TURVA-2012: Performance assessment

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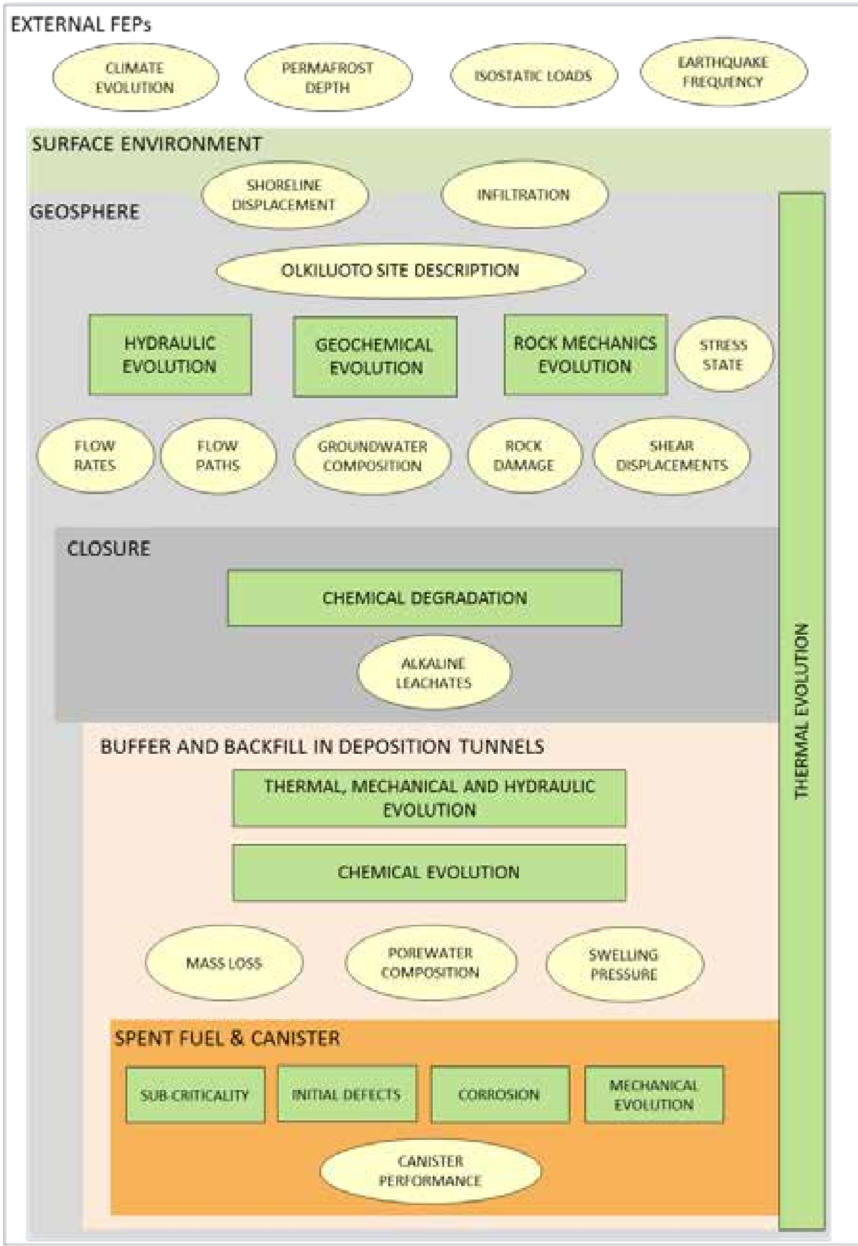
Introduction

TURVA-2012 is Posiva's safety case in support of the Preliminary Safety Analysis Report (PSAR) and application for a construction licence for a repository for disposal of spent nuclear fuel at the Olkiluoto site in south-western Finland. Posiva's safety concept is based on long-term isolation and containment, which is achieved through a robust engineered barrier system (EBS) design and favourable geological conditions at the repository site. The reference design considered in the TURVA-2012 safety case is the KBS-3V design, with the EBS consisting of a copper-iron canister, a buffer of swelling clay material, a backfill in the deposition tunnels of low-permeability material and closure of the central tunnels and other underground openings. The host rock acts as a natural barrier. Each barrier contributes to safety through one or more safety function. The conditions needed for the barriers to fulfil their respective safety functions are expressed in terms of performance targets for the EBS and the target properties for the host rock.

The performance assessment (Posiva, 2013), which is a key component of TURVA-2012, analyses the ability of the repository system to provide containment and isolation of the spent nuclear fuel during the long-term evolution of the system and the site. The conditions needed for the barriers to fulfil their respective safety functions are expressed in terms of performance targets for the engineered barriers and target properties for the host rock, for example properties related to the corrosion resistance and mechanical strength of the canister as well as groundwater flow and composition.

The analyses take into account the uncertainties in the initial state, the subsequent thermal, hydraulic, mechanical and chemical evolution of the repository system and uncertainties in the evolution. The conclusions of the performance assessment are based mostly on the output of key modelling activities shown in Figure 1. Whenever modelling is not possible the conclusions are based on empirical evidence and knowledge of natural analogues. The possibility of a canister with an initial penetrating defect being emplaced in the repository has been considered as an incidental deviation in the analysis. Both likely and less likely lines of evolution, including the possibility of disruptive events, are identified and assessed. Account is taken of the natural evolution of the environment, chiefly driven by climatic evolution, which imposes external loads on the repository system, and also of internal loads, chiefly arising from the effects of excavation and

Figure 1: Overview of the key modelling activities for performance assessment (green boxes), which may consist of several different modelling studies. Yellow ovals present the main input and outcomes of the models. Closure consists of backfill and plugs in other tunnels than deposition tunnels, shafts and investigation holes.



emplacement of the spent nuclear fuel and the engineered barriers. Conditions that could lead to deviations from performance targets and target properties and, in particular, to release of radionuclides are identified, and the likelihood and effects of the deviations from the expected evolution estimated whenever possible. Feedback on further research and development work is also provided.

The performance of the repository system has been systematically analysed in three time windows: *i)* during the excavation and operational period up to closure estimated to last about 100 years; *ii)* up until 10 000 years after closure; *iii)* beyond 10 000 years up to one million years.

Excavation and operation up to closure of the disposal facility

Repository construction and operation cause changes in the host rock, including increased groundwater flow, which also affects the groundwater composition, changes in the stress field and potential rock damage around the underground openings and increase in temperature due to the heat generated by the spent fuel. Further, introduction of foreign materials and the presence of oxygen have an impact on the geochemistry and thereby on the performance of the engineered barrier system.

The increase in flow rates in the rock volume surrounding the repository is estimated to be approximately two orders of magnitude compared with pre-construction rates. After backfilling and closure, the flow rates return to near pre-excavation rates; however, a few deposition holes with flow rates and transport resistances outside the range defined by the target properties may remain. The average salinity around the repository remains similar to the pre-construction phase. However, the increased groundwater flow into the repository volume may lead to either more dilute or more saline conditions locally at repository depth. The disturbed conditions are related to the main hydrogeological zones and the ONKALO facility, not necessarily to the repository panels themselves. Moreover, the disturbed conditions are likely to last a limited time, in the order of tens of years, and thus the impact on the performance of the buffer and backfill is limited.

Calculations of temperature evolution show a maximum temperature at the canister surface of 95°C assuming an unsaturated buffer and 75°C for a saturated buffer. The maximum rock temperature at the deposition hole wall is about 65°C at around 50 years after emplacement. Thus, temperature in the buffer will remain below 100°C as required.

Excavation will cause a damaged zone (EDZ) to form, especially below the tunnel floors, although the damage is probably not continuous based on a dedicated study in the ONKALO facility. In addition, excavation and the heat produced by the spent nuclear fuel may cause spalling or other types of stress-induced rock damage around the excavated openings. The uncertainties concerning the properties of the EDZ and the rock damage around the deposition holes are taken into account in groundwater flow modelling.

Before full saturation, some buffer and backfill material may be lost through piping and erosion. Based on calculated inflows to deposition holes and tunnels, some limited buffer and backfill loss is expected. The average buffer and backfill density does remain high enough that the necessary low hydraulic conductivity and sufficient swelling pressure will be achieved as the buffer and backfill saturate. Thus, the performance targets of the buffer and backfill are fulfilled, even considering piping and erosion.

The consumption of oxygen in the backfill and buffer will be relatively rapid, due to its reaction with pyrite and other accessory minerals. Thus, anoxic, reducing conditions will be quickly established around the emplaced canisters. The maximum corrosion depth on the surface of the copper canisters due to atmospheric and initially trapped oxygen is expected to be less than 0.5 mm. Cementitious leachates from grouting of fractures, from grout used to stabilise rock bolts and from the plug in the deposition tunnel may locally affect the backfill. However, no cement is in direct contact with the buffer and the flux of cementitious leachates reaching the buffer is estimated to be of little significance.

Post-closure period during the next 10 000 years

Over the next 10 000 years, the climate is expected to remain essentially as today, i.e. a temperate climate with a boreal ecosystem. Groundwater flow and composition will recover from the disturbances caused by excavation, and will slowly evolve as a response to naturally occurring gradients. Key processes during this period will be water uptake, swelling and homogenisation of the clays in the buffer, backfill and seals, and the decline of the residual heat from the spent nuclear fuel.

Crustal uplift will continue, but at gradually lower rates, and higher hydraulic gradients will develop close to the shoreline. After 1 000 to 2 000 years, the shoreline will have retreated far enough that further retreat will not affect the flow rates in the repository volume. The heat from the spent nuclear fuel increases the flow rates at the repository depth by a factor of 2 to 3 compared with the natural state during the first hundreds of years. The heat tends to result in an upward driving force for the water, but when combined with the stronger natural downward forces, the flow remains mainly downwardly directed. Heat production declines to very low levels after the first few thousands of years, and the flow returns to its natural state.

The effect of the tunnel EDZ and the rock damage around the deposition holes (including thermally induced damage) on local flow rates around the deposition holes an on flow-related transport parameters has been modelled using a discrete fracture network approach (DFN flow model). The presence of the damaged zone increases the connectivity of fractures and flow around the deposition hole, but the effects on the natural fractures are limited, and flow rates in natural fractures and the transport resistances in the vicinity of the deposition holes are consistent with target properties for most deposition holes.

After closure of the repository, the disturbances caused by the repository construction cease and the salinity field at repository depth recovers, but at a much slower rate than the flow field. The natural salinity state is reached within hundreds of years. Groundwater composition also stabilises and the variation seen during the operational period diminishes. At repository depth, the pH remains close to 7.5 and reducing conditions prevail. In the longer term, salinity, chloride concentration and total charge equivalent of cations all decrease very slowly, due to the infiltration of meteoric water, but the concentrations remain consistent with the target properties over the time window in question.

Groundwater flowing into the repository leads to saturation and swelling of the buffer and backfill. Initial differences in the density and swelling pressure will be largely evened out (homogenisation). The time to reach full saturation in the buffer is calculated as a few tens to several thousands of years, depending on the local hydraulic conditions. Calculations show that a sufficiently high buffer density will be maintained in spite of any expansion of the buffer into the backfill.

Various gradients, including thermal gradients associated with heat generated by the spent nuclear fuel, will drive thermo-hydro-mechanical-chemical evolution and lead to limited geochemical changes in the buffer and backfill. After saturation and development of the full swelling capacity, the changes will be even lower, constrained by diffusive processes. The production of sulphide via microbial processes in the buffer will be minor, but cannot be ruled out in localised zones of low backfill density. Further, the already minor impact of cementitious leachates on the buffer and backfill is estimated to diminish, due to low concentrations of alkalis in the leachates.

Sulphide is the main copper corrosion agent in anaerobic conditions. Microbially produced sulphide in the buffer is negligible in this period; sulphide supply from the backfill is limited by the precipitation of iron sulphide and losses to the rock mass. Moreover, the sulphide has to diffuse through a thick layer of bentonite to reach the canister. Corrosion calculations coupled with groundwater flow modelling, and taking account of the possibility of early buffer erosion, show that the total corrosion depth will be negligible during the first 10 000 years. Moreover, the initially intact canisters will remain intact for all conceivable loads that could occur during the first 10 000 years and thus the spent nuclear fuel remains contained within the canister.

Evolution during repeated glacial cycles up to one million years

Over the longer term, major climatic changes are expected, including permafrost, glaciation and associated sea-level changes. These changes affect the isostatic load, rock stresses, and groundwater flow and composition, as well as the mechanical and thermal evolution of the EBS and host rock.

During the continued temperate climate up to 50 000 years AP, there is a slight increase in the groundwater flow rates in the upper part of the bedrock, due to surface environment changes. The flow rates at repository depth are not significantly affected. The continuing infiltration of meteoric water results in slowly decreasing salinity so that, towards the end of this period, a few canister positions may experience dilute conditions, at least if the chemical reactions in the overburden and with the fracture coating minerals and rock matrix minerals are not taken into account. Dilute conditions could give rise to chemical erosion of the buffer and backfill.

Groundwater flow and salinity have been modelled for two representative periods of permafrost development, during which permafrost reaches depths of about 80 m and 300 m. The effects of an ice sheet have also been modelled considering an ice margin staying over the Olkiluoto Island for 1 000 years, and a constantly retreating ice sheet. Under permafrost conditions, the hydraulic conductivity in the rock is reduced by several orders of magnitude and infiltration of the water from the surface is very low. As a result, the groundwater salinities remain at the level prevailing before the onset of the permafrost. During ice-sheet retreat, the flow rates through the repository volume depend on the location of the ice margin with respect to the repository. While the repository is still below the ice sheet but the ice margin is close, the flow rates are significantly increased (by a factor of 4 to 7) and directed downwards. As the ice passes the site, the main flow direction is upwards and flow rates reduce as the distance to the ice margin increases. Some canister locations might then experience higher flow rates and lower transport resistances than those specified in the target properties. Nevertheless, for most of the deposition holes, the host rock target properties related to groundwater flow are fulfilled during ice-sheet retreat.

Although there is no evidence that fresh meltwater ever reached repository depth at Olkiluoto during the last glacial cycle or during the previous ones, dilute conditions around some of the deposition holes during a future ice-sheet retreat phase might be possible and thus could lead to chemical erosion of the buffer and backfill. Other geochemical properties (pH, redox conditions, chloride concentration, total charge equivalent of cations sulphur and iron species) are all expected to remain consistent with the target properties throughout the period, including during ice-sheet retreat and melting. Oxygen will be consumed within short distances from the surface and will thus not reach the repository level.

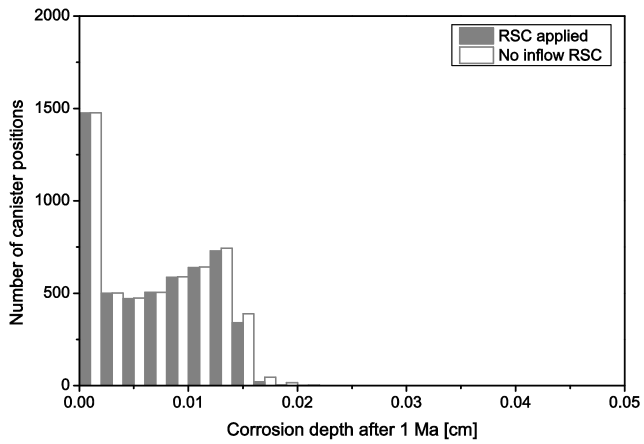
The possibility of a large earthquake leading to secondary shear movements on fractures intersecting deposition holes and to canister failure, especially during and after glacial retreat periods, cannot totally be excluded. The risk of canister failures due to secondary shear movements in the event of a large earthquake can be reduced by locating the deposition holes away from large deformation zones and by avoiding large fracture intersections in deposition holes, but it is estimated that a few tens of canisters may still be in positions such that they could potentially fail in such an event over a one million year time frame. On the other hand, the average annual probability of an earthquake large enough potentially to lead to canister failure due to secondary movements on fractures is estimated to be low, in the order of 10^{-7}. This is based on the frequency of occurrence of earthquakes in the Olkiluoto area and the fact that there are around five fault zones within and around the area of the repository that could host such an earthquake. Thus, during the first glacial cycle, there is little likelihood of canister failure due to rock shear, although the possibility of such failures cannot be discounted over a one million year time frame.

Freezing of the buffer or the deposition tunnel backfill is not a threat because, based on evidence from the past, permafrost will not reach the repository depth. In any case, the buffer and backfill would withstand the freeze/thaw cycles without damage to their safety functions. The evolution of porewater salinities in the buffer and backfill will follow those in the surrounding groundwaters, which will remain within the required target ranges, except perhaps for short times during ice-sheet retreat and melting period. Under these conditions, dilute groundwater conditions might cause some chemical erosion of buffer and backfill. With the reference assumptions on groundwater flow and evolving groundwater composition, one canister position is calculated to undergo buffer erosion during the first glacial cycle to an extent that advective conditions could arise. This calculation should be seen as illustrative, being based on only a single realisation of the DFN flow model. Taking a more cautious view on this and other uncertainties, buffer erosion might result in advective conditions in a few canister positions.

As at earlier times, sulphide is the main agent for corrosion of the copper canisters. Although groundwater data clearly indicate sulphide values below 1 mg/L, a pessimistic upper bound of 3 mg/L is adopted in corrosion calculations. The results show that, assuming the adopted value of 3 mg/l and that the buffer performs as designed, the overall corrosion depth will not exceed a few tenths of a millimetre even over one million years (Figure 2). Thus, no canister failures due to corrosion are expected. Furthermore, even if the buffer is affected by chemical erosion, few if any canister failures due to corrosion are expected during the first glacial cycle, as long as conditions otherwise correspond to the expected evolution. Using more cautious assumptions around three canister failures are calculated to occur within the first glacial cycle, and a few tens of failures in the million year time frame.

Figure 2: Number of canister positions as a function of corrosion depth over 1 Ma

With and without the rock suitability classification (RSC) inflow screening in the case of direct diffusion of sulphide across the buffer from a fracture intersecting the deposition hole with increased flow around the deposition hole due to rock damage; it is assumed that the groundwater sulphide concentration is 3 mg/L



Successive glacial cycles will impose similar loads as considered during the first glacial cycle. Thus, over the one million year assessment time frame:

- the potential for buffer erosion increases for deposition holes that experience dilute groundwater conditions during ice-sheet retreat;
- the number of deposition holes that suffer a shear displacement sufficient to cause canister failure could increase;

- the extent of canister corrosion in deposition holes that suffer buffer erosion could increase.

Conclusions

The analyses show that, under most conditions and lines of evolution, all performance requirements for the host rock and engineered barriers will be met. In this case, the copper canisters will remain intact and no radionuclide release will occur over at least one million years. Uncertainties in the initial state of the barriers and in the long-term evolution of the repository system, in particular during glaciations (Table 1), that may potentially lead to radionuclide releases are considered in various radionuclide release scenarios.

Table 1: Summary of deviations from performance targets and target properties as may occur and are relevant in each time window

Deviations	Up to closure of the disposal facility	Up to 10 000 years	During repeated glacial cycles
Possibility of an initial penetrating defect in one or a few canisters	Ö	Ö	Ö
Higher flow rate or lower transport resistance than the target values for a few deposition holes	Ö	Ö	Ö
Groundwater composition outside the target range for a short time during operation and soon after closure for a few deposition holes	Ö	Ö	–
Low density areas in the backfill where sulphate reduction to sulphide cannot be ruled out	–	Ö	Ö
Erosion of buffer in some deposition holes due to long-term infiltration of meteoric water or dilute glacial meltwater	–	–	Ö
Canister failure by corrosion due to unfavourable groundwater conditions and buffer erosion	–	–	Ö
Canister failure due to shear displacements in fractures during ice-sheet retreat	–	–	Ö

Some uncertainties still remain, but they do not affect conclusions regarding long-term safety. During the coming years uncertainties will be addressed through further research and technological development (RTD) activities for the operational license application, to either resolve them through a modified design or gather further data to better understand their long-term safety impact. The focus of research and development in the coming years is on:

- a better understanding of the processes affecting canister corrosion and erosion of buffer and backfill;
- rock conditions in potential volumes of rock for the repository and the application of rock suitability classification (RSC) criteria for the selection of repository panels, tunnels and deposition holes;
- demonstration of the implementation of the repository system components at full scale according to the technical design and quality performance requirements.

Further investigations of the properties of the rock in the repository area will reduce the probability of locating the canisters in unfavourable positions with respect to future loads. The processes affecting the performance of the engineered barriers will continue to be experimentally studied. Technical tests will be carried out to demonstrate that the repository can be implemented according to the assumptions made in the safety case.

Reference

Posiva Oy (2013), *Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto – Performance Assessment 2012*, POSIVA 2012-04, ISBN 978-951-652-185-8, Posiva Oy, Eurajoki, Finland.