SSM's Evaluation of the Long-Term Safety of the Proposed Repository for Spent Nuclear Fuel at the Forsmark Site in Sweden: Early Experiences from the Main Review Phase - 14555

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ABSTRACT

The Swedish Radiation Safety Authority (SSM) is currently reviewing the Swedish Nuclear Fuel and Waste Management Company's (SKB's) license application for the construction of a KBS-3 spent nuclear fuel repository at the Forsmark site in Sweden. In support of SSM's review of long-term safety SSM has engaged about 30 external experts or organizations to review different aspects of SKB's safety report. After having completed the initial review phase, SSM concluded that SKB's application and its supporting documents fulfilled the basic requirement related to comprehensiveness and overall quality. SSM therefore decided to move to the in-depth review of safety critical issues in the main review phase. This paper describes the early experiences from the main review phase including examples from the procedures of public procurement, methods for review issues identification and resolution, as well as the handling of a selection of technical review issues that have been identified during the initial review phase.

We focus on three critical failure modes that may result in breaching of the canister, namely corrosion failure, shear failure and isostatic collapse, which are reported in SKB's post-closure safety report. Examples of review issues that have been identified by SSM or SSM's external experts are provided for each of the three failure modes. We also describe the review handling of Features Events and Processes (FEPs) related to canister performance that SKB has screened out from detailed modelling treatment in SR-Site.

INTRODUCTION

The Swedish Radiation Safety Authority (SSM) is currently reviewing the license applications for construction of a KBS-3 spent nuclear fuel repository at the Forsmark site in Sweden and a plant for encapsulating spent fuel in copper canisters in Oskarshamn, which were submitted by the Swedish Nuclear Fuel and Waste Management Co (SKB) in March 2011. In parallel with SSM's licensing review, which is carried out according to the Swedish nuclear legislation, the Land and Environmental Court is conducting a review according to the environmental legislation. Both bodies will prepare a statement with a recommendation for a government decision. After having consulted the municipalities where the proposed facilities will be located (municipal veto applies), the government will eventually make a decision on SKB's applications.

The KBS-3 disposal method entails encapsulating the spent nuclear fuel in copper canisters with a cast-iron insert. The canisters will be disposed of at a depth of about 500 m in crystalline bedrock. Each canister will be surrounded by a buffer composed of compacted bentonite clay blocks and bentonite clay pellets. The deposition tunnels will be backfilled with compacted clay blocks and clay pellets. SKB's repository application comprises a top document and safety reports for operational and post-closure safety. The latter, referred to as SR-Site [1], is structured around SKB's 11 steps in their safety assessment and is supported by another 19 SKB technical reports. The SSM's method of reviewing repository post-closure safety together with a discussion of selected technical review issues are provided in the subsequent text.

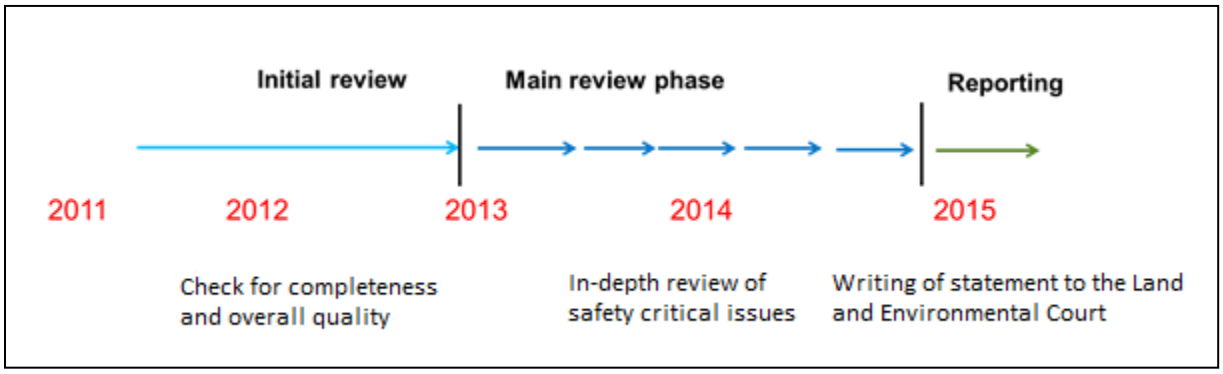

Fig.1. Phases of SSM's licensing review.

SSM'S INITIAL REVIEW PHASE

SSM's licensing review is divided into three phases: the initial review phase (IRP), the main review phase and the associated reporting phase (see Figure 1). The IRP started with SKB's submission of their construction license applications in March 2011 and was completed at the end of 2012.

The initial review comprised: (1) an assessment of the overall quality of SKB's license applications, (2) identification of safety critical review issues and (3) identification of the need for complementary information. Specific activities included:

- Public procurement of external experts
- First broad review of SR-Site and supporting references
- First round of SSM's independent modeling, focusing on reproduction of SKB's consequence analysis calculations
- First round of a national consultation of SKB's license applications
- Conduct of an international peer review of SKB's license application organized by OECD's Nuclear Energy Agency [2]
- Development of Requests for Complementary Information (RCIs)
- Development of a statement to the Land and Environmental Court [3] concerning the completeness of SKB's application.

In support of SSM's review of long-term safety SSM has engaged almost 30 external experts or organizations to review different aspects of SKB's safety report. After having completed the initial review phase, SSM concluded that SKB's application and its supporting documents fulfilled basic requirement related to comprehensiveness and overall quality. SSM therefore decided to move to the in-depth review of safety critical issues in the main review phase. All external expert assessments from the initial review phase have been published as Technical Notes on SSM's webpage (the views in these reports represent those of the external experts). Each Technical Note covers a specified area of the safety assessment with focus on for instance missing pieces of information, adequacy of model and data set descriptions, scientific support and justifications, coverage of uncertainties, safety assessment relevance and strategies as well as engineering feasibility.

EXPERIENCE FROM USING PUBLIC PROCUREMENT

The basic conduct of SSM's public procurement of external experts for the licensing review has previously been reported [4].

During the pre-licensing phases of the Swedish repository program external expert support was procured using single-tender procedures. However, the start of a formal review of a license application made it necessary to fully adopt the Swedish legal requirements on competitive bidding and public procurement of SSM's external expert support. This represents a major change of the conditions for SSM's licensing review because almost one half of SSM's total review capacity can be attributed to the external experts.

The use of public procurement contributes to openness since anyone can participate in the tendering for framework agreements. Selection of suppliers depends strictly on the fulfillment of competence requirements and cost, and not on previous assignments for the authority. The consistent application of strictly defined impartiality requirements has been a necessary and useful basis for this procedure especially given the sensitive nature of the license application. SSM has also through the public procurement procedure been able to identify new experts not previously engaged by the authority, which has meant that a number of new ideas and review perspectives have been introduced compared to the pre-licensing stage. The majority of framework agreements involve renewed competition for a specific review assignment. The competition between, in most cases, three independent suppliers means that SSM is not as previously dependent on a single supplier.

On the negative side, the use of public procurement is rather inflexible both for SSM and for the different suppliers. The fixed definition of a review assignment prior to any communication with the suppliers means that for instance a pre-defined time constraint may prevent highly qualified experts from participating. Each tendering based on renewed competition requires several different time consuming steps such as specification of the assignment, publication of invitation to submit tenders, evaluation of incoming tenders, notification of awards, development and execution of supply agreements and the handling of possible appeals against SSM decisions made to the County Administrative Court. As a result the pace of the review becomes relatively slow. Another experience related to the formalistic approach is less contact between SSM and SSM's external experts regarding scientific and technical details during the course of review work. SSM needs to evaluate the experiences so far such that these difficulties with public procurement are mitigated in the future.

ISSUES RESOLUTION DURING THE MAIN REVIEW PHASE

New Assignments and Modeling Work during Main Review Phase

The main review phase started with the formulation of about 30 new external review assignments related to issues that were judged by the SSM staff to require further assessment. While the review assignments in the initial review phase broadly covered a particular area with a possibility for the external reviewers to themselves identify important new issues, the review assignments of the main review phase are specified to a greater extent. The results of these assignments will also be published in SSM's report series.

The independent modeling by SSM's staff and by external experts has continued during the main review phase, now with focus on exploring the safety significance of certain barrier functions and conceptual assumptions made by SKB in their safety case. The accompanying paper by Xu et al. [5] provides more detail concerning SSM's independent modelling in support of the licensing review.

Requests for Complementary Information

Currently about 60 RCIs have been submitted to SKB. The different requests vary considerably in scope. While the purpose of some are just minor clarification related to SKB's reporting, others include multiple review issues within a review area being addressed with for instance new literature studies or calculation cases, or even in a few cases related to the copper canister new research. SKB has by the end of 2013 responded to almost all the requests for complementary information but some supporting documents are still missing. All submitted requests for complementary information along with responses from SKB are published on SSM's webpage (most information only available in Swedish).

After having reviewed all the responses from SKB along with reporting from all outstanding external review assignments, SSM may need to submit additional requests for complementary information during the early part of 2014. Although it cannot completely be ruled out that significant entirely new review issues will emerge during this late stage, most probably the new requests for complementary information will be narrowly defined aiming at clarification of previously submitted information. There is a limit beyond which the procedure of requesting complementary information becomes tedious and complicated, e.g. due to overlap between different requests for complementary information submitted during the various stages of the review. If problems in interpreting a particular part of the safety assessment remain after having received written responses from SKB, another option is to organize direct meetings between SSM and SKB staff. This option has so far been utilized in the canister and biosphere review areas. Meeting notes are provided by SSM to ensure traceability.

Issue Classification and Workshops

SSM early on adopted a review issue database based on review experiences prior to the licensing review. It turned out that this review issue database was too extensive and elaborate to guide practical review work. It is presently not used but it may fulfill a limited purpose as a completeness check in the writing up of SSM's final review report. SSM has recently developed a new much smaller and simpler review issue database based on a simple issue classification system for internal prioritization and issue resolution during the compliance evaluation. Each SSM reviewer has the possibility to propose review issues within following categories:

- Red issues - can alone determine the outcome of SSM's compliance evaluation
- Yellow issues – can together with other issues determine the outcome of SSM's compliance evaluation
- Green issues – issues judged not to be critical for compliance evaluation but may be of delicate character for other reasons

If a reviewer wishes to suggest that a review issue will be of importance in the context of the compliance evaluation, he/she first need to consult with the other members of SSM's internal review group. Some review issues which are originally proposed to be red may be graded down as yellow or green after a broader consideration of their safety context. All issues cannot reasonably be of equal importance. Red issues require after the first consultation with the colleagues in the review group further treatment and dialogue with SSM's management. In order to limit the size of the database, all remaining review issue not considered to be of importance in the above mentioned contexts are only addressed by the SSM reviewers themselves within their respective review area and not in the review issue database.

Even if SSM has only recently adopted this review tool, it can be concluded that it is helpful tool for establishing a joint SSM position and for forming an overview of the current status of the review. SSM will not publish any grading of review issues because such grading is expected to gradually change as a result of new information or an evolving understanding of a particular issue. Ultimately, SSM's viewpoint

about the various review issues will be reflected in the licensing review report addressing repository long-term safety.

As a basis for forming an opinion about the sufficiency of SKB's reporting in a particular area, SSM has conducted a series of workshops with external experts during 2013. The objective was to facilitate multidisciplinary discussions among experts covering different but related disciplines of importance for a particular part of the safety assessment. The following workshops have been held so far:

- Repository post-closure seismic risk analysis with coverage of mechanisms involved in earthquakes and their rock mechanical responses
- Canister corrosion rate caused by general copper corrosion with coverage of groundwater chemistry, mass transport and hydrogeology (localized corrosion was not being addressed since some of the outstanding requests for complementary information were regarded as necessary for continued review)
- Rock damage with coverage of rock mechanics, rock engineering including coupling to hydrogeology
- Biosphere analysis
- Selection of scenarios and completeness of the SR-Site

In addition to the workshops conducted with external experts, SSM has also organized an internal meeting series to facilitate SSM's compliance evaluation. The issue classification system described above has been implemented during these meetings. The meetings have followed a scheme mainly based on the different time scales of the safety assessment rather than different subject areas. This is because the regulatory requirements differ for different time periods with more stringent requirements for early periods compared to the more distant time scales [6, 7]. The meetings covered repository and site evolution during the first 1000 years, repository and site evolution up to 100 000 years, repository and site evolution after 100 000 years and repository consequence analysis. Other meetings have covered SKB's site selection and SKB's selection of the KBS-3 concept as a disposal method.

TECHNICAL ISSUES DISCUSSED IN SSM'S COMPLIANCE EVALUATION

The following is a brief discussion of review work related failure modes of the copper canister that are directly related to the containment safety function used in SR-Site. This discussion addresses issues of relevance for evaluating compliance with SSM's risk criterion for long term repository safety as key requirement in the applicable regulations and guidelines [6, 7]. The risk criterion states that the repository shall be designed so that the annual risk of harmful effects does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk [7]. The analyzed Features, Events and Processes (FEPs) vary in safety significance and range from next to certain during the course of repository evolution to very improbable. They are therefore addressed with varying level of detail. No definitive conclusions can be drawn from the examples reported here since they are still subject to further review work. Review work related to the buffer failure modes, geosphere performance, and climate evolution has been carried out by SSM but is essentially not reported here.

Corrosion/Erosion Failure Mode

The corrosion/erosion failure mode of copper canisters is covered in SKB's main risk contributing scenario in SR-Site [1]. SKB expects that a number of high-flow deposition holes far into the future will be subjected to groundwater with very low salinity (cationic strength < 4 mM) in connection with a glaciation. Bentonite colloids are stable under such groundwater conditions and can be transported away in fractures cross-cutting the deposition holes [8]. Figure 2 shows how the resulting loss of buffer material may create buffer cavities in a small fraction of the deposition holes such that copper surfaces are directly exposed to flowing groundwater [9]. In the deposition holes with the highest flow rates and the highest

sulphide content, complete failure of the copper shell may occur due to general corrosion by sulphide ions in the groundwater.

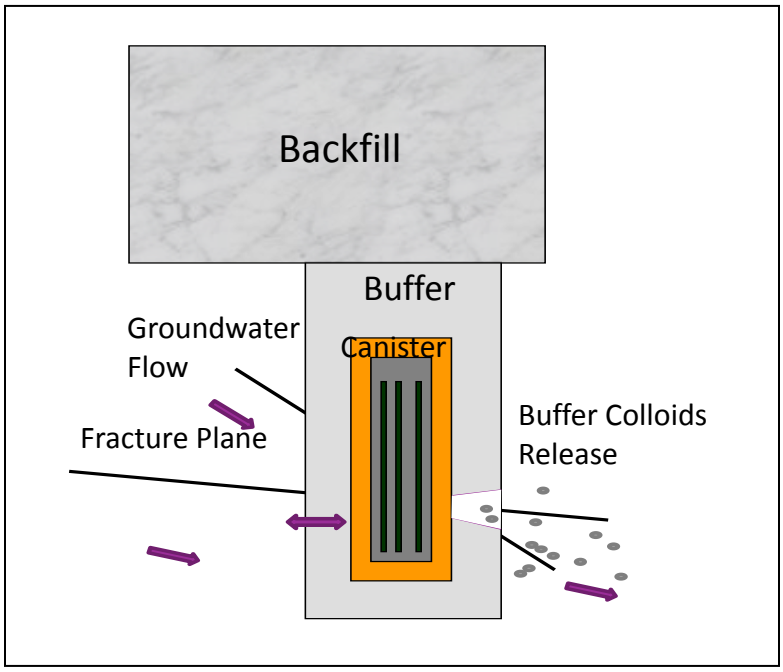

Fig. 2. Conceptual model for a KBS-3 deposition hole affected by a buffer erosion cavity in which more rapid corrosion of copper takes place

Examples of review issues related to this scenario that have been discussed by SSM or SSM's external consultants [10-15] are:

- The corrosion rate assessment is based on the long-term flow rate distribution for deposition hole positions. The comprehensive DFN modeling work established for addressing flow rate distribution involve various conceptual and data uncertainties [16]. SKB has addressed this issue through propagation of uncertainties to calculation of risk. Nevertheless, because of the key role of DFN modelling, the uncertainties are further addressed in SSM's main review phase using independent modelling, requests for complementary information and review of SKB's quality assurance used throughout modelling work.
- SKB's conclusion that only a very limited number of deposition holes will ever be subjected to buffer erosion chemical conditions is a safety argument related to groundwater chemistry which is scrutinized in SSM's review. SKB's analysis starts from the measured initial groundwater salinity distribution at Forsmark including matrix pore water composition. The predictions of groundwater chemistry evolution at the Forsmark site [17] also utilize the results from the groundwater flow modeling. The prediction of buffer erosion rate once it has been initiated [8] has a lower overall influence on the risk since only a small fraction of deposition holes are at all affected by erosion of the buffer. Although canisters will be more vulnerable in deposition holes affected by buffer erosion, SKB expects that they will still contribute essentially to long-term safety.
- SKB uses a distribution of measured sulphide concentrations at the Forsmark site for calculating corrosion rates for canisters in deposition holes subjected to buffer erosion assuming that these concentrations will remain the same far into the distant future [9]. SSM's review has so far

covered SKB's procedure for selecting and using representative sulphide concentration values. The possibility of additional sulphide being generated by microbial sulfate reduction has been identified as a request for complementary information. The possible microbial contribution to additional sulphide depends on viability and concentration of different substrates that can contribute to microbial activity. Furthermore, the access to ferrous iron may be another limiting factor considering the precipitation of iron sulphide (FeS(s)). Of importance is also whether microbial sulfate reduction would occur in the general bedrock volume surrounding the repository (benign case) or if the reaction would occur directly at the exposed copper surfaces (worst case).

- The computation of canister failure time also relies on the assessment of the fraction of the copper canister area that is being subjected to direct contact with groundwater (the height of the affected canister area is assumed to be equal to the buffer thickness). If the area of corrosion attack is smaller, copper corrosion rates may be higher provided that the transport rate of sulphide remain similar.

The contribution of risk from SKB's formulation of the corrosion/erosion scenario is solely due to the erosion failure mode of the buffer. SKB suggests that there are significant margins to the corrosion canister failure limit for a canister in a deposition hole with an intact buffer [9]. The risk associated with this scenario is partially amenable to design measures. A potentially efficient option is to avoid high groundwater flow positions in the bedrock by appropriate selection of deposition hole positions. Adjustment of the reference copper shell thickness of 5 cm is much less effective [1]. In spite of this, some degree of uncertainty is likely to persist since critical features of this scenario can only be expected to be broadly predictable, for example the future evolution of groundwater chemistry and availability of corroding species in the groundwater far into the future. SKB acknowledges a potential role for deposition hole rejection criterion related to this failure mode but more work is needed to devise measures that can be implemented in practice [1]. If buffer erosion could be eliminated from safety assessment consideration by additional research or design modification, the risk associated with this specific scenario formulation is also eliminated (other corrosion mechanism is dealt with in the section Screened Out Features Events and Processes).

Shear Loading or Seismic Hazard Failure Mode

The shear loading scenario is the only other scenario that directly contributes to risk in SKB's compliance demonstration and it is the second failure mode of SKB's copper canisters. This scenario is initiated by a magnitude 5 earthquake or larger in the vicinity of the repository area [1]. SKB's scenario analysis is based on earthquake frequency estimates that are assumed to apply for the safety assessment time period of 10^6 years.

A number of deformation zones in the Forsmark area capable of hosting major earthquakes have been identified, and rapid earthquake movement in those zones may propagate into movement in fractures that cut across deposition holes. SKB used a rock mechanics approach to trace the displacement magnitude from the primary fault movement to individual fractures that may be critical in relation to deposition hole locations [18]. The calculated shear slip magnitudes for the deposition holes are compared with the criterion for canister failure currently set at 5 cm [1]. Modelling of canister deformation in response to shear loading suggests that the 5 cm shear slip or larger may result in canister failure [19]. Key elements in SKB's strategy to minimize seismic hazard include totally avoiding the area near deformation zones by applying a respect distance of 100 m, and by applying deposition hole rejection criteria to avoid large fractures in the rest of the bedrock volume [20]. Detailed requirements related to manufacturing of the inserts are needed to ensure the required mechanical performance of the canister for shear loading conditions [21].

Extension of pre-existing fractures in critical positions could in theory gradually increase deposition hole fracture intersection with time, but SKB rules out this case as marginal since the slip magnitude can be

expected to be small near the tip of such a fracture. SKB accounts for the possibility of repeated earthquakes, but since stress relaxation occurs during the first earthquake, an account has to be made of a long period needed to restore the stress field for a repeated earthquake to occur [1].

Examples of review issues related to this scenario which have been discussed by SSM or SSM's external consultants [22-25] are:

- There are uncertainties associated with the selection of earthquake probability. These involve the approach for scaling down of seismicity to a small area around the repository (5 km diameter). Identification of potentially instable fault zones is related to the conceptual understanding of the background stress state in the bedrock. One reviewer addressed "distributed faulting" which would involve simultaneous displacement on various faults some distance from the primary fault [25]. This could possibly extend the proposed earthquake affected radius.
- Uncertainties may also exist that are related to the possibility to locate deposition holes in positions of the bedrock that will remain essentially unaffected by future earthquakes. SKB suggests that deterministic faults have been identified during site characterization work and that almost all stochastic target fractures of sufficient size can be identified during a future repository construction. However, consideration of a hypothetical undetected "blind" fault affecting repository performance has been proposed during SSM's review [22].
- There may also be an uncertainty in the capacity of a canister to withstand shear movement associated with large earthquakes. For this loading case, insert defects in the size range of several mm are probably of importance. The reliability for detection of such defects with non-destructive testing methods needs to be determined. Detection of realistic rather than idealized types of defects is ultimately needed. In addition, the reliance of the load bearing capacity of the insert is more uncertain if shear movement across canisters occur very near the top or the bottom.
- Cementation of buffer material next to the canister surface may reduce the capacity of the buffer to damp shear movement. Modelling work during the earlier SR-Can safety assessment suggested that the influence is modest if cementation is restricted to the buffer part closest to the canister.

The risk contribution from this scenario can to some extent be influenced by design measures and quality control of the engineered barriers as well as by adjustment of the deposition hole locations based on further information about near-field rock conditions. Further rock characterization work during repository construction is the main expected source of such information. In spite of all reasonable efforts some risk contribution is likely to be unavoidable given the inherent uncertainties associated with prediction of large earthquakes far into the future and given the circumstance that complete knowledge of all relevant features in the rock would be extremely difficult to achieve in practice.

Failure Mode for Isostatic Loading Of Canisters

The copper canisters will be subjected to an external isostatic load comprised of the combined hydrostatic pressure at repository depth and by the swelling pressure exerted by the bentonite buffer. This is the third of the canister failure modes addressed in SKB's SR-Site [1]. As opposed to the other two, the isostatic failure mode is ruled out and provides no risk contribution. If the external pressure exceeds the load bearing capacity of the canister a so called isostatic collapse may occur during which the capacity to isolate the spent nuclear fuel is lost. In the design basis for the canister account must be made for the future occurrence of glacial conditions that may substantially increase the isostatic loading. In the most conservative case, it is assumed that all the weight of the full 3 km ice thickness must be added to the weight of the water pillar in the bedrock. The canister must thus withstand an external pressure of about 44 MPa (5 MPa hydrostatic + 13 MPa buffer swelling pressure + 26 MPa from ice load; [1]). SKB concluded that both laboratory tests and numerical modeling suggest that global isostatic collapse is not expected to occur below external pressures of 90 MPa [26], i.e. a considerable safety margin in relation to

relevant external pressures. However, the margin is much smaller in relation to what is called local collapse which is SKB's design requirement.

Examples of review issues related to this scenario which has been discussed by SSM or SSM's external consultants [27-28] are:

- Creep ductility of the copper should be sufficient for deformation of the copper shell due to the developing buffer swelling pressure and the restoration of the hydrostatic pressure at repository depth. Although experimental evidence confirms a short-term favorable performance of phosphorous doped OFP copper, issues have been raised regarding the understanding of the role of phosphorous in providing the favorable long-term creep properties of copper and the long-term preservation of these favorable material characteristics of OFP copper [27].
- Mechanisms related to embrittlement of copper may influence long-term mechanical properties of the canisters, e.g. creep properties described above. Hydrogen formed during the corrosion of copper may be introduced into the metal and may directly affect its mechanical properties. The introduction of copper oxides in the weld area of the canisters is also relevant in this context since these oxides may form water by reaction with corrosion generated hydrogen [29].
- Integrity of the copper shell may be vulnerable after periods of extensive corrosion. The resilience to high isostatic loading of a very thin remainder of a copper shell extensively affected by corrosion may be uncertain.

All canisters will be exposed to reasonably similar and well defined isostatic loading conditions and considerable efforts are therefore warranted to ensure reliable and robust performance of the canisters under these circumstances. The design of the canisters would have to be modified if extensive failures were to be predicted. However, SKB concludes that no canister failures are expected provided that all manufactured canisters meet the required design specifications. This put high demands on the reliability of manufacturing and non-destructive testing procedures.

Screened Out Features, Events and Processes

SKB's coupled containment and consequence analysis is focused around a limited number of Features Events and Processes (FEPs) that are judged to be most important for the isolation of the spent nuclear fuel. However, there is a range of other FEPs that could conceivably affect the isolation function in various time scales. SKB's treatment of FEPs that subsequently were ruled out from the consequence analysis varies from the use of comprehensive experimental investigations and detailed mathematical modelling such as those used in the isostatic loading scenario above to the use of simple scooping calculations or use of screening arguments. SSM's experience is that the review of screening arguments may be difficult due to their on-off character. The arguments may be correct and then there is no safety implication, but it may be difficult to determine if there is a sufficient basis for the arguments and/or if any deviation would result in marginal or considerable consequences. SSM has so far mainly addressed such instances by developing a number of requests for complementary information.

Examples of review issues related to such FEPs, which have been discussed by SSM or SSM's external consultants, are:

- SKB has ruled out the possibility for canisters to be initially defective with a breached isolation of the copper shell resulting from errors in the manufacturing process.
- Stress corrosion cracking of copper canister could occur due to the presence of sulphide during the long anoxic period following consumption of all initially present oxygen [31]. Experiments have also been conducted showing that sulphide may diffuse into the grain boundaries of copper and affect canister properties [32, 33]. SKB ruled out this process on the basis that experimental sulphide concentrations were much higher than what could be expected in groundwater [34]. It

was also suggested that the interfacial sulphide at the canister surface should be very low or close to zero due to mass transfer limited corrosion [35]. Further investigation of this phenomenon has been proposed [29].

- Pitting corrosion of copper is known to occur under certain conditions and could in principle be an important corrosion process since significant damage on the copper canister would not necessarily be related to large accumulated mass transfer across the buffer. SKB rules out this process on the basis that pitting depends on access to O_2 or Cu(II), which is not expected in the reducing repository environment [34]. Further assessment based on coverage of all feasible groundwater chemical conditions and possibly the use of probabilistic approaches has been recommended [30].
- Anoxic corrosion of copper under hydrogen evolution in pure water is a mechanism which has been proposed and experimentally investigated by Szakalos et al. [36]. This process could occur alone or at least in theory in combination with microbial consumption of generated hydrogen and/or presence of high groundwater chloride content which may affect the corrosion scenario. SKB suggests that the influence of this process (if shown to be persistent in the repository environment) is small since transport of generated hydrogen away from the canister will be slow [9]. The partial equilibrium pressure of hydrogen for this corrosion reaction uncertain but has been proposed to about 1 mbar [36]. A more detailed assessment of this reaction involving derivation of further experimental data especially under saline conditions has been proposed [29].
- Corrosion of copper may also occur under unsaturated conditions in the buffer during the resaturation periods extending up to several thousands of years. During unsaturated conditions reactive gaseous species such as hydrogen, methane or hydrogen sulphide gas may influence microbial reactions in the buffer and possibly the corrosion processes at the canister surface. An accumulation of salts near the canister surface due to drying has also been proposed as a corrosion relevant influence on the local chemical conditions near the canister surface [29].

It should be mentioned that SKB has accounted for the possibility that an unknown process could disrupt the performance of the buffers, the canisters or both. This has been achieved through the inclusion of what-if consequence calculations in SR-Site [37]. For instance the first bullet in the list above is captured quite well by the pin-hole what-if calculation cases. There is also another case illustrating severe damage to the copper canisters which would resemble the isostatic collapse case. This case is also combined with complete loss of the buffer. The what-if calculations are used for illustrative purposes however, and are not accounted for in the quantification of post-closure risk.

Consequence Analysis

SKB has based the consequence analysis in SR-Site on the outcome of the containment analysis [1]. A consequence of the three different failure modes of the copper canisters described above is that the conditions for radionuclide release and transport are different [37]. For the corrosion scenario, the assumed erosion of the buffer material means that radionuclides will not be retarded by the buffer after being released from a corrosion damaged canister. Since the ability of the buffer to filter radionuclide colloids is also lost, solubility limits for radionuclides are not accounted for in calculation cases involving substantial loss of buffer mass. In the shear loading scenario, a slip has occurred across a deposition hole and a reduced buffer thickness is thus assumed. The reactivation of a large fracture during the shearing event means that the geosphere retardation performance is assumed to be lost for this scenario. For the scenario involving failure due to isostatic loading of copper canisters, the retardation performance of buffer and geosphere are not affected. The discussion of review issues related to the consequence analysis is beyond the scope of this paper. Xu et al. [5] provide a review of a number of consequence analysis cases based on an independent reproduction of key SKB results.

CONCLUSION AND DISCUSSION

This paper mainly focuses on the SSM's handling of review issues related to the integrity of copper canisters in the KBS-3 spent nuclear fuel disposal concept and the three analyzed canister failure modes in the SKB's SR-Site report [1]. The reason for this perspective is that SKB's results in SR-Site suggest that the copper canister will with high probability inhibit radionuclide releases within the full safety assessment time scale of 10^6 years. SR-Site only generates fractional canister failures during this period with failures occurring far into the future. Review assignments for a detailed assessment of this outcome have been initiated. Secondly, SSM's regulatory requirements suggest that uncertainties shall reported more in detail during the first 1000 years in relation to the remaining longer time frame addressed in the safety assessment [7]. The occurrence of significant radiological consequences during this early time frame would suggest that SKB's handling of canister FEPs potentially leading to early canister failure is lacking. The review handling such FEPs is briefly described in this paper.

The reliance on the copper canister in SR-Site is not solely related to the properties of the canister itself, but also to the tight rock conditions at the Forsmark site. SKB expects that the vast majority of copper canisters will be exposed to very limited groundwater flow and small accumulated mass-exchange between the surrounding groundwater and the corroding copper canisters even in the extremely long time scale. The basic property of limited flow is also used for treatment of other safety relevant issues such as the possibility of "piping/erosion" of buffer materials during the repository construction phase [1]. The third main barrier in the KBS-3 concept, the buffer, has a less obvious role in the compliance demonstration (since compliance is claimed without considering the mass transfer resistance of the buffer). Nevertheless, the buffer adds robustness through its safety functions related to canister performance and contributions to radionuclide retardation in case of canister failure.

The result presented here are very preliminary since review work is still ongoing. The status of the various review issues is gradually changing as a result of SSM's own review work, review results from SSM's external experts, and complementary information from SKB. SSM will also carry out a second broad national consultation before completion of the review which can be expected to generate further review issues for detailed consideration. So far Features Events and Processes (FEPs) that SKB has screened out from detailed modelling treatment in the SR-Site safety assessment have generated a substantial number of review issues, in addition to the review issues that are related to FEPs that are more explicitly dealt with in the SR-Site. This does not necessarily mean that such FEPs in the end will turn out to be essential for the final outcome of the review, but a substantial amount of review work is needed to address them.

Regarding the efficiency of SSM's licensing review, the use of a simple and practical system for identification and tracking of the key review issues has been shown to be important for the compliance discussion. Knowledge and reasonable agreement of what constitutes key issues in the compliance evaluation is needed for planning purposes and ultimately to be able to conclude the licensing review. It is easy to adopt a too complicated approach at the onset which may turn out to be very difficult and time consuming to follow. Another lesson learned is that public procurement requires unexpectedly large staff resources in all stages from invitations to submit tenders for framework agreement, to the handling of contracts and call-offs, and to the publication of reports. Public procurement is a legal requirement through a directive in the European Union and this must be accounted for in resource and time planning. Another potentially time consuming and difficult issue is determining whether anything less than a definitive resolution of a review issue as a result of requests for complementary information is sufficient. For certain types of issues definitive resolution are extremely hard to achieve and may not be needed. This in turn requires thorough discussion among staff members of the detailed implementation of regulatory requirements to ensure coherency of the review and consistency across all disciplines.

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