A STRUCTURED APPROACH TO INDEPENDENT MODELLING IN SUPPORT OF A LICENSING REVIEW

Shulan Xu[1], Björn Dverstorp[1], Georg Lindgren[1], Maria Nordén[1] and Klaus-Jürgen Röhlig[2]

[1] Swedish Radiation Safety Authority (SSM), SE-17116 Stockholm, Sweden
[2] Clausthal University of Technology, Germany
shulan.xu@ssm.se, bjorn.dverstorp@ssm.se, georg.lindgren@ssm.se, maria.norden@ssm.se, klaus.roehlig@tu-clausthal.de

This paper describes the use of independent modelling in support of a licensing review of a deep geological repository for spent nuclear fuel. The modelling focusses on the consequence analysis but, based on the experiences gained from this study and earlier modelling work, we propose an integrated modelling approach that may be applied also to the regulatory review of other parts of the post-closure safety assessment.

I. INTRODUCTION

In 2011 the Swedish Nuclear Fuel & Waste Management Co. (SKB) submitted a license application for construction of a geological repository for spent nuclear fuel according to the KBS-3 disposal method. The KBS-3 method involves disposing of the spent fuel in cast iron canisters with an outer layer of 5 cm copper. The canisters will be deposited in vertical deposition holes at approximately 500 m depths in crystalline bedrock. Each canister is surrounded by a buffer of swelling bentonite clay. The license application is supported by a post-closure safety assessment; SR-Site.[1] Together with other parts of the application, SR-Site is currently being reviewed by the Swedish Radiation Safety Authority (SSM). SSM has divided the review of SKB's license application into three phases; the initial review phase with a broad review of the completeness and overall quality of SKB's application, the main review phase with in-depth review of safety critical review issues and finally, the reporting phase. SSM is currently resolving review issues in the main review phase.

The review of SR-Site is a challenging task due to its broad scope, complexity and multidisciplinary nature. The main method for review of SKB's license application is document review, which is carried out by SSM's staff and supported by SSM's external experts. However, SSM's document review is also supported by regulatory modelling. Experiences from regulatory review of SKB's earlier safety assessments have shown that independent modelling provides valuable insight and understanding of the methodology and calculations presented by the applicant.

This paper describes the regulatory modelling carried out in support of the review of SKB's consequence analysis in SR-Site. In Section II we describe SKB's methodology for consequence analysis. In Section III we start by proposing an integrated modelling approach for independent modelling. Next we describe the application of this approach to the regulatory review of SR-Site. In SR-Site two scenarios leading to canister failure could not be ruled out by SKB, namely canister failure due to corrosion and due to shear load. This paper focusses on the corrosion scenario.

II. SKB'S CONSEQUENCE ANALYSIS

II.A. Modelling chain for consequence analysis

SKB's modelling chain for consequence analysis is shown in Fig. 1, modified from the main SR-Site report.[1] The models used for consequence analysis in SR-Site include three parts: models for radionuclide transport in the near-field, in the far-field and models for radionuclide transport in the biosphere and dose calculations. In addition there are a number of more or less detailed models (e.g. process models providing input for the consequence calculations) and other information needed for describing the system evolution and developing scenarios as indicated in the figure.

SKB's derivation of the mean number of canister failures for the corrosion scenario is based on models for buffer erosion and copper corrosion. The main corrosion reaction that can occur on the copper in the repository environment is by sulphide when the buffer is severely eroded.[2] An empirical model[3] is used to describe the buffer erosion rate as a function of the flow rate and fracture aperture. The corrosion rate is described by a simple mass balance model between the corrodant (sulphide in this case) and the corrosion product.[2] Once the buffer erosion and corrosion rates are known the canister failure time can be calculated simply as the sum of the time to reach advective conditions in a deposition hole and the the time of penetration of copper by corrosion. Further, the mean number of failed canisters is obtained by considering the only combinations of flow rate (i.e. deposition hole) and sulphide concentration for which a failure occurs within the assessment timeframe: i) the equivalent flow rates in the 6,000 deposition holes, and ii) the 46 sulphide concentrations measured in the groundwater at the Forsmark site.

Radionuclide transport in the near-field is modelled with the compartment model COMP23 (Ref. 4) that models processes related to radionuclide release and transport in the canister interior, the bentonite buffer and in the deposition tunnel backfill. SKB uses the FARF31 (Refs. 5,6) and the MARFA[7] codes for far-field transport calculations. The two codes solve radionuclide transport along one-dimensional flow paths and handle advection, dispersion, matrix diffusion with equilibrium linear sorption to the rock, and radioactive decay as part of the transport of radionuclides in the water phase. In SR-Site FARF31 is the main tool for consequence analysis. MARFA has some functions that FARF31 does not have, such as to handle calculations with unsteady flow caused by climate evolution and colloid transport. In addition to the numerical transport codes SKB used a simplified analytical transport model[8] for the near- and far-field for benchmarking against the numerical codes.

A new so-called Radionuclide Model is used to describe the distribution of radionuclides in the environment whereby radionuclide releases to distinct hydrological basins/sub-catchments (termed 'objects') are represented.[9] The Radionuclide Model has a general form to describe all kinds of biosphere objects, and consists of two parts, an aquatic and a terrestrial part described by a number of traditional compartments. A set of landscape evolution models[10] is used to describe how the size and properties of each biosphere object evolves with time. Most biosphere objects are expected to undergo four main stages: a marine, a transitional, a lake and a terrestrial stage. The biosphere at the repository site at Forsmark is represented by a number of hydrologically interconnected biosphere objects. The end product of the dose calculations with the Radionuclide Model is a set of Landscape Dose conversion Factors (LDFs). An LDF value is defined as annual dose for a representative individual in the most exposed group at a constant discharge rate of 1 Bq/year for each radionuclide and biosphere object. The Radionuclide Model is used to calculate how the LDF values evolve with time for each biosphere object as a result of an evolving temperate climate state (up to 10 000 years into the future). For the consequence analysis in SR-site the maximum radionuclide-specific LDF value, across all biosphere objects and over the whole simulation period, was selected and is called a basic LDF. The basic LDF is only used for single canister release calculations. LDF values were also calculated for other climate states including permafrost and glacial conditions, but these all resulted in lower LDF values. In addition, two types of modified LDF have been derived: i) a LDF for pulse releases (pulse LDF) that is applicable to a radionuclide release that reaches the biosphere in a pulse within a time period of years to hundreds of years, ii) a LDF for releases distributed to several biosphere objects (distributed LDF) that is applicable to several sources that have continuous long-term releases with constant rates to the biosphere in different objects. Hereafter, the Radionuclide Model is simply referred to as the LDF model.

Finally, doses for any given scenario are estimated by multiplying the modelled release rates from the geosphere with the radionuclide specific LDF values.

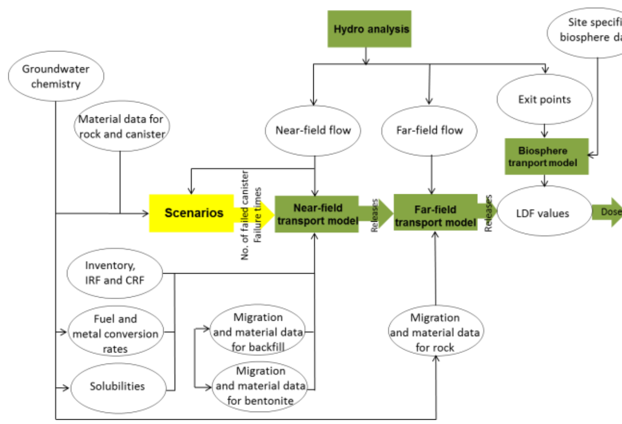

Fig. 1 Models and data for the consequence calculations (Modified based on SKB, Ref. 1).

II.B. SKB's uncertainty and sensitivity analysis

II.B.1. The Corrosion Scenario

The uncertainty and sensitivity analysis for the corrosion scenario was a combination of deterministic and stochastic calculations. Uncertainty of flow rates modelled by hydrogeological Discrete Fracture Network (DFN) models were evaluated by considering three variants of models: uncorrelated, semi-correlated and fully correlated in the relation between fracture size and transmissivity. Moreover, several realizations of the underlying DFN model were generated for each model variant. Uncertainties of buffer density were evaluated by three deterministic cases, the base case with SR-Site erosion model[3], and the two bounding cases of initial advection in all deposition holes and no advection throughout the assessment period. The bounding case where initial advective conditions occur in every deposition hole is deemed unrealistic, but was included to illustrate the impact of the uncertainties covered by this case. Uncertainty of the corrosion model was not evaluated except for some deterministic sensitivity analyses concerning a pessimistic corrosion geometry and twice the highest sulphide concentration (see Ref. 2). Fig. 2 shows the uncertainties of the calculated mean number of failed canisters for the corrosion scenario considering the three identified cases.

The case with the semi-correlated hydrogeological DFN variant combined with the SR-Site model for buffer erosion is known as a central corrosion variant.

Hydrogeological DFN model		Mean number of advectice positions (at 10^5 yrs)	(at 10^6 yrs)	Mean number of failed canisters (at 10^5 yrs)	(at 10^6 yrs)
Uncorrelated	Initial advection	(6000)	6000	(0.055)	1.2
	SR-Site erosion model	(1.2)	280	(0.004)	0.65
	No advection	(0)	0	(0)	0
Semicorrelated	Initial advection	(6000)	6000	(0.013)	0.18
	SR-Site erosion model	(0.6)	19	(0)	0.12
	No advection	(0)	0	(0)	0
Fully correlated	Initial advection	(6000)	6000	(0.043)	0.86
	SR-Site erosion model	(1.2)	68	(0.005)	0.57
	No advection	(0)	0	(0)	0

Fig. 2 Mean number of advective deposition positions and mean number of failed canisters for the calculation cases identified as relevant for the corrosion scenario (After SKB, figure 12-18 in Ref.1).

II.B.2. Biosphere dose assessment

The uncertainties related to the biosphere assessment have been classified into three types: i) System uncertainties due to inability to make accurate predictions of the long-term development of the biosphere and the future use of the biosphere by humans, ii) Model uncertainties due to imperfect knowledge of the processes affecting the behaviour of radionuclides in the biosphere, iii) Parameter uncertainties due to the natural variability and imperfect and insufficient measured data.

System uncertainties were investigated by testing different starting times of the releases to each assessed biosphere object deterministically, i.e., from the start of the marine stage (used for the derivation of basic LDFs), after the end of the marine stage and after the end of the transitional stage. Uncertainty regarding future use of the biosphere by humans was investigated by assuming different usage of well water and different food supplies. The model uncertainties were investigated by a fine discretization of the low regolith and disregarding contamination from upstream biosphere objects. The effect of time-independent transport parameters with uncertain values on LDFs was studied by performing probabilistic simulations using Monte Carlo methods (see Fig. 3). According to SKB, the uncertainty analysis shows that the handling of system, model and parameter uncertainties is balanced, and that the effects of quantified uncertainties are limited.[9] Consequently, SKB concludes that the maximum LDFs derived by deterministic calculations used in SR-Site are best estimates for a representative individual of the most exposed group.

Sensitivity analysis was performed with First Order Sensitivity Index (FOSI) and Standardized Rank Regression Coefficient (SRRC) methods using results from the probabilistic simulations of the parameter uncertainty analysis mentioned above. The relative importance of parameters for LDF uncertainty varied between radionuclides. For example, the first three parameters from the sensitivity analysis for Ra-226 in descending order are well capacity, concentration ratio from soil to vegetables and Distribution Coefficient (K_d) value for lower regolith.

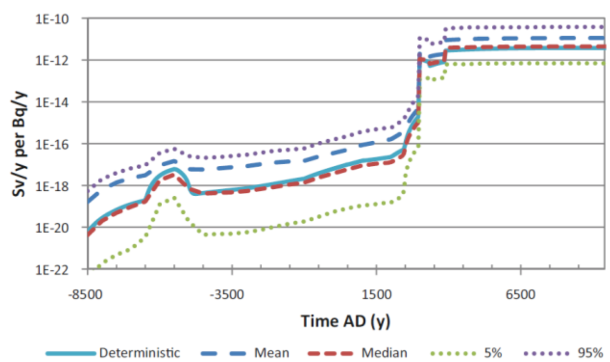

Fig. 3 Evolution of the LDF in time for Ra-226, showing the effect of uncertain parameters. The deterministic LDF values are also shown for comparison. (From SKB, figure 5-36 in Ref. 9).

II.B.3. Transport in near- and far-field and effective doses

It can be seen from Fig. 1 that the effective doses for the corrosion scenario are estimated by multiplying the LDF values with modelled release rates from the geosphere. Inputs to the transport models for near- and far-field are the calculated average number of failed canisters and the 56 calculated failure times[5] as shown in Fig. 1. For each of the 56 calculated failure times 50 realisations reflecting parameter uncertainty related to the radionuclide transport models for the near- and far-field were calculated, the dose values then obtained by multiplying the release with the LDFs (the latter given as deterministic values). Figure 4 shows the uncertainties of calculated effective dose for the central corrosion case.[1] Subsequently sensitivity analysis was carried out using the results from these probabilistic calculations. The sensitivity analysis was performed using the SRRC method that was motivated by the (*a priori* known) monotonicity of the modelled system. The SRRC analysis of the total dose at 1 million years suggests the following relative importance, in descending order, of the input variables: fuel dissolution rate, flow-related transport resistance (F) along the geosphere flow path and canister failure time. Finally, Fig. 5 summarizes the uncertainty calculations for the corrosion scenario based on the cases identified in Fig. 2.

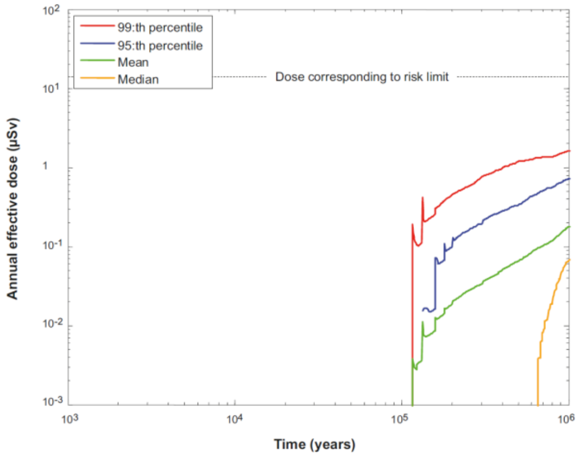

Fig. 4 Far-field annunal effective doses (mean, median, 95th and 99th percentiles) for the probabilistic caluculation of the central corrosion case (From SKB, figure 13-19 in Ref. 1).

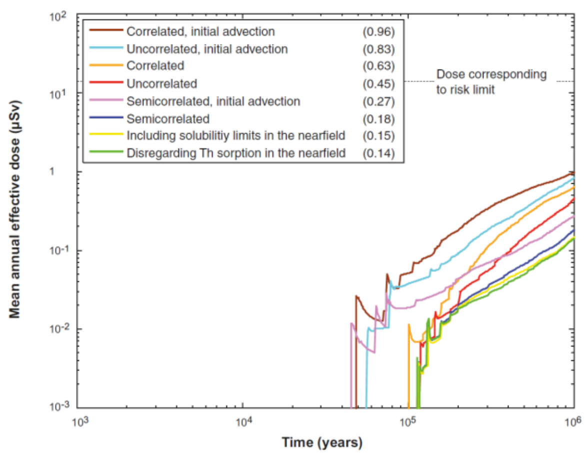

Fig. 5 Summary of far-field mean annual effective dose for uncertainty calculations performed for the corrosion scenario. The peak doses are given in parentheses in μSv (From SKB, figure 13-40 in Ref. 1)

III. SSM'S INDEPENDENT MODELLING

III.A. Regulatory modelling approach

SSM and its predecessors have, for several decades, been developing independent models to support regulatory reviews of post-closure safety assessments for geological repositories.[11,12] Modelling teams have been established, combining both in-house and external expertise.[13] SSM's independent modelling can be referred to one of the following three categories: i) use of SKB's own models (but with other equation solvers), ii) use of alternative conceptual models, iii) use of bounding case calculations.

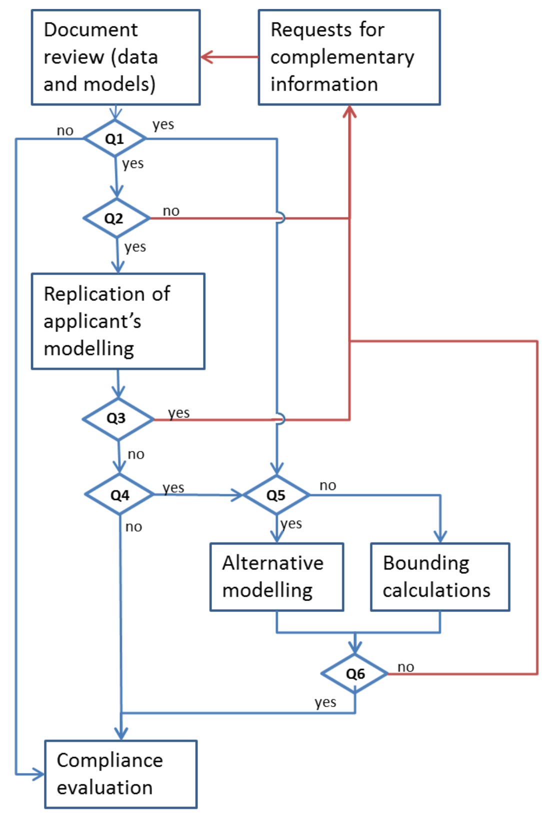

Fig. 6 Schematic of the integrated modelling approach for regulatory review of a consequence analysis, with the following decision points: Q1: Necessary to reproduce? Q2: Feasible to reproduce? Q3: Any errors or ambiguities identified? Q4: Any remaining unresolved review issues, e.g. conceptual model uncertainty? Q5: Does SSM have access to an alternative model? Q6: Sufficient understanding for compliance evaluation? See text for details.

Based on the experiences from SSM's earlier regulatory modelling, an integrated modelling approach has been developed, schematically illustrated in Fig. 6. In addition to the traditional document and data review there are three modelling activities: replication of the applicant's modelling, exploration of uncertainty with alternative conceptual models and bounding calculations. The answers to the questions associated with the decision points (Q1-Q6) guide the way forward in the modelling scheme. The decision point Q1 involves deciding the need for independent modelling. This decision depends on e.g. the complexity and transparency of the model in question and its importance for the compliance evaluation. Q2 is about the feasibility to conduct replication modelling. For example, if there is not sufficient information for replicating the applicant's model a request for complementary information is needed. By means of replication of a model calculation one may identify errors, ambiguities or quality problems that require clarification or complementary information from the applicant (Q3). At decision point Q4 it has to be decided whether there are any remaining unresolved review issues that require further independent modelling and, depending on availability of regulatory models (Q5), either an alternative (conceptual) model may be used or simplified bounding calculations. Finally, if the independent modelling has not resolved the critical review issues further requests for complementary information must be developed (Q6).

Each of the modelling activities can identify a review issue that require a request for complementary information (RCI) to be resolved, hence there may be several iterations between document review, independent modelling and requests for complementary information. It will be shown in section *III.B.1*. that also data review may involve a modelling activity.

III.B. Application of SSM's modelling approach in the licensing review for a spent nuclear fuel repository

In the following we describe how the various elements of the modelling approach illustrated in Fig. 6 were applied in SSM's ongoing licensing review of SKB's repository application.

III.B.1 Data review

The input data used for radionuclide transport calculations were mainly K_d values for bentonite, rock and surface environmental media, solubility limits, fuel dissolution rates and flow related parameters such as transport resistance (F), advective travel time (t_w), and advective flow (q).

SSM's external expert reviews by Randall[14], Bertetti[15] and Beresford et. al.[16] covering SKB's handling of sorption issues are to a large extent in agreement with the position taken by SKB.

For the corrosion scenario where the buffer is severely eroded the flow through the deposition hole is often too high for solid phase to precipitate. Thus, solubility limits are not included in the calculation cases where the canister fails due to corrosion.

The flow related data are generated by the hydrogeological flow model (see Fig. 1). To review the flow related data obtained by SKB an independent modelling was conducted by one of SSM's external experts.[17] However, due to the complexity of SKB's hydrogeological flow model it has not been feasible to replicate SKB's work in detail.[18] Using a similar modelling strategy to that proposed in this paper, alternative modelling codes based on a higher degree of simplification have been used. The flow related parameters such as F and q calculated by SSM's external expert is of the same order of magnitude as those presented by SKB.[18] The review of the fuel dissolution rate is ongoing and no conclusions can be drawn at this moment.

III.B.2. Replication of applicant's modelling

In order to have a thorough understanding of SKB's consequence analysis SSM and its external experts have reproduced a large part of SKB's model calculations, including the calculation of the mean number of failed canisters failing due to corrosion, radionuclide transport in near- and far-field for the central corrosion case, a variant case adding initial advective conditions in the deposition holes and the basic LDF values.[19,20,21,22]

The information provided in SR-Site was sufficient for SSM to replicate SKB's consequence analysis except for the need for a few clarifications regarding the calculation of LDF values and the mean number of failed canisters due to corrosion. Generally SSM and its external experts' calculations are in good agreement with SKB's calculations mentioned above.[19,20,21,22] Among the calculation cases the central corrosion case were checked by both SSM and its external experts.[20,21] In addition, SSM's external experts replicated a number of calculation cases relating to SKB's residual scenarios and the barrier-function-loss what-if analyses.[20,22] SSM's external experts reasonably replicated the dose results of SKB's cases within factors of five or less.

A number of requests for complementary information were sent to SKB based on the findings gained from the replication of SKB's calculations. These requests concern issues like inconsistency between the documents and the actual modelling performed in SKB's dose assessment, QA problems, and insufficient justification of assumptions. The replication also resulted in the identification of a number of review issues.

Based on the replication modelling we found that SKB's calculation of radionuclide transport in near- and far-field are transparent, model descriptions are adequate, and data are reasonably complete to allow an experienced radionuclide transport modeller to reproduce the calculations. SSM appreciated that SKB used simplified analytical models for the modelling of radionuclide transport in the near and far field and compared the analytical results with the numerical calculations. However, concerns regarding the derivation of LDF values and uncertainties associated with the calculated numbers of failed canisters due to corrosion remain. Further regulatory analyses of these two issues are presented in the following.

III.B.3 Alternative modelling

Based on SSM's document review and the replication of SKB's calculations, SSM had some concerns about SKB's biosphere assessment and derivation of LDF values in particular. SKB's methodology for the biosphere dose assessment in SR-Site is complex and includes many calculation steps and models supported by a large number of reports. The description of the derivation of parameters in the modelling chain is not always clear. For example, SSM and its external experts found that it is not transparent how the flow related parameters used in the LDF model were derived from the surface hydrological modelling.[23,24,25] One of SKB's investigations of system uncertainty was to test different starting times in the deterministic calculation of the releases to a biosphere object. However, because the basic LDF values were calculated assuming a constant release rate of 1 Bq/year from the geosphere to the biosphere for the whole modelling period, it is obvious that delaying the time for release will only result in less time for accumulation in the biosphere object and, hence, a lower LDF value.

Another limitation of SKB's approach to biosphere modelling is related to the fixed description of the landscape evolution that is used as a basis for all calculations of LDF values, which means that all properties within the biosphere objects are fixed in time. This approach does not allow for a study of potentially important aspects of uncertainty including longer time periods of accumulation of radionuclides in sediments and changes of size of basins on final dose conversion factors.

SSM has shadowed SKB's development of biosphere modelling; over the past decade modelling techniques have been developed that allow numerical reviews of aspects of the license application to be investigated using alternative conceptual models. In order to evaluate the suitability of SKB's biosphere dose assessment model and to explore the model uncertainties, two benchmark calculations using alternative models were performed. The first model comparison was performed using simplified reference biosphere models against SKB's LDF model, which is described below. The second model comparison was performed using a model that includes biosphere evolution. For details of the second model comparison please see the accompanying paper by Kłos et al. (Ref. 24).

Simplified reference biosphere models were developed to represent the most plausible transport processes and various types of 'objects' such as a well, agricultural land, lake and wetland.[25] The output from these simplified models is a set of dose conversion factors for various types of 'biosphere objects' resulting from a constant unit release rate. The models draw on the data used in SR-Site as much as possible to help ensure meaningful comparison of the results with SKB's results. However, the simpler models do not include an explicit representation of the succession between different biosphere systems (e.g. succession from marine to lake to mire to terrestrial systems) and changes of 'object' size with time.

The simplified reference biosphere models for agricultural land, associated with use of a deep groundwater well, provide the highest dose conversion factors among the six biosphere objects. Consumption of water from a deep well contributes more than 50% to the dose associated with agricultural land for 32 out of the 39 radionuclides studied.[26] The simple biosphere model produces dose factors that are consistent with the SR-Site LDFs for interglacial conditions (see Fig. 7). Here it should be pointed out that the agricultural land defined in these calculations is small and only can sustain a small group with a few individuals so the risk criterion applied is 10^{-5} instead of 10^{-6} per year.[27] The reason that the simple model bounds the LDFs is because the well pathway dominates in LDF models. The results are consistent with SKB's sensitivity analysis that suggests well capacity is the most sensitive parameter for derived LDF values. The well pathway is independent of the radionuclide transport modelling and its importance effectively masks the other aspects of the modelling.

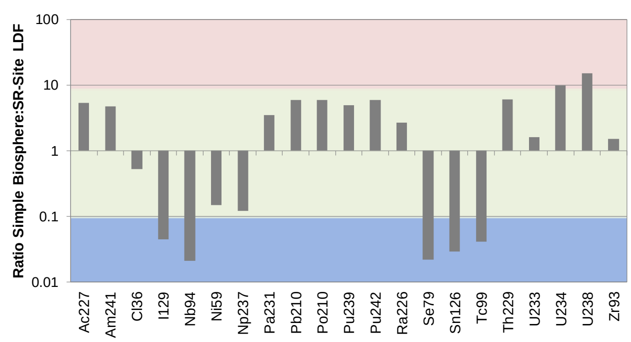

Fig. 7 Maximum dose factors for groundwater release to combined agricultural land with a deep well compared with SR-Site basic LDFs (Ref. 26). Results for 20 out of 39 radionuclides are displayed.

III.B.4. Bounding calculations

Although the three cases of different hydrogeological model variants related to buffer advection conditions were propagated with the bounding case of initial advection in all deposition holes (see Fig. 2), uncertainties associated with SKB's corrosion model were not included in SKB's uncertainty analysis. SSM's concern is that potentially important effects of spatial and temporal variability of both groundwater flux and sulphide concentration in the groundwater have not been fully explored.[18,28] Because there is no alternative corrosion model available at the moment SSM carried out bounding calculations. The uncertainties associated with the corrosion model were studied by selecting a bounding case with the highly pessimistic assumption of instantaneous canister failure by corrosion when advective conditions occur. These bounding calculations were coupled with the three variants of SKB's hydrogeological DFN model, the uncorrelated, the correlated and the semi-correlated hydrogeology model variants, that combined with SKB's buffer erosion model resulted in a mean of 280, 68 and 19 deposition holes with advective conditions, respectively.

In order to calculate dose consequences we also need information about the distribution of times for reaching advective conditions in the deposition holes. Because this information was not explicitly given in SR-Site the canister failure times were sampled from uniform distributions ranging between 50,000, 70,000 and 90,000 years to 1 million years, for the uncorrelated, the correlated and the semi-correlated variants, respectively. The distribution of times for reaching advective conditions in the deposition holes for the semi-correlated variant was calculated using SKB's buffer erosion model and the flow data from a single realisation of SKB's semi-correlated hydrogeological DFN model.[29] The distributions for the other variants were postulated in lack of more detailed information.

Since there is no buffer hindering the outward transport of radionuclides the radionuclide releases and transport in the near field is controlled by the fuel dissolution rate and the flow rate through the deposition hole. Thus, the near field transport model, COMP23, is simplified to have two compartments (see Ref. 5, p. 315). The radionuclide transport in the far field is modelled by the FARF31 model. Both the near- and far-field models were implemented in the compartment modelling software, Ecolego[30], where a discretization method[31] was used to implement FARF31. The parameter values were found in the SKB report (see Ref. 5). For each case the probabilistic (with respect to fuel dissolution rate, transport parameters and time to reach advective conditions) calculation was performed with 100 realisations. Compared with SKB's calculations SSM did not account for possible correlation between local flow and transport properties in the deposition holes and those of the corresponding far-field transport paths.

Finally, the calculated radionuclide fluxes from the geosphere were multiplied with SKB's distributed LDF values to obtain dose consequences in the biosphere. The reason to use distributed LDF values is that in these cases the releases are from several canisters. Fig. 8 shows the probabilistic calculations for these three bounding cases with the three alternative hydrogeological DFN model variants and the SR- Site erosion model. As can be seen from Fig. 8 the number of deposition holes with advective conditions and, hence, assumptions concerning the hydrogeological model variant have significant effects on the calculated doses. This is in contrast to SKB's bounding calculations that exclude uncertainty regarding the copper corrosion model, compare Fig. 5 that illustrates impact of hydrogeological model uncertainty for a situation with advective conditions in all 6000 deposition holes directly after closure. Although the assumption of instantaneous canister failure by corrosion at the onset of advective conditions is deemed unrealistic, our bounding calculation still highlights a potentially important uncertainty associated with SKB's main corrosion scenario, that require further review efforts.

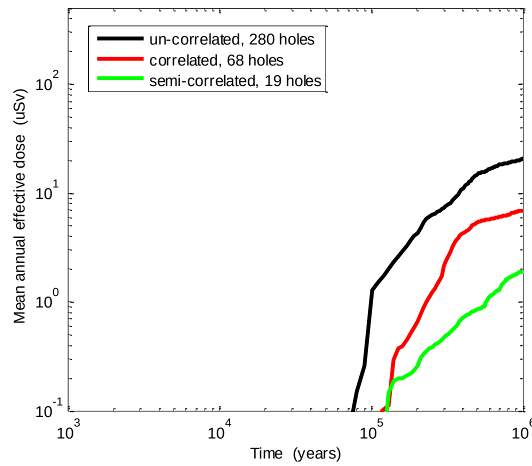

Fig. 8 Far-field annual effective dose for bounding cases calculated probabilistically for corrosion cases.

IV. CONCLUSIONS

In this paper we have illustrated a structured approach to independent regulatory modelling in support of the ongoing licensing review of a safety case for a spent nuclear fuel repository in Sweden. The experiences gained so far demonstrate that such modelling may support the review process in several ways:

1. Provides insight into the applicant's modelling: By replicating SKB's calculations with their own models or SSM's interpretations thereof, SSM has gained insight into the details of SKB's calculations that could not have been attained by just reviewing SKB's modelling reports. For example, the replication of SKB's complex biosphere modelling and the use of alternative conceptual models have helped developing a better understanding of their modelling approach and provided a quality check of SKB's calculation results.
2. Helps identifying review issues: By means of copper corrosion bounding calculations SSM has identified a potentially important review issue related to SKB's main corrosion scenario, that require additional review effort.
3. Provides a basis for developing requests for complementary information: By the replication of

different parts of SKB's consequence analysis SSM has identified a large number of questions that had to be resolved by requesting complementary information or clarification from SKB.

4. Helps building confidence in the applicant's safety case: The use of alternative conceptual models provides a means to explore different types of uncertainty related to safety critical review issues. For example, although SKB's approach to calculating dose conversion factors is not very transparent, SSM's use of alternative models has helped strengthening confidence in SKB's modelling results.
5. Supports compliance judgments: SSM's bounding calculations provide a check of reasonableness of SKB's calculation results and robustness of the barrier system.

Although there are several benefits of carrying out independent modeling in support of a licensing review it should be recognized that it requires time and resources during the review as well as a long period of competence building and other preparations prior to the licensing review.

Finally, one should note that, because SSM's licensing review is still ongoing, SSM cannot at this stage draw any definitive conclusions regarding the compliance of SKB's application with SSM's regulatory requirements. SSM's final statement to the government regarding SKB's license application is currently scheduled for 2017.

REFERENCES

1. SKB, "Long term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project," *SKB TR-11-01*, Svensk Kärnbränslehantering AB, (2011).
2. SKB, "Corrosion calculations report for the safety assessment SR-Site," *SKB TR-10-66*, Svensk Kärnbränslehantering AB, (2010).
3. L. Moreno, I. Neretnieks, and L. Liu, "Modelling of erosion of bentonite gel by gel/sol flow," *SKB TR-10-64*, Svensk Kärnbränslehantering AB, (2010).
4. K. A. Cliffe and M. Kelly, "COMP23 version 1.2.2 user's manual," *SKB R-04-64*, Svensk Kärnbränslehantering AB, (2006).
5. SKB, "Radionuclide transport for the safety assessment SR-Site," *SKB TR-10-5*0, Svensk Kärnbränslehantering AB, (2010).
6. S. Norman, and N. Kjellbert, "FARF31 – A far field radionuclide migration code for use with the PROPER package," *SKB TR-90-01*, Svensk Kärnbränslehantering AB, (1990).
7. S. Painter and J. Mancillas, "MARFA version 3.2.2 user's manual: migration analysis of radionuclides in the far field," *SKB R-09-56*, Svensk Kärnbränslehantering AB, (2009).
8. A. Hedin, "Integrated analytic radionuclide transport model for a spent nuclear fuel repository in saturated fractured rock," *Nuclear Technology*, 138, pp 179–205, (2002).
9. R. Avila, P-A. Ekström, P-G. Åstrand, "Landscape dose conversion factors used in the safety assessment SR-Site," *SKB TR-10-06*, Svensk Kärnbränslehantering AB, (2010).
10. SKB, "Biosphere analyses for the safety assessment SR-Site – synthesis and summary of results, *SKB TR-10-09*, Svensk Kärnbränslehantering AB, (2010).
11. S. Xu, A. Wörman, B. Dverstorp, R. Kłos G. Shaw and L. Marklund, "SSI's independent consequence calculations in support of the regulatory review of the SR-Can safety assessment." *SSI Report 2008:08*. (2008).
12. P. Maul, P. Robinson, A. Bond and S. Benbow, "Independent calculations for the SR-Can assessment," *SKI Report 2008:12*, (2008).
13. S. Xu, B. Dverstorp, G. Lindgren, and M. Nordén, "Developing a regulatory performance assessment approach for geological disposal of spent nuclear fuel." *Transactions of European Nuclear Conference, 30 May to 2 June, 2010, Barcelona, Spain*. (2010).
14. M. Randall, "Review of Radionuclide Sorption on Bentonite and Forsmark Bedrock Material," *SSM Technical Note 2012:63*, Swedish Radiation Safety Authority, Stockholm (2012).
15. F. P. Bertetti, "Detailed assessment of radionuclide Kd-values for the geosphere," *SSM Technical Note 2014:38*, Swedish Radiation Safety Authority, Stockholm (2014).
16. N. Beresford, P, Boyer and B. Howard, "Assessment of the derivation and use of distribution coefficients (Kd) and concentration ratios (CR) – Main Review Phase," *SSM Technical Note 2014:32*, Swedish Radiation Safety Authority, Stockholm (2014).
17. J. E. Geier, "Hydrogeological modelling of the Forsmark site," *SSM technical note 2012:67*, Swedish Radiation Safety Authority, Stockholm (2012).
18. B. Strömberg, G. A. Lindgren and B. Dverstorp, "Regulatory assessment of a spent fuel repository at the Forsmark site Sweden; Evolution of groundwater site conditions," *Int. High-Level Radioactive Waste Management Conference (IHLRWM), Charleston, South Carolina, April 12–16, 2015*. (Submitted), (2015).
19. O. Pensado, S. Mohanty, and P. Laplante, "Verification of Calculational Cases in Performance Assessment for KBS-3 Repository. "*Proc. Int. High-Level Radioactive Waste Management Conference (IHLRWM), Albuquerque, New Mexico, April 29–*

May 2, 2013. La Grange Park, Illinois: American Nuclear Society (2013).

20. S. Mohanty, and O. Pensado, "Reproduction of SKB's Canister Failure Calculations - What-If and 'Residual' Scenario to Illustrate Barrier Functions" *SSM Technical Note 2014:44*, Swedish Radiation Safety Authority, Stockholm, (2014).
21. S. Xu, B. Dverstorp, and N. Nordén, "Modeling in Support of SSM's Licensing Review of a Geological Repository for Spent Nuclear Fuel." *Proceedings of WM symposia 2014, 2-6, March, 2014. Phoenix, Arizona, USA*, (2014).
22. J. Penfold, "Further Reproduction of SKB's Calculation Cases and Independent Calculations of Additional "What If?" Cases," *SSM Technical Note 2014:55*, Swedish Radiation Safety Authority, Stockholm, (2014).
23. R. Kłos, L. Limer, G. Shaw and A. Wörman, "Modelling comparison of alternative biosphere models with LDF models and evaluation of selected parameter values used in the biosphere dose assessment - Main review phase," *SSM Technical Note 2014:35*, Swedish Radiation Safety Authority, Stockholm, (2014).
24. R. Kłos, D. Perez-Sánchez and S. Xu, "Results from post-closure dose assessment models with 'alternative' levels of details," *Int. High-Level Radioactive Waste Management Conference (IHLRWM), Charleston, South Carolina, April 12–16, 2015*. (Submitted), (2015).
25. R. Walke, "Modelling Comparison of Simple Reference Biosphere Models with LDF Models – Main Review Phase," *SSM Technical Note 2014:34*, Swedish Radiation Safety Authority, Stockholm, (2014).
26. R. Walke and L. Limer, "Further Modelling Comparison of Simple Reference Biosphere Models with the LDF Modelling Approach," *SSM Technical Note 2014:54*, Swedish Radiation Safety Authority, Stockholm, (2014).
27. SSM, "The Swedish Radiation Safety Authority's Regulations and General Advice Concerning the Protection of Human Health and the Environment in Connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste," *SSMFS 2008:37*, Swedish Radiation Safety Authority, Stockholm, (2008).
28. K-J., Röhlig, "Review of uncertainty propagation and sensitivity analysis in SR-Site – Main review phase", *SSM Technical Note 2015:05 (in press)*, Swedish Radiation Safety Authority, Stockholm, (2015).
29. SKB, "Svar till SSM på begäran om komplettering rörande osäkerheter I hydrogeologiska beräkningar," *DokID 1396324*, Svensk Kärnbränslehantering AB, (2013). (in Swedish).
30. Ecolego. [Online]. Available at: http://ecolego.facilia.se/, (2011).
31. R. Broed, and S. Xu, "User's manual for Ecolego Toolbox and the Discretization Block." *SSI Report 2008:10*. (2008).