be designed to allow flexibility in order to incorporate new knowledge and accommodate changes in repository design or in the spent fuel inventory while ensuring long-term safety. Requirements and especially RSC at repository scale provide tools for locating the repository in a way that allows flexibility without significant sensitivity to safety case findings.

REFERENCES

1. POSIVA OY. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Design Basis 2012*. POSIVA 2012-3. Posiva Oy, Eurajoki, Finland (2012).
2. SKBF/KBS. *Final storage of spent nuclear fuel – KBS-3. Volumes I–IV (in Swedish: Kärnbränslecykelns slutsteg. Använt kärnbränsle – KBS-3. Del I–IV).* Art717 1-4. Swedish Nuclear Fuel Supply Co. (SKBF), Stockholm, Sweden (1983).
3. POSIVA OY. *Olkiluoto Site Description 2011*. POSIVA 2011-2. Posiva Oy, Eurajoki, Finland (2013).
4. I. AALTONEN (Ed.), M . LAHTI, J. ENGSTRÖM, J. MATTILA, M. PAANANEN, S. PAULAMÄKI, S. GEHÖR, A. KÄRKI, T. AHOKAS, T. TORVELA and K. FRONT. *Geological model of the Olkiluoto site - version 2.0.* Working Report 2010-70. Posiva Oy, Eurajoki, Finland (2010).
5. S. GEHÖR, J. KARHU, A. KÄRKI, J. LÖFMAN, P. PITKÄNEN, P. RUOTSALAINEN and O. TAIKINA-AHO. *Fracture calcites at Olkiluoto: Evidence from Quarternary infills for palaeohydrogeology*. POSIVA 2002-03. Posiva Oy, Helsinki, Finland (2002).
6. A. HAGROS, *Host Rock Classification (HRC) system for nuclear waste disposal in crystalline bedrock*. Publications of the Department of Geology D8, University of Helsinki, Finland (2006).
7. POSIVA OY. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Description of the Disposal System 2012*. POSIVA 2012-05. Posiva Oy, Eurajoki, Finland (2012).
8. T. McEWEN, S. ARO, P. KOSUNEN, J. MATTILA, T. PERE, A. KÄPYAHO and P. HELLÄ, *Rock Suitability Classification - RSC 2012*. POSIVA 2012-24. Posiva Oy, Eurajoki, Finland (2013).
9. A. HAGROS, T. McEWEN, P. ANTTILA and K. ÄIKÄS, *Host Rock Classification phase 3: proposed classification system (HRC-system)*. Working Report 2005-07. Posiva Oy, Eurajoki, Finland (2005).

10. P. HELLÄ (Ed.), A. IKONEN, J. MATTILA, T. TORVELA and L. WIKSTRÖM, *RSC-programme - Interim report. Approach and basis for RSC development, layout determining features and preliminary criteria for tunnel and deposition hole scale*. Working Report 2009-29. Posiva Oy, Eurajoki, Finland (2009).
11. T. PERE (Ed.), J. MATTILA, S. ARO, H. AHOKAS, T. VAITTINEN and L. WIKSTRÖM, *Layout Determining Features, their Influence Zones and Respect Distances at the Olkiluoto Site*. POSIVA 2012-21. Posiva Oy, Eurajoki, Finland (2012).
12. T. KIRKKOMÄKI. *Design and stepwise implementation of the final repository 2012 (in Finnish with an English abstract).* Working Report 2012-69. Posiva Oy, Eurajoki, Finland (2012).
13. J.-P. SALO, T. KUKKOLA, L. PÖLLÄNEN, R. RIEKKOLA and T. SAANIO, *Spent fuel repository, Preliminary design* (in Finnish). Teollisuuden Voima Oy, Helsinki, Finland (1990).
14. T. SAANIO (Ed.), A. IKONEN, P. KETO, T. KIRKKOMÄKI, T. KUKKOLA, J. NIEMINEN and H. RAIKO, *Design of the disposal facility 2012 (in Finnish: Loppusijoituslaitoksen suunnitelma 2012)*. Working Report 2012-50. Posiva Oy, Eurajoki, Finland (2013).
15. POSIVA OY. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Models and Data for the Repository System 2012*. POSIVA 2013-01. Posiva Oy, Eurajoki, Finland (2013).
16. L. HARTLEY, J. HOEK, D. SWAN, P. APPLEYARD, S. BAXTER, D. ROBERTS and T. SIMPSON. *Hydrogeological modelling for assessment of radionuclide release scenarios for the repository system 2012*. Working Report 2012-42. Posiva Oy, Eurajoki, Finland (2013).
17. POSIVA OY. *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Performance Assessment 2012*. POSIVA 2012-04. Posiva Oy, Eurajoki, Finland (2012).
18. POSIVA OY. *Safety case for the disposal of spent nuclear fuel at Olkiluoto – Assessment of Radionuclide Release Scenarios for the Repository System 2012*. POSIVA 2012-09. Posiva Oy, Eurajoki, Finland (2012).
19. POSIVA OY. *Safety case for the disposal of spent nuclear fuel at Olkiluoto – Biosphere Assessment BSA-2012*. POSIVA 2012-10. Posiva Oy, Eurajoki, Finland (2013).
20. POSIVA OY. *Safety case for the disposal of spent nuclear fuel at Olkiluoto – Formulation of Radionuclide Release Scenarios 2012*. POSIVA 2012-08. Posiva Oy, Eurajoki, Finland (2012).
21. K. IKONEN and H. RAIKO. *Thermal dimensioning of Olkiluoto repository for spent fuel*. Working Report 2012-56. Posiva Oy, Eurajoki, Finland (2013).
22. L. HARTLEY, J. HOEK, D. SWAN, S. BAXTER and H. WOOLLARD. *Hydrogeological discrete fracture modelling to support Rock Suitability Classification*. Working Report 2012-48. Posiva Oy, Eurajoki, Finland (2013).
23. J. LÖFMAN and T. KARVONEN. Simulations of hydrogeological evolution at Olkiluoto. Working Report 2012-35. Posiva Oy, Eurajoki, Finland (2012).
24. L. HARTLEY, P. APPLEYARD, S. BAXTER, J. HOEK, D. ROBERTS and D. SWAN. *Development of a hydrogeological discrete fracture network model for the Olkiluoto Site Descriptive model 2011*. Working Report 2012-32, Volumes I-II. Posiva Oy, Eurajoki, Finland (2012).