SKB'S UPDATES OF THE FORSMARK SNF REPOSITORY LICENSE APPLICATION – LONG-TERM SAFETY

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SKB applied for a license for a KBS-3 repository at the Forsmark site in Sweden in 2011. In the review of the assessment of long-term safety, the Swedish Radiation Safety Authority, SSM, has requested supplementary information in a number of areas. The large majority of issues have now (November 2014) been responded to by SKB. Whereas many of the requests concern clarifications and more detailed accounts of the technical analyses and arguments for safety, some have required substantial new studies. SKB's central conclusion of the safety assessment SR-Site is that a KBS-3 repository at Forsmark would fulfil all long-term safety requirements. According to SKB, this conclusion is not altered when taking the material in the supplementary information into account. The risk contributing scenarios are the same as in SR-Site and only minor adjustments to the calculated risks have been made. This paper summarizes the supplementary information and SKB's conclusions from it.

I. INTRODUCTION

In March 2011, the Swedish Nuclear Waste Management Co. (SKB) submitted a license application for a KBS-3 final repository for spent nuclear fuel at the Forsmark Site in south central Sweden. Long-term safety was evaluated in the safety assessment SR-Site [1] that formed a central part of the license application. The application is currently subject to regulatory review by the Swedish Radiation Safety Authority, SSM, and it will also be tried by an Environmental Court.

In the KBS-3 disposal concept, copper canisters with a load-bearing cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1. The primary safety function of the KBS-3 repository is complete containment of the spent nuclear fuel in the canisters.

A risk limit of 10^{-6}/yr for exposed individuals in the vicinity of the repository is the primary compliance criterion according to SSM's regulations and the stipulated assessment time is one million years.

During the course of the review, SSM has requested supplementary information in a number of areas of the safety case. Many of the requests by SSM and responses by SKB concern clarifications and more detailed accounts of the technical analyses and arguments for safety in SKB's licence application, while in some areas more comprehensive, new studies have been undertaken. All requests and responses are available at SKB's and SSM's websites, however much of this material is in Swedish.

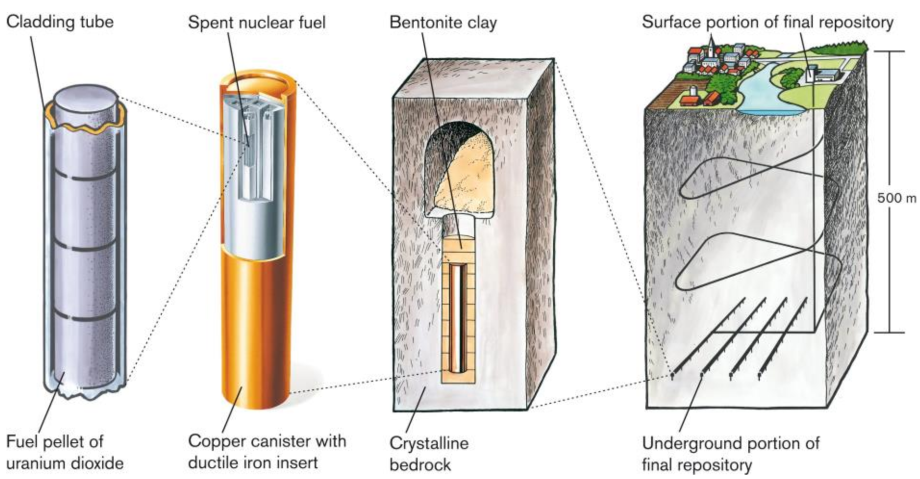

Fig. 1. The KBS-3 concept for final disposal of spent nuclear fuel.

The following sections II-IV deal with three examples of areas where substantial new information has been provided as supplementary information. These are copper corrosion in oxygen free water, a hypothetical scenario where criticality is assumed in the repository and buffer piping/erosion as the buffer undergoes water saturation. Substantial new information has been provided in several other areas, and section V provides an overview of supplementary information in all areas. SKB's conclusions regarding long-term safety when taking all the supplementary material into account are given in section VI.

II. COPPER CORROSION IN OXYGEN FREE WATER

Copper is used as a container material in the KBS-3 concept since copper, according to established thermodynamic data, has favourable corrosion properties in deep granitic groundwaters.

Since 2007, this view has been challenged by a group of researchers at the Royal Institute of Technology, KTH, Stockholm, see e.g. [2]. One important basis for the claims by the KTH researchers has been the observation of hydrogen gas evolution in their experiments with metallic copper in pure water. The authors have interpreted the observations of hydrogen gas evolution as evidence for copper corrosion, but have not presented any explanation, consistent with established thermodynamic data, of the amount of hydrogen gas formed, or of the alleged equilibrium pressures attained in the experiments.

Since 2010, SKB has pursued two main experimental projects to resolve the issue of copper corrosion in pure, O_2 free water. One is a study at Uppsala University [3] in a set-up similar to that used by the researchers at KTH. This type of set-up consists of a lower and an upper stainless steel chamber connected through a palladium foil that allows permeation of hydrogen, but no other gases, between the chambers. Metallic copper is immersed in water in a glass container in the lower chamber. The upper chamber is initially evacuated and the increase in gas pressure is monitored in this chamber. It has been difficult to reach conclusive results with the Uppsala set-up, mainly due to issues related to the tightness of the set-up with respect to hydrogen, and to out-gassing of hydrogen from the stainless steel. One important finding has, however, emerged: No evidence of corrosion products has been observed on copper surfaces exposed to pure, O_2 free water during more than one year [3].

In parallel, an alternative, comparatively simple and fast method of detecting hydrogen evolution from copper samples in O_2 free water, has been developed at Microbial Analytics AB (Micans) in Gothenburg, Sweden, in cooperation with and financed by SKB. The development phase is reported in [4]. In the following, a summary of recent results obtained with Micans' method after the publication of [4] is given. A more detailed report of the results has been given to SSM.

In the method developed at Micans [4], typically two $10\times1\times0.2$ cm^3 copper pieces are placed in a test tube and immersed in 16 cm^3 of pure O_2 free water, leaving 6 cm^3 of gas phase above the water. The tubes are sealed with butyl rubber stoppers. The preparation of the tubes is carried out in an N_2 atmosphere in a glove box and the tubes are stored in an inert atmosphere throughout the experiment. The gas phase in the tubes is sampled by inserting a syringe through the stopper, initially and then at intervals of typically a few weeks. The gas samples are analysed in a gas chromatograph. The method is able to detect oxidation of down to a single layer of copper atoms.

A range of copper qualities and surface cleaning techniques were explored in order to clarify whether any combination of them could yield evolution of hydrogen gas.

Figure 2 shows the results of samples of 99.95% Cu-OF (oxygen free), pre-treated with different methods. Irrespective of treatment, the samples do not yield hydrogen evolution above the approximately 0.2 mbar background level (dashed line). It is noted that the hydrogen evolution observed in the KTH experiment [2], if interpreted and expressed as a molar generation rate per unit surface area of copper, would yield a continuous pressure increase of around 10 mbar in 100 days in the Micans set-up, which is not at all observed in Figure 2. Untreated, "as received" 99.95% Cu-OF from the same supplier was used in the KTH experiment. According to [2] the hydrogen evolution is expected to cease at a partial pressure of around 1 mbar, i.e. a pressure that is never attained in Micans' experiment with this particular copper quality. Also several samples of 99.9% and 99.9999% Cu-OF surface cleaned with different techniques have been tested without detection of hydrogen evolution. Samples studied "as received", i.e. without any cleaning may yield initial evolutions of hydrogen gas up to about 0.4 mbar that cease after at most a few days.

Copper samples obtained from canister lid material at SKB's Canister Laboratory have in earlier experiments yielded significant and sustained hydrogen evolution [4]. An important finding in the recent experiments at Micans is that if such copper samples are heated to 400 °C in vacuum, no hydrogen evolution is observed when the samples are subsequently submerged in O_2 free water. Also, significant outgassing of hydrogen was observed when the samples were heated prior to being exposed to water. The conclusion regarding this type of copper samples is thus that the earlier observed hydrogen evolution is due to outgassing and not to corrosion.

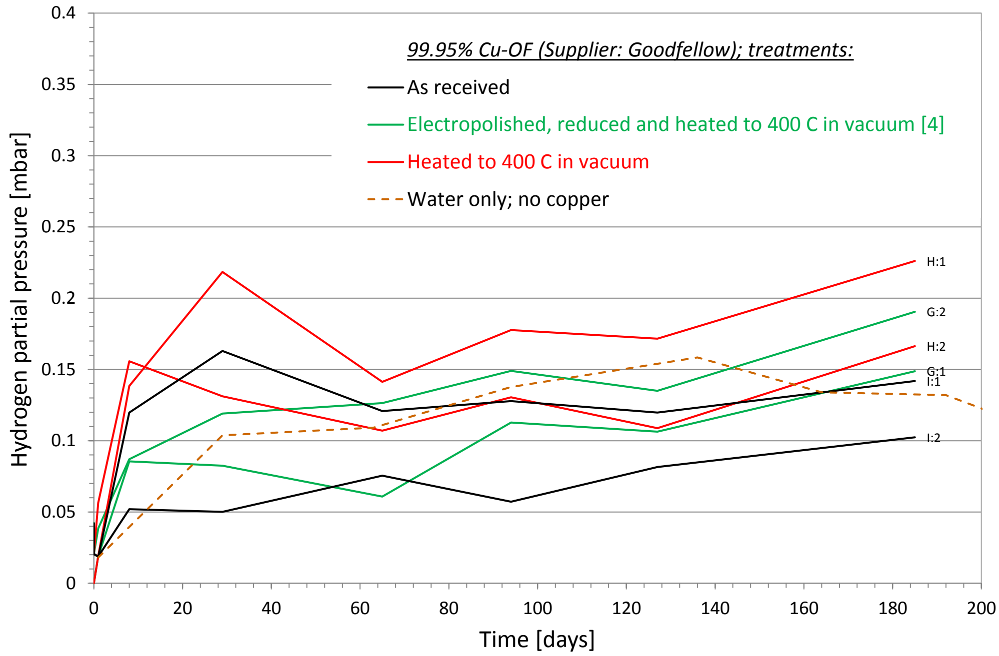

Fig. 2. Samples of 99.95% Cu-OF with different treatments.

Based on these recent studies, SKB concludes that there is no support for a sustained corrosion of copper in pure, O_2 free water above the very limited extent predicted by established thermodynamic data. A more comprehensive account (in Swedish) to SSM of SKB's view of the issue of corrosion in O_2 free water is underway, as well as a more detailed report of the Micans experiments.

As mentioned in the introduction, SKB has also pursued corrosion experiments in vacuum systems similar to those used by the KTH researchers. Those experiments are more complicated and expensive and also require longer run-times. The palladium foil used to selectively allow hydrogen to pass from the lower to the upper chamber may act as a catalyst and, particularly at low partial pressures, entail a considerable sink for hydrogen. Both these effects complicate the interpretation of data from the experiments. The stainless steel in the equipment contains and releases hydrogen that also complicates the interpretation of the results. SKB finds the account of all hydrogen sources and sinks in the publications from the KTH researchers insufficient for an evaluation of the total turnover of hydrogen in their experiments.

III. THE "WHAT IF" CRITICALITY SCENARIO

In the safety assessment SR-Site [1] it was concluded that nuclear criticality will not occur in the final repository, either during the operational or during the post-closure phase, including situations where a canister is assumed to be water filled.

In its review of SKB's licence application, SSM has requested an account of the consequences of a postulated nuclear criticality event in the post-closure phase as a residual scenario. A summary of the account given to SSM is reported below.

III.A. General system development

Since nuclear criticality in the post-closure phase of the final repository was argued to be ruled out in SR-Site, some assumptions in violation of the conclusions of the safety assessment are required in the definition of a residual scenario to illustrate consequences of nuclear criticality. This is in line with the procedure for defining so called "what if" scenarios in a safety assessment. In the following, it is assumed that the spent fuel configuration in a canister is such that it will become critical if the canister is filled with liquid water, i.e. in direct conflict with *i*) the stated requirement on the encapsulation process that the spent fuel properties and geometrical arrangement in the canister should be such that criticality is avoided even if water should enter a defective canister, and *ii*) the verifying criticality calculations for water-filled canisters done in SR-Site.

For water to enter the canister, it is required that the canister containment fails, and the two failure modes that could not be ruled out in SR-Site are considered. These are *i*) failures caused by sulfide corrosion, at an enhanced rate due to the loss of the protecting buffer through erosion and *ii*) failures due to earthquake induced secondary shear movements in fractures intersecting the deposition hole.

III.A.1. Case with missing buffer

The following sequence of events is considered in a deposition hole where the buffer is missing e.g. due to buffer erosion.

- The canister containment fails, in the form of an opening in the copper shell, caused by sulfide corrosion. In accordance with the results of the corrosion analyses, this is assumed to occur sufficiently far into the future that the host rock temperature is no longer influenced by the residual power of the spent fuel.
- Water intrudes into the canister insert and slowly fills the void volume, including that between the fuel elements. Even for a deposition hole with a high groundwater flow rate of 100 L/yr, it would take several years to fill the 1 m^3 canister void, if all water flowing into the deposition hole is assumed to enter the canister interior. Any realistic description of the size of the corrosion induced opening, the transport resistances in the canister interior and the role of corrosion of the cast iron insert including impacts on water flow of the expected evolution of hydrogen in that corrosion process, suggests that it would take hundreds of years to fill the canister interior with water.
- At some point, when a sufficient amount of water has entered the canister, it is assumed that the fuel configuration becomes critical, i.e. that $k_{eff} = 1$. Since, in reality, no critical configurations will be allowed in the canister, it is in this what-if case assumed that this occurs for an almost completely water filled canister, i.e. for one with an almost maximal amount of moderating water. (An example of a disallowed criticality situation would be a water filled canister fully loaded with fresh fuel enriched to at least 3.5 %.)
- Fission commences and the temperature increases. As the temperature increases k_{eff} is expected to decrease due to the negative temperature coefficient of the configuration with respect to criticality, caused by the nuclear Doppler effect and the thermal expansion of the moderating water. More water is then required in order to resume critical conditions. The further development is determined by the competition between the inflowing water, leading to an increased k_{eff}, and the increasing temperature, yielding a decrease in k_{eff}. The system is expected to evolve slowly due to the negative feedback loop and the slow rate of water ingress. In principle, a certain water level in the canister should correspond to a given fuel temperature, up to the boiling temperature of water under repository conditions. A slow increase in water level and hence k_{eff} is expected until the boiling temperature is reached. For the hydrostatic pressure of 5 MPa at a depth of 500 m, the water boiling point is 264 °C. The system is maintained in steady-state at this temperature and a certain, constant power is generated by the fissions. If the temperature rises slightly beyond the boiling point, some water is expelled from the canister through boiling, rendering the system subcritical. Additional water enters and the cycle is repeated. This would be a “near-steady-state” situation where the temperature is again close to the boiling point of water and where pulses of energy release rates slightly higher than those in the steady-state situation are compensated by intermediate periods of subcritical conditions.

III.A.2. Case with buffer in place

In a case where the buffer is assumed to be in place, e.g. if failure occurs due to a shear movement in a fracture intersecting the canister position, a similar sequence of events is considered, but with an even lower water filling rate due to the low hydraulic conductivity of the buffer. As water enters the canister through the gas-tight buffer, the internal pressure will increase as the void volume decreases. Hydrogen generation due to corrosion of the cast iron insert is also expected to contribute to the pressure build-up and may in the long term lead to considerable internal overpressures. The buffer, if functioning as expected, is able to contain overpressures of up to 20 MPa [1]. The inflow of water will cease when the internal pressure reaches the external hydrostatic pressure. If criticality has not been reached at this point, it is not expected to develop at all since no additional water can enter. If criticality is reached at an internal pressure below the hydrostatic pressure, a development similar to the case without buffer is expected, leading, through boiling and internal pressure increase, to a steady-state pressure equal to the hydrostatic pressure.

III.B. Quantitative assessment of the steady-state situation

A deeper analysis of the steady-state situation yielded the following conclusions:

- The temperature in the critical canister is limited by the boiling point of water under repository conditions. This temperature is around 264 °C for a hydrostatic pressure of 5 MPa.
- The power developed in a critical canister is limited by the finite capacity of the rock to carry away the generated heat by thermal conduction. A canister maintained at 264 °C is calculated to develop a power of around 14 kW in the host rock in Forsmark.
- The resulting increase in temperature in the host rock is not sufficient to cause any damage to the bentonite buffer in adjacent deposition positions, see Figure 3. The calculated temperature increases are lower than those caused in the short term after deposition by the residual power of the fuel.
- The increased rock temperatures may affect the rock nearest to the critical canister negatively as regards mechanical properties and effects. However, the rock

mechanical properties are important in particular to ensure intact containment of the canister and in the criticality case the canister is failed by definition.

- The fuel dissolution rate in a steady-state criticality situation is judged to possibly be an order of magnitude higher than for sub-critical conditions.
- Using this higher fuel dissolution rate, the radiological consequences for a steady-state criticality situation in a failed canister are calculated to be about a factor of six higher than for the corresponding sub-critical situation.

Finally, it is recalled that this is an unrealistic "what if" case, building on an assumption of criticality, whereas in the safety assessment SR-Site, it was concluded that criticality in the post-closure phase of the final repository can be ruled out.

IV. BUFFER PIPING/EROSION DURING SATURATION

In SR-Site, a hydraulic issue during the operational and water saturation phase concerns piping and associated erosion effects in the buffer and backfill [1]. Water inflow into the deposition holes will take place mainly through fractures intersecting the holes. If the inflow is localised to fractures that carry more water than the swelling bentonite can absorb, a water pressure in the fracture will act on the buffer. The swelling bentonite is initially a gel, for which the density increases with time as the water goes deeper into the bentonite. The gel may be too soft to stop the water inflow, resulting potentially in piping in the bentonite, formation of a channel and a continuing water flow and a consecutive erosion of bentonite particles. A large number of erosion tests have been performed and were used to formulate an empirical piping/erosion model in SR-Site. According to the model the accumulated mass of eroded bentonite is related to the accumulated mass of eroding water [1].

The Forsmark site is sparsely fractured at repository depth and a considerable portion of the fractures are not water conducting. In an extreme case where all water to the entire tunnel comes from one single deposition hole, the eroding mass of bentonite could, according to the model used in SR-Site, be up to 164 kg of bentonite. The calculations of the swelling and homogenisation (levelling of density gradients) after erosion show a decrease in density and swelling pressure in the eroded volume due to the friction in the bentonite. About 100 kg of dry bentonite may be lost due to erosion without jeopardizing the function of the buffer. Beyond this loss, the required swelling pressure of 2 MPa is not guaranteed in the eroded area, whereas the buffer functions as a diffusion barrier for also considerably greater losses. The 2 MPa criterion relates to the buffer's ability to hinder microbial activity.

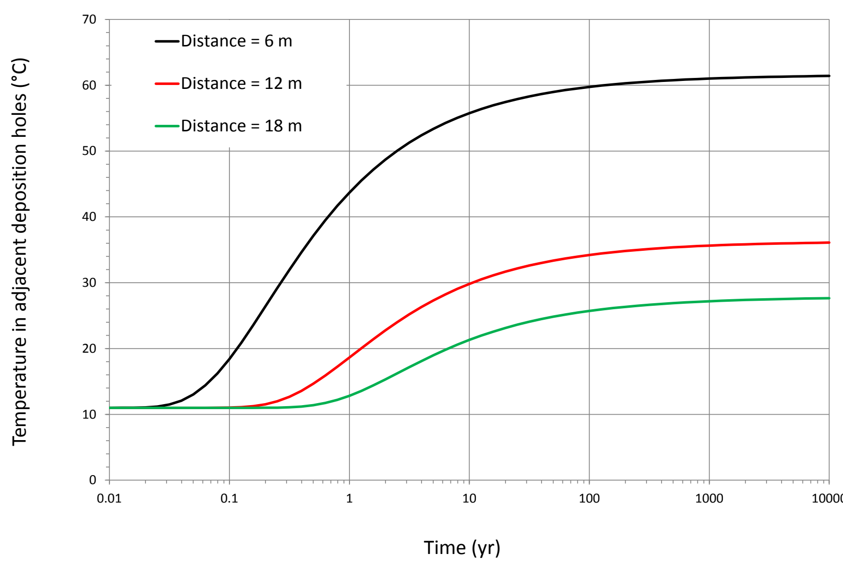

Fig. 3. The temperature development in the three nearest deposition positions to a critical canister maintained at 264 °C. In accordance with the repository layout in SKB's license application, the three positions are located 6, 12 and 18 m from the critical canister, respectively. The background temperature of the rock is 11.2 °C. The bentonite buffer material will remain functional for temperatures up to at least 100 °C [1]. The canister failure due to corrosion is assumed to occur sufficiently far into the future that the host rock temperature is no longer influenced by the residual power of the spent fuel.

In SSM's review, additional information was requested regarding the piping/erosion process. A key issue concerned the probability for the phenomenon to occur at the Forsmark site.

The extent of erosion caused by piping has been estimated [5] with the empirical model developed in SR-Site, together with calculated data for inflow to tunnels and deposition holes. The results, summarised in Table I, show that there are in total 5 deposition holes out of 6916 where the erosion exceeds the 100 kg requirement, with the maximum loss in a hole being 170 kg. The calculated example thus shows that erosion caused by piping may exceed the requirement of 100 kg in a very limited number of deposition holes. This is difficult to avoid with engineering measures since many of the inflows are too small to be readily detected. It is also recalled that after a loss of 170 kg, the buffer would still function as a diffusion barrier. If the buffer density becomes sufficiently low to allow microbial activity, it has been shown by mass balance considerations that the extent would be limited by supply of nutrients to microbes, limiting the corrosion depths to a few millimetres during the assessment time [1].

TABLE I. Calculated distribution of mass losses in the 6916 deposition holes.

Mass loss (kg)	Number of holes
<0.01	5890
0.01-1	474
1-10	345
10-35	136
35-100	66
>100	5

V. OVERVIEW OF SUPPLEMENTARY INFORMATION

This section gives a broader account of the supplementary information submitted to SSM to date (November 2014). The discussion is structured around the canister failure scenarios in the SR-Site assessment. Three modes of containment failure were identified in SR-Site, each corresponding to a dedicated scenario: failures due to corrosion, to shear loads and to isostatic loads.

V.A. The erosion/corrosion scenario

In this scenario, the rate of canister corrosion due to sulfide in the groundwater is enhanced following loss of the buffer caused by colloid formation during periods of dilute groundwater intrusion. This is one of the two scenarios where canister failures could not be ruled out in the one million year assessment time in SR-Site and the scenario thus gives a contribution to the calculated risk. The risk contribution is influenced by the extent of erosion and corrosion and by radionuclide transport and dose assessments, all of which are in part determined by the hydrogeology of the site. All these factors are discussed below.

Hydrogeology: During the course of the review, SSM has required a more in-depth discussion of uncertainties relating to the hydrogeological modeling. Such an account has been given, and SKB maintains its conclusion that whereas some aspects of uncertainty have been pessimistically treated, more definite conclusions regarding hydrogeological uncertainties can only be reached with additional data from the underground investigations to be carried out as the planned repository is excavated. SKB is sufficiently confident in the current understanding of the hydrogeology of the Forsmark site to invest in this next step.

Related to this, SSM has also requested an analysis of the hydrogeochemical evolution for more extended periods of temperate climate than those analyzed in SR-Site. Such an analysis has been carried out with a new tool that couples the geochemical calculations with the groundwater flow and transport calculations [6]. The results show that there are only moderate changes in the geochemical environment of the site when the 8000 BC to 9,000 AD period of temperate climate, considered for SR-Site, is extended to 20,000 AD. The calculated changes for the period between 20,000 AD and 60,000 AD are very small.

Buffer erosion: Additional information provided to SSM in the review has not altered SKB's view of the basic understanding and the quantitative extent of erosion due to piping (see section IV above) or colloid formation. The impact of buffer loss due to short-term piping/erosion and long-term erosion due to buffer colloid formation when dilute groundwaters contact the buffer was pessimistically treated in SR-Site. The compliance discussion in SR-Site is based on a case where the protecting function of the buffer is pessimistically disregarded throughout the assessment time. This case is an upper bound on the impact of uncertainties relating to hydrogeology and geochemistry on erosion, as well as on conceptual uncertainties regarding the short- and long-term erosion mechanisms.

Copper corrosion: As discussed in section II, SKB maintains its conclusion in SR-Site that the extent of corrosion in pure, O_2 free water is described by established thermodynamic data and that it is hence negligible for KBS-3 canisters under repository conditions in a one million year perspective.

An in-depth analysis of corrosion due to stray currents from ground electrodes for present and potential future power transmission lines has been carried out [7], in response to a request for additional information from

SSM. The conclusion from the simpler analysis in SR-Site is maintained, namely that such corrosion will not significantly reduce the 5 cm copper corrosion barrier in a million year perspective.

SKB has also made a more detailed analysis of the prerequisites for localized corrosion [8]. The conclusion is that the composition of the pore water in the bentonite favors general corrosion and not the formation of a passive film, that would be necessary for localized corrosion to occur.

SKB has also provided a more detailed account of corrosion under unsaturated conditions and demonstrated how sulfide corrosion under such conditions is limited by mass transport arguments. Also, it has been recognized that in order to limit the potential extent of corrosion by oxygen under unsaturated conditions, an additional requirement on gas-tightness must be put on the deposition tunnel plugs. This will be included in SKB's updated design premises.

In the SR-Site assessment it was concluded that sulfide in the groundwater is the dominating long-term corroding agent. SSM has requested additional information in support of the view held in SR-Site that it is pessimistic to assume that the rate of corrosion due to sulfide is mass transport limited. In response to this request, an evaluation of recent experimental results has been provided. The results support SKB's view in SR-Site.

Overall, the extent of corrosion is, as in SR-Site, by far dominated by long-term corrosion due to sulfide, also when considering all SKB's responses regarding corrosion in SSM's review. SKB considers the upper bound on this extent given in the compliance discussion in SR-Site as still being valid.

Radionuclide transport and dose calculations: In response to requests by SSM, SKB has clarified the basis for the assumed conversion rate of the fuel matrix if a canister fails and water contacts the fuel. Furthermore, the radionuclides Rn-222 and Po-210 in the U-238 chain have now been included in the radionuclide transport calculations, and it has been demonstrated that they do not significantly impact on the total dose.

Additional information has also been requested and provided regarding the landscape specific release-to-dose conversion factors that represent the biosphere in the SR-Site assessment. The conclusion in SR-Site, that the conversion factors are cautious, remains also when considering this additional information. In response to another request by SSM, a more comprehensive assessment of doses to non-human biota has been provided [9]. It is also noted that the biosphere assessments in support of SR-Site have been described in a series of papers in a special issue of Ambio [10].

Overall conclusion regarding the erosion/corrosion scenario: SKB concludes that the compliance case for the erosion/corrosion scenario in SR-Site represents a reasonable upper bound on the risk associated with this scenario, also when considering the additional information provided by SKB in SSM's review. The highest doses for this case occur at the end of the one million year assessment period and the margin to the stipulated risk limit is then about one order of magnitude.

V.B. The shear load scenario

In the shear load scenario, it is assessed to what extent canisters may fail due to shear movements in fractures intersecting the deposition hole, where the shear movements are caused by large earth quakes in major deformation zones in the vicinity of the repository. Also for this scenario canister failures could not be ruled out in the one million year assessment time in SR-Site and the scenario thus gave a contribution to the calculated risk. The risk assessment is based on *i*) the extent of shear movements that may occur in the deposition holes given the repository layout in relation to major deformation zones and given the selection rules applied for canister positions, and *ii*) the canisters' resilience to such shear movements. The design premise in SR-Site states that the canisters should withstand a 5 cm shear movement for the maximum allowed stiffness of the buffer and for a pessimistically estimated shear velocity.

Regarding the extent of shear movements exceeding 5 cm and the selection of deposition positions, a few clarifying responses have been given to issues raised by SSM. Regarding the canisters' resilience to shear movements, a number of issues have been raised regarding the underlying strength calculations and the manufacturing and control procedures that will ascertain that the design premises are met. Most of these have been responded to and SKB will also submit, as part of the on-going review, its plan for updating the design premises and the canister production and control program during the next phase of the repository program.

SKB's assessment of the risk associated with the shear load scenario is unaltered. Also this risk contribution reaches its maximum at the end of the one million year assessment time and the margin to the stipulated risk limit is then about two orders of magnitude.

V.C. The isostatic load scenario

In this scenario it is assessed whether canisters may fail due to isostatic loads. The highest isostatic loads are expected for glacial conditions, when an ice sheet covering the site may lead to a considerable increase in hydrostatic pressure at repository depth. This pressure, together with the swelling pressure of the bentonite buffer surrounding the canisters, will determine the isostatic load on the canisters. The canisters' resilience to isostatic loads will determine if failures occur and the conclusion in SR-Site was that such failures could be ruled out.

SSM has requested a more in-depth assessment of uncertainties related to the maximum expected thickness of an ice sheet that could cover the site. In response to this, SKB initiated a comprehensive climate and ice sheet modelling study at the Euro-Mediterranean Center on Climate Change, Bologna, Italy. The resulting maximum estimated future ice thickness at Forsmark, 3500 m [11], is slightly higher than the 3400 m estimated in SR-Site [1]. SSM has also requested additional information regarding the strength calculations that, together with manufacturing and control procedures, are used to argue that the canisters will withstand the design load. Refined 3D strength calculations have demonstrated that the 2D calculations used in SR-Site are pessimistic.

SKB's plan for updating the design premises and the canister production and control program during the next phase of the repository program, mentioned in the preceding section, will include also the isostatic load case.

SKB's conclusion in SR-Site, that no canisters are assessed to fail due to isostatic loads, is unaltered.

VI. SKB'S OVERALL CONCLUSION REGARDING LONG-TERM SAFETY

SKB's central conclusion of the safety assessment SR-Site is that a KBS-3 repository constructed at the Forsmark site in accordance with the design premises and other requirements as provided in the license application will fulfil all long-term safety requirements. According to SKB, this conclusion is not altered when taking the material in the supplementary information into account.

The risk contributing scenarios are the same as in SR-Site and only minor adjustments have been made to the calculated risks. An additional "what if" scenario, assessing the consequences of postulated criticality in the final repository has been analysed. The results show that the consequences are less than an order of magnitude higher than for the corresponding sub-critical situation.

It is noted *i*) that this paper is written in November 2014, when a few final review issues are yet to be responded to, *ii*) that the above discussion gives an account of what SKB sees as important review issues for long-term safety but that not all safety related issues brought up in SSM's review are discussed and *iii*) that the contents of this paper is consistent with the information provided by SKB to SSM during the course of the review but that SKB's statements in this paper do not supersede the more detailed discussions and conclusions in SKB's direct responses to SSM.

REFERENCES

All SKB reports are available at www.skb.se.

1. SKB, "Long-term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark. Main Report of the SR-Site Project", SKB Technical report TR-11-01 (2011).
2. G. HULTQUIST, M. J. GRAHAM, P. SZAKÁLOS, G. I. SPROULE, A. ROSENGREN and L. GRÅSJÖ, "Hydrogen gas production during corrosion of copper by water," *Corrosion Science* **53**, pp 310–319 (2011).
3. M. BOMAN, M. OTTOSSON, R. BERGER, Y. ANDERSSON, M. HAHLIN, F. BJÖREFORS and T. GUSTAFSSON, "Corrosion of copper in ultrapure water," SKB Report R-14-07 (2014).
4. A. BENGTSSON, A. CHUKHARKINA, L. ERIKSSON, B. HALLBECK, L. HALLBECK, J. JOHANSSON, L. JOHANSSON and K. PEDERSEN, "Development of a method for the study of H_2 gas emission in sealed compartments containing canister copper immersed in O_2-free water," SKB Technical report TR-13-13 (2013).
5. S. JOYCE, D. SWAN and L. HARTLEY, "Calculation of open repository inflows for Forsmark," SKB Report R-13-21 (2013).
6. S. JOYCE, H. WOLLARD and N. MARSIC, "Future evolution of groundwater composition at Forsmark during an extended temperate period," SKB Report R-14-26 (2014).
7. C. TAXÉN, B. SANDBERG and C. LILJA, "Possible influence from stray currents from high voltage DC power transmission on copper canisters," SKB Technical Report TR-14-15 (2014).
8. F. KING and C. LILJA, "Localised corrosion of copper canisters in bentonite pore water," SKB Technical report TR-13-27 (2013).
9. B. JAESCHKE, K. SMITH, S. NORDÉN and B. ALFONSO, "Assessment of risk to non-human biota from a repository for the disposal of spent nuclear fuel at Forsmark. Supplementary information," SKB Technical report TR-13-23 (2013).
10. U. KAUTSKY, T. LINDBORG AND J. VALENTIN(eds.), "Humans and Ecosystems Over the Coming Millennia: A Biosphere Assessment of Radioactive Waste Disposal in Sweden," *Ambio*, **42**(4) pp 381-526 (2013).
11. F. COLLEONI, C. WEKERLE and S. MASINA, "Long-term safety of a planned geological repository for spent nuclear fuel in Forsmark – estimate of maximum ice sheet thicknesses," SKB Technical Report TR-14-21 (2014).