



Strålsäkerhetsmyndigheten

Swedish Radiation Safety Authority

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Technical Note

**2014:22**

Workshop on seismic hazard  
at Forsmark

Main Review Phase



## **SSM perspektiv**

### **Bakgrund**

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information och göra expertbedömningar i avgränsade frågor. Workshopar organiseras för att diskutera läget för SSM:s aktuella granskningsinsatser samt konsulternas uppdragsresultat om specifika processer, säkerhetsfunktioner och barriärer av stor vikt för SKB:s säkerhetsanalys SR-Site för kärnbränsleförvaret i Forsmark. Synpunkter samt slutsatser som resulterar från workshoparna är workshopdeltagarnas åsikter och inte nödvändigtvis SSM:s.

### **Workshopens syfte**

Det övergripande syftet med denna workshop är att föra samman experter inom seismologi och bergmekanik för att diskutera förekomsten av jordskalv som kan påverka den långsiktiga stabiliteten för det planerade geologiska slutförvaret för använt kärnbränsle i Forsmark. Workshopen diskuterade förutsättningarna samt tillförlitligheten på SKB:s beräkningar av kapselbrott på grund av jordskalv från nutid fram till 1 miljon år efter förslutning. Vidare bidrog workshopen till att identifiera de frågeställningar som SSM bör fokusera på i sina fortsatta bedömningar av scenarier rörande jordskalv samt skjubbelastning på kapseln.

### **Sammanfattning av workshopen**

Rapporten beskriver resultatet från en workshop om seismisk risk i Forsmark som SSM organiserade den 4 och 5 juni, 2013. Rapporten redovisar de frågeställningarna som diskuterats samt summerar viktiga synpunkter som uppnåtts. Redovisningen bör inte ses som en fullständig dokumentation av alla diskussioner under workshopen. Även individuella påståenden från deltagarna bör hanteras som deras uppfattning och inte SSM:s ståndpunkt.

Deltagarna tillfrågades om kvalificerade och oberoende bedömningar av varje ingående parameter i analyserna för jordskalvscenarierna i SR-Site. Workshopen kom fram till att värdena för jordskalvsfrekvens kan vara större än de som SKB har tagit fram. Dessutom kan antalet kapselpositioner som kan påverkas av skjubning vid jordskalv och leda till förhöjda doser vara större än det som redovisas i SR-Site men det verkar osannolikt att dos skulle överskrida föreskriftsgräns.

### **Projektinformation**

Kontaktperson på SSM: Lena Sonnerfelt och Flavio Lanaro

Diarientnummer ramavtal: SSM2011-3635

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## **SSM perspective**

### **Background**

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) license applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information and provide expert opinion on specific issues. Workshops are organized for the discussion of the current status of SSM's review findings and consultants' opinions reached on particular processes, safety functions and barriers of central importance in SKB's safety assessment SR-Site for a final disposal of spent fuel at Forsmark. The viewpoints and conclusions expressed at the workshops are those of the workshop participants and do not necessarily coincide with those of SSM.

### **Objectives of the workshop**

The objective of this workshop was to bring together experts in the field of seismology and rock mechanics together to discuss intersecting issues related to earthquake occurrence and the long-term stability of the proposed system of a deep geological repository for nuclear waste at Forsmark. The workshop sought to consider the context of and determine the robustness of SKB's estimate of canister failure due to earthquakes from present up to 1 million years after closure. A further goal was to identify critical issues regarding earthquake scenarios and shear load on the canister that might need to be focused on in SSM's further evaluations.

### **Summary of the workshop**

This report describes the outcome of the workshop organized by SSM on seismic hazard at Forsmark that was held in Stockholm on the 4 and 5 of June, 2013. The report summarizes the issues discussed and extracts the essential viewpoints that have been expressed. It should not be considered as a comprehensive record of all the discussions at the workshop and individual statements made by workshop participants should be regarded as opinions rather than SSM's point of view.

The participants had been asked to provide qualified, independent judgments for each parameter pertaining the analyses of the earthquake scenarios in SR-Site. The workshop postulated that the value of the earthquake frequency may be greater than considered by SKB. Furthermore, there is a possibility that there might be more canisters in positions that would undergo shearing due to an earthquake and give rise to higher doses than assumed by SKB, but it seems improbable that dose would exceed regulatory dose limit.

### **Project information**

Contact person at SSM: Lena Sonnerfelt and Flavio Lanaro



**Strålsäkerhetsmyndigheten**

Swedish Radiation Safety Authority

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## Technical Note 52

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This report was commissioned by the Swedish Radiation Safety Authority (SSM). The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of SSM.

# Contents

<b>1</b>	<b>Background .....</b>	<b>3</b>
<b>2</b>	<b>Purpose .....</b>	<b>5</b>
2.1	Goal of the Workshop .....	5
2.2	Introduction, and presentation of participants .....	5
<b>3</b>	<b>Presentations by SSM Reviewers and Consultants .....</b>	<b>7</b>
3.1	Consequence analyses .....	7
3.2	Seismology – Frequencies and Mechanisms.....	7
3.3	Review of approach to post-glacial earthquakes.....	8
3.4	Structural geology and tectonic evolution of the Forsmark area .....	9
3.5	Critical radii and respect distances.....	10
<b>4</b>	<b>Group Discussions .....</b>	<b>11</b>
4.1	Group 1 Discussions.....	11
4.2	Group 2 Discussions.....	12
<b>5</b>	<b>Concluding Discussion .....</b>	<b>15</b>
<b>6</b>	<b>References.....</b>	<b>17</b>
	<b>Appendix 1 Agenda of the workshop.....</b>	<b>19</b>
	<b>Appendix 2 List of participants.....</b>	<b>21</b>



# **1 Background**

In 2011 the Swedish Nuclear Fuel and Waste Management Company (SKB) has delivered a Licence Application to construct, own and operate a repository for the Swedish spent nuclear fuel at Forsmark and an encapsulation facility at Simpevarp. The Swedish Radiation Safety Authority (SSM) is evaluating the application under the Act on Nuclear Activities (1984:3). As part of the evaluation, SSM has commissioned consultants to carry out work to obtain information on specific issues, one of which concerns the so-called ‘earthquake scenario’, the possibility that and instability mechanisms whereby a nearby, large magnitude earthquake could affect the safe functioning of the repository. Workshops are then held for summarizing the preliminary outcomes of the review and draw conclusions.



## **2 Purpose**

The objective of this workshop was to bring experts in the field of seismology and rock mechanics together to discuss intersecting issues related to seismology, rock mechanics and the long-term stability of the proposed system of a deep geological repository for nuclear waste at Forsmark. More specifically, the purpose of the Workshop was to combine the knowledge and evaluations of the seismologists with the initial thinking of the rock mechanic modellers in order to ensure an integrated understanding can be developed of the factors controlling the so-called ‘earthquake scenario’. Based on the outcome of the workshop, SSM intends to direct any further evaluation and modelling activities related to this scenario. A somewhat similar workshop was organised by SSM in Stockholm, March 23-25, 2010, for assessment of seismicity, late glacial faulting and fracturing in Swedish bedrock by SKB (Stephansson et al., 2012).

### **2.1 Goal of the Workshop**

SSM specified the goal of the Workshop and selected the experts and participants from SSM and organizations participating in the scientific assessment of the SKB License Application. The main goal of the Workshop was to consider the context of and determine the robustness of SKB’s estimate of 0.079 failed canisters in the whole repository in 1 million years due to earthquakes. A further goal was to identify critical issues regarding earthquake scenarios and shear load on the canisters that might need to be focused on in the future evaluation.

### **2.2 Introduction, and presentation of participants**

Lena Sonnerfelt of SSM welcomed the participants who presented themselves. Lena gave a short introduction and a description of the present status of the review process within SSM organization.



### 3 Presentations by SSM Reviewers and Consultants

SSM staff and consultants had been working on evaluation of the SKB documentations. Each expert was asked to summarise their findings to date.

#### 3.1 Consequence analyses

Shulan Xu of SSM presented the two main scenarios in SKB's safety case: (1) Canister failure due to corrosion and (2) Canister failure due to shear load. SKB's deterministic calculation for a postulated failure of one canister at 100,000 years is well below the dose corresponding to the risk limit. The probabilistic calculations by SKB are presented in Section 10.4.5 of SKB TR-11-01. SKB is using two different equations to calculate the canister failure frequency due to shear load induced by an earthquake. The first:

$$N_{failed} = 5 \cdot f \cdot t \cdot N_{crit}$$

where  $t$  is the time,  $f$  is the annual frequency for earthquakes  $\geq M5$  within a 5 km radius area and  $N_{crit}$  is the average number of canisters in a critical position with respect to fractures considered large enough to shear by  $> 5$  cm (fractures typically larger than 100 m). For the time interval 500,000 to 1,000,000 years, in which it is assumed that a second seismic event occurs, SKB uses another relationship:

$$N_{failed} = 1/2(5 \cdot f)^2 \cdot (10^6 - T)^2 \cdot N_{crit,2nd}$$

where  $N_{crit,2nd}$  is the average number of canisters in a critical position with respect to fractures considered large enough to shear by  $> 2.5$  cm and  $T$  is the recurrence time of the earthquakes.

As stated in the caption of Figure 10-124, the area under the graph yields the mean number of failed canisters to be 0.079 at 1,000,000 years for the whole repository with 6000 canisters (about 0,0013% of the emplaced canisters).

Shulan Xu raised the question whether SKB's modelling results appear to be reasonable. This issue was discussed in the group meetings the following day and is reported later in this note.

#### 3.2 Seismology – Frequencies and Mechanisms

Hilmar Bungum and Conrad Lindholm (NORSAR, Norway) reported the main findings from the review of five SKB reports about seismology and related areas published over a period from 2004 to 2011. Specific considerations have been given to completeness of the safety assessment, scientific soundness, relevant models, handling of uncertainties, and safety significance. Bungum and Lindholm concluded that the presented work by SKB is comprehensive and of high scientific quality.

The report by Bödvarsson et al. (2006, SKB R-06-67) has been 'overstressed in use'. The report is lacking data from a high-quality seismic risk analysis following Eurocode 8 standard, an assessment of maximum magnitude is missing, recurrence values are missing and earthquake impacts during the repository operational period are missing.

The downscaling of a 650 km long distance to the area around Forsmark of inhomogeneous seismicity is not well justified in the report. The report is based on contemporary seismicity but the data are used to specify the seismicity during glacial conditions, where neotectonic processes add to the likelihood of seismicity and control its nature. Furthermore, the likelihood of seismicity for the 5 km radius around Forsmark is distributed to the 30 deformation zones observed in that area. When considering the repository site (area of radius approximately 2.5 km), only 5 active zones are observed and the likelihood of seismicity is reduced to a sixth of that for the area of 5 km radius.

NORSAR presented a comprehensive review of the report by Fälth et al. (2010, SKB TR-08-11). One of the important results from the discrete element modelling with 3DEC is the identification of deformation zone ZFMA2 as the only fault in the repository area that is considered potentially active in a thrust fault regime. For the mixed-mode regime, 5 zones were found possibly active at long term.

There is a modern update by Leonard (2010) of the magnitude-frequency curve in the classical paper by Wells & Coppersmith (1994) that needs to be included in any calculations. The faults and other discontinuities in 3DEC modelling are treated as single planes with zero thickness. There is a need to include the width of the discontinuity in modelling strength and deformability of faulted rock masses. The empirical calibration of the results from 3DEC modelling only contains data from the Chi-Chi earthquake (Taiwan) that occurred in a different geological environment than Forsmark. This type of data from large earthquakes now exists for a number of additional earthquakes and could have been better exploited in the calibration activities for the 3DEC models.

Following classical thinking, NORSAR assumes that a second and third earthquake will happen after the stress and strain energy have built up again. In the report edited by Hedin (SKB TR-10-48) the ridge push from the Mid-Atlantic ridge is considered to be the only viable tectonic source of stress in Scandinavia and thereby ignores more regional and local stress sources like folding, intrusion, faulting, thrusting, glacial rebound etc. NORSAR see the need to study and compare stress models derived from different possible geological settings and glacial cycles.

SKB (TR-10-48 and SKB TR-11-01, p. 479) reduces the earthquake frequency by 50% in the calculations with the argument that large earthquakes are normally deep-sourced. NORSAR claims that this statement may not be correct for large magnitude neotectonic earthquakes, which appear most important for a deep geological repository. Earthquake maximum magnitude in SKB's reports is mostly inferred from mapped fault sizes and repeated glaciations and, as a consequence, magnitudes  $M > 6.8$  are ruled out for Forsmark. NORSAR points out that blind faults can "surface" in M6.5 to M7 events and this has to be considered in estimation of maximum magnitude for the Forsmark area. SKB has studied the influence of earthquake shaking during the construction stage and thereafter but has applied an old version of the Global Seismic Hazard Assessment Program (GSHAP, Wahlström and Grünthal, 2000) and therefore estimated a too low exceedance probability.

### 3.3 Review of approach to post-glacial earthquakes

James McCalpin (GEO-HAZ Consulting Inc., USA) presented his review of and commentary on the SKB documentation on post-glacial earthquakes and made comparisons with how the issue might be dealt with by the NRC in the USA. As it is generally found that only  $> M6.5$  earthquakes cause surface rupture, the Gutenberg-Richter relationship has to be based on observed fault scarps from earthquakes of this size or greater and extrapolated to smaller events. Discussing the proposed indicators of 54 regional post-glacial earthquakes of Mörner (e.g. 2012), he noted that, in the US regulatory system, the NRC would expect to see such extensive claims, based on publications, rebutted on a point-by-point basis by the proponent – this has not formally been done. He also considered that the assertions by Lagerbäck and Sundh (2003) on water escape features in northern Uppland being non-seismic would not stand up to NRC review.

A key point is that modern LIDAR techniques for producing digital elevation models are proving extremely successful at characterising fault scarp structures and connectivity of distributed faulting in forested terrain. Whilst LIDAR was used by SKB at Laxemar, it was not deployed in the region around Forsmark and would help to clarify whether there are any structures that have indications of reactivation in the late Pleistocene and Holocene. LIDAR is the standard best practice, rather than using only aerial photogrammetry.

IAEA (SSG-9, 2010) suggests that Probabilistic Fault Displacement Hazard Analysis (PFDHA) is carried out for nuclear power plants (NPPs) that may be prone to hazards from 'capable' faults. The relevance of these guidelines has not been discussed by SKB and the method has not been used at Forsmark.

The issue of 'distributed' faulting taking place was raised: co-seismic rupture on faults that could be many kilometres away from the primary seismogenic fault itself – outside the 5 km radius considered by SKB. Evidence for such distributed faulting was shown from earthquakes in the western USA.

It was pointed out that a standard Probabilistic Seismic Hazard Analysis PSHA (looking at ground acceleration, rather than fault displacement), normally required for any new nuclear facility, does not appear to have been carried out for the repository and its surface infrastructure. It was questioned whether the Forsmark NPP already had a PSHA.

The recommendations from James McCalpin's review are that SKB should:

- use LiDAR DEMs to confirm whether post-glacial faulting exist in the same seismic source zone that contains Forsmark;
- if they do, use PFDHA to assess the probability and displacement of distributed faulting within the repository area (the PFDHA method also accommodates distributed faulting on both pre-existing fractures and new faults);
- compare PFDHA displacements/frequencies to those from SKB's rock mechanics approach: if they are the same, there is no problem;
- rather than predicting the return period of M>5 earthquakes from strain rates (500,000 years) and assuming that earthquake probability is uniform in space and can be scaled down from large areas to small ones without limit – predict it from a more traditional seismological basis. That is, define the magnitude-frequency distributions of the smaller areal seismic source zone in which Forsmark lies, during the Interglacial, Glacial Buildup/Maximum and the rapid Deglaciation Periods (as defined in SKB's Reference Glacial Model). If the M>5 earthquake rates are the same, there is no problem.

McCalpin thus recommends comparing the results of these ‘seismologically based’ approaches to ground shaking and fault displacement estimates with those from SKB’s rock mechanics approach, as a reality check on a forward numerical model.

### **3.4 Structural geology and tectonic evolution of the Forsmark area**

Sven Tirén (Geosigma, Sweden) gave an overview of the structural geology and tectonic evolution of the Forsmark area and its surroundings based on the content of SKB TR-08-05. In the presentation he made a special emphasis on the tilted block structures and the way they can be used to determine young glacial and post-glacial brittle structures in the bedrock. SKB has not been using existing topographic data presented in SKB TR-10-05 to localize major tilted rock blocks as indicators of neotectonic displacements.

Airborne magnetic measurements have been used by SKB to estimate the size, orientation and characteristics of major fault zones and the results has been of utmost importance for characterization of the major fault structure in the area. Tirén also mentioned that the Singö fault zone east of Forsmark has been identified and characterized with airborne magnetic and can be followed all the way from the Forsmark area into the Finnish Bay. Hence, the Singö deformation zone has a greater importance for the interpretation of the seismo-tectonics around Forsmark than expected by SKB.

The so-called Forsmark lens consists of granitic rocks forming the core of a large open fold where metavolcanic and metasedimentary rocks wrap around the hinge and limbs of the open fold structure. The repository is planned to be located at about 500 m depth in the granitic rocks of the elongated lens. According to Tirén the total length of the granitic core and the fold is not known. Also SKB does not have information on the depth extent of the large deformation zones with a known length > 3 km.

3-D seismic investigations were of utmost importance to locate and characterize the gentle SE-dipping brittle fracture zones in the target area of the site. More than 60 brittle deformation zones with a length > 3 km have been identified from the surface mapping and drillcore analyses. Tirén has conducted several independent studies of the structures in the Forsmark area. Flavio Lanaro asked Sven Tirén if he has found any major geological structure in addition to the one reported by SKB. No additional major structure of importance for the long-term stability and safety of the repository have been found.

In summary, the presentation by Sven Tirén indicates the following key conclusions:

- the extent of some of the major brittle deformation zones in the area up to about 5 km radius around the site is uncertain and there is a possibility that some of the >3 km long structures may have dog-leg connections;
- there is no evidence of block (between deformation zones) tilting as a result of post-glacial movement
- the vertical extent of deformation zones is uncertain;

- there are no actual field observations of secondary fracture displacement (e.g. on fractures equivalent to those being modelled as of critical radius) associated with post-glacial faulting.

### 3.5 Critical radii and respect distances

Flavio Lanaro of SSM presented the main content of the structural 3-DEC model of Forsmark and the Fälth et al. (2008, SKB TR-08-11) report and supporting SKB documentation, including Munier (2010, SKB TR-10-21) on the Extended Full Perimeter intersection Criterion (EFPC). This includes SKB's assessment of what may be potentially unstable faults at and around Forsmark (up to 600 m from the repository footprint). He raised questions for the review groups to consider with respect to:

- Are fault zones much longer than 5 km that lie only about 1 or 2 km from the repository likely to be important in the analysis?
- The Pärvie and Lansjärv faults seem to have hosted earthquakes with  $M_w$  8.2 and  $M_w$  7.8 respectively, but SKB has only modeled up to a maximum magnitude  $M_w$  7.5. Would this be realistic? SKB does not report a stability analysis for these zones nor a comparison with the large zones at Forsmark (e.g. ZFMA2, Forsmark and Singö zones).
- Are the assumptions used on the stress state likely to maximise average fault displacement? Is there an alternative to maximise target fracture displacement?

On the first and last points, it was suggested that a factor of safety approach might assume that any large fracture could host a large magnitude earthquake, in which case one could then apply the more conservative radii values that apply near the deformation zones (e.g. a value of 62.5 m) to the whole repository and recalculate  $N_{crit}$ .

There was a discussion on whether the derivation of fracture radii was robust to variations in fracture orientation, friction assumptions, stress field, fault orientation, target fracture irregularity (e.g. non-circular fractures), shape of the deformation profile across the circular fracture and linearly scaling of deformation with the length of the fracture. The underlying question was whether SKB has done enough simulations to capture these variables adequately.

## 4 Group Discussions

The participants of the Workshop were divided into two groups and each group was given a set of SSM prepared questions to assess.

Flavio Lanaro instructed the groups that the consultants will be asked to provide qualified, independent judgements and, for each treated parameter, to try to estimate a minimum possible value, a believed average value and a maximum possible value with, if needed, an uncertainty interval.

### 4.1 Group 1 Discussions

Group 1 was asked to assess the following three questions:

1. Discuss the frequency estimation approach and results for M>5 earthquakes in Table 10-14 of SKB TR-11-01. Postglacial earthquakes are not taken into account in this calculation. What would be the impact on frequency estimation if post-glacial earthquakes were taken into account? How should SSM address very low probability events in its regulatory considerations?
2. How reasonable is the frequency of canister failures due to earthquakes over a 1,000,000 years period shown in Figure 10-124, SKB TR-11-01?
3. Consider the probability of earthquakes (magnitudes and frequencies) in the Forsmark area with respect to different time frames.

The group expressed scepticism about the numbers presented in Table 10-14 of SKB TR-11-01. The annual frequency of earthquakes  $\geq M5$  resulting from post-glacial faulting (PFG) should be recalculated for time periods of 120,000 and 500,000 years from present to be relevant for the geological development of the Forsmark area. Also the Gutenberg-Richter relationship should be applied for present day frequency,  $f_1$ . The frequency distribution for post-glacial time  $f_2$  can be obtained from the NORSAR catalogue (Bungum and Lindholm, 2013, SSM Technical Note 2013:33).

The group recommended the performance of a complete seismic hazard analysis including site specific data together with local and regional clustering. Such an analysis should contain:

- Maximum magnitude for frequency  $f_1$  and  $f_2$
- Present day seismicity
- Geological information plus GPS data.

The group did not address the question how SSM should address very low probability events.

The group made a first attempt to apply the Probabilistic Seismic Hazard Assessment (PSHA) to the Forsmark area and post-glacial conditions. The PSHA graph presented by NORSAR, with an assumed magnitude M7.2 earthquake that applies for a zone with a length of 70 km (Wells & Coppersmith, 1994) located about 2 km from the repository gave a frequency of  $2 \cdot 10^{-6}$  at the Forsmark Fault. For the number of critical positions, the same value of 0.11 assumed by SKB was adopted. Inserting these data in the equation for the number of failed canisters:

$$N_{failed} = 5 \cdot f \cdot t \cdot N_{crit}$$

for a time period of 120,000 years, the group obtained a result of 0.132 failed canisters.

Applying the Bödvarsson et al. (2006) earthquake frequency for  $M \geq 5$  for present day data and considering a distance reduction from 650 km to 5 km, a reduction in the number of faults from 30 to 5 gives ( $f$  for one zone =  $7.8 \cdot 10^{-8}$ ), SKB obtained a number of failed canisters between  $2.2 \cdot 10^{-3}$  and  $5.4 \cdot 10^{-3}$  for the 120,000 years period (Table 10-20, SKB TR-11-01).

When applying the equation for failed canisters to a magnitude M7.2 earthquake on the Forsmark fault in hypothetical post-glacial conditions, the number of failed canisters over 1,000,000 years will be of the order of 1.1 (0.02% of all emplaced canisters), which would imply a dose about 70 times smaller than the regulatory dose limit.

From this first attempt of using PSHA approach, the estimated number of failed canisters becomes about 14 times higher, compared with the analysis presented by SKB in Figure 10-124 in SKB TR-11-01.

## 4.2 Group 2 Discussions

Group 2 was tasked with assessing:

1. The robustness of the method behind and the numbers of critical deposition positions with different DFN-models in SR-Site Tables 10-17 and 10-18 and whether the critical numbers are adequately bounding for possible scenarios.
2. The robustness of the EFPC-method: is it going to be feasible to utilise in a real repository construction environment and will the constraints that it might impose be adversely limiting with respect to any safety-related feature of the repository and the site?

The core task of the group was to assess the robustness of the value of  $N_{crit}$ , the number of deposition holes that might be in critical locations where a shear by > 5 cm could occur due to an earthquake. As noted above, along with earthquake frequency  $f$ ,  $N_{crit}$  is one of the two key parameters used by SKB in determining the number of canister failures in the earthquake scenario, in the equation:

$$N_{failed} = 5 \cdot f \cdot t \cdot N_{crit}$$

for the first earthquake that could occur.

The group constructed a ‘tree’ of questions that SSM would need to be satisfied about in order to determine whether SKB has arrived at an appropriate value for  $N_{crit}$ . This is shown in Table 1. The third column discusses possible means that SSM can use to answer the questions.

Table 1. Review questions and their review or independent modelling effort.

No.	Question	Review or independent modelling effort
1	Is the rock mechanics model used to estimate displacements on target fractures away from the earthquake-hosting fault robust and correct?	A simple scoping evaluation can be made that explores the impacts of varying the following parameters associated with the target fracture: <ul style="list-style-type: none"> <li>• orientation</li> <li>• friction properties</li> <li>• shape</li> <li>• stress field</li> <li>• displacement profile from centre to edge.</li> </ul>
2	Are the critical fracture radii derived from the above model conservative and robust, or could smaller fractures (e.g. with radii less than 100 m) exhibit shear >5 cm?	Test the SKB statistical model underpinning the size of fractures and their FPI behaviour by substituting other values of radius.
3	If smaller radii are feasible, is the FPI concept still applicable in practice in the disposal tunnels?	Discuss with the fracture network consultant(s). Is it possible that there may be more fractures in the 10-100 m length range than accounted for?
4	Is the DFN model an adequate/robust and bounding representation of real fracture length distributions, given that there are poor data in the critical 10 – 100 m length range?	This will require a proper audit of SKB's statistical analysis, by tracing some of the calculations.
5	Based on the above, is the number of fractures in the DFN that have critical radii with respect to the earthquake shear mechanics model correct?	
6	If so, does the statistical model also produce correct values of $N_{crit}$ , based on SKB's assumptions?	
7	Is the approach of reducing the number of capable faults in the repository region from 30 to 5 within a 5 km radius appropriate? Is dividing the total frequency between those 30 appropriate? Are there other justifiable approaches?	Another approach might be tested by a simple calculation that adopts a 'factor of safety' in layout with respect to distance of deposition holes from capable faults: <ul style="list-style-type: none"> <li>• assume that any fracture zone &gt;3 km long are capable</li> <li>• on this basis, apply more conservative values of critical radius across the whole repository, as all areas could be 'in range' of a capable fault</li> </ul>
8	What is the probability of a single canister failure? SKB states a number of canister failures of 0.079 during 1,000,000 years. This equates to a 100% probability of 0.079 failures, or 8% probability of a single failure during that period of time.	'Whole number' canister failures are a more meaningful way of understanding repository behaviour.

The scale of additional uncertainties that might be imposed by pessimistic answers to these questions was considered to be perhaps up to a factor of 10 each for questions 2 and 4.

An alternative and simpler view was also taken, that works backwards through the list from the viewpoint of calculated radiological impacts of shear failure. SKB's dose estimates for 0.079 failures (Figure 13-48, SKB TR-11-01) indicate that it would require 70 to 80 times the number of failures to

exceed the regulatory dose constraint after 1,000,000 years (see Figure 13-48, SKB TR-11-01), which corresponds to a number of failures of about 6.

For the first period of 120,000 years, to reach the regulatory dose limit, it would require  $N_{crit}$  to be about 100 (i.e. about 1000 times larger than the value of 0.11 used by SKB) and in this case the number of failures would be about 5 assuming an earthquake frequency of  $7.8 \cdot 10^{-8}$  (Table 10-20, SKB TR-11-01). Not only is a  $N_{crit}$  of 100 a very large number, but it would also have to be associated with a single capable fault, as it applies to only a single earthquake. The group considered this almost inconceivable.

During the discussion, however, it was recognised realistic that 1 canister would be in critical position (i.e. about 10 times  $N_{crit}$  considered by SKB) during an earthquake due to problems and/or errors in identifying all the long fractures in real geological settings. This corresponds to a number of canisters failures of 0.05 for a period of 120,000 years. This alone would lead to a regulatory dose about 100 times below the regulatory limit for the first 100,000 years, and approximately 10 times below the regulatory limit for 1,000,000 years.

It was also observed that, being the number of critical positions  $N_{crit}$  assessed by SKB equal to 0,11 and being the number of failures 0,079 for the whole repository for a time frame of 1,000,000 years, the likelihood of a large earthquake able to cause canister failure within 1,000,000 year is nearly 1, and, on first hand approximation, nearly 0,1 for the first 100,000 years. Thus, a misjudged number of critical positions  $N_{crit}$  is of great weight in the risk calculation.

The conclusion is that, whilst these questions need to be checked carefully as SKB has presented calculations based on them, the possibility of there being considerably more canisters in poor positions that would shear and give rise to high doses seems extremely improbable. This analysis then needs to be combined with the previous assessment of earthquake frequency to get an overall answer.

On the question of whether the FPI approach would be useable at an industrial scale in real operational conditions and time constraints, the group considered that this was yet to be demonstrated. SKB has elevated the FPI model in such a way that it has now become core to their design and operation strategy. Now, not only must SKB be able to show that they can identify FPI fractures in a drill-and-blast environment before it is employed for real, they must also be auditable by independent regulatory checks of each and every measurement section.

The group also observed that there are no actual observations of secondary shear along 100 m long fractures adjacent to earthquake-hosting faults in a crystalline basement environment. This makes the whole earthquake shear model highly conceptual.

## 5 Concluding Discussion

The two working groups reported in plenary and the results were discussed. Bringing together the conclusions of both working groups allows the following observations to be drawn:

- Does an earthquake shear scenario have any greater safety significance than estimated by SKB? Group 1 postulated that the value of the earthquake frequency  $f$  may be greater than considered by SKB when taking into account post-glacial earthquakes. Group 2 considered that the possibility of there being considerably more canisters in poor positions that would shear and give rise to high doses seems possible but maybe improbable. SKB has presented calculations leading to the number of fractures of critical radius that escape the EFPC criterion, which need to be checked carefully upon. A quantitative analysis should combine the considerations made by the groups to get an overall appreciation of the safety significance of the earthquake scenario.
- If the above evaluation does indicate a case where safety impacts are significantly greater than those presented by SKB and of concern with respect to the regulations, this will need to be pinned down and further evaluation might be needed by SKB. In this case, the set of recommendations made by James McCalpin (see Section 3.4) about clarification of the existence of capable faults using LIDAR survey and carrying out a PFDHA, come into play. There are clearly some overlaps between any such work and other aspects of what SKB may do, or be required to do via license conditions, at the site in the future, in particular with future geodetic and microseismic monitoring programmes and with whether it will carry out a probabilistic seismic hazard assessment PSHA for the whole surface and underground facility (which would be a logical companion to a PFDHA, see below).
- Regardless of approach taken or assumptions made, a key conclusion of the workshop was that SKB should carry out a formal PSHA for the construction and operation of the facility (both surface and underground facilities) and it would be advisable to extend this to the post-closure period too. There are recognised approaches to PSHA for nuclear facilities and extensive worldwide experience in carrying them out. Participants assumed that it would be a normal regulatory requirement from SSM that SKB must present a PHSA for at least the construction and operational safety case of the repository.

Another of the key topics for discussion was whether the empirically observed presence of distributed fault displacements in some earthquakes reported by Youngs et al. (2003) and McCalpin (2013) would affect the values of the area-related earthquake probability estimated by SKB. An assertion was made that, if displacements of a large percentage of the displacement of the main earthquake-hosting fault could occur on faults many kilometres away from the main fault, then this was equivalent to an effective increase in the value of  $f$  (earthquake frequency within a particular area) for the repository. There was insufficient time or information to explore the topic of distributed faulting in any depth, but contextual comments were presented by Neil Chapman. In his opinion, the data presented are for normal faults in relatively young, basin and range environments of the western USA (and sources were cited for similar data on reverse and strike-slip faults), so there is a need to assess whether there is any equivalent evidence for distributed faulting in ancient crystalline basement rocks, especially as a result of post-glacial earthquakes. If a distributed fault movement occurred at a distance from a primary post-glacial seismogenic fault it may be of the order of decimetres (up to metres) in magnitude, but would seem to be limited in surface area, and if one occurred near a repository it would presumably be most likely to occur on a pre-existing fault or deformation zone, which should be avoided by SKB's layout of the repository. Distributed fault movements are part of the energy released by the overall main event, therefore they should be smaller than for the main event.

SKB's approach is to look at the energy released in an earthquake that occurs on a major deformation zone nearby the repository, the source deformation zone. SKB propagates this into a rock mechanics model to look at small fracture displacements. Whatever the origin of the earthquake, SKB concludes that it would need to be  $> M6$  at close range to affect the repository. Presumably, distributed fault displacements don't equate to  $M6$  events. Group 1 had also observed that it would take an event involving a large fault such as the Forsmark Fault, the major feature about 2 km from the repository, to host a  $M7.2$  earthquake. So it seems to be the likelihood of the large magnitude event that is the key factor, not distributed movement on deformation zones.



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## **Appendix 1**

### **Agenda**

#### **Earthquake Workshop**

**4-5 June, 2013**

**Stockholm**

**Venue: SSM office, room “Långholmen”**

#### **June 4<sup>th</sup>**

13.00 – 13.15	Welcome, introduction and presentations of participants, Sonnerfelt
13.15 – 13.45	Consequence analyses, Xu
13.45 – 14.15	Coffee
14.15 – 15.15	Seismology, mechanisms and frequencies, Bungum and Lindholm
15.15 – 16.15	Seismology, paleoseismicity and post-glacial seismicity, McCalpin
16.15 – 16.45	Structural geology, deformation zones at Forsmark, Tirén

#### **June 5<sup>th</sup>**

08.30 – 09.00	Introduction of workshop topics and assignment, Lanaro and Xu
09.00 – 10.00	Workshop assignment discussion
10.00 – 10.30	Coffee
10.30 – 12.00	Workshop assignment discussion
12.00 – 13.00	Lunch
13.00 – 14.45	Workshop assignment discussion
14.45 – 15.15	Coffee
15.15 – 16.30	Workshop assignment discussion
16.30 – 17.00	Summary of technical findings and workshop evaluation, Chapman and Sonnerfelt



## **List of participants:**

Tobias	Backers	Geomecon
Hilmar	Bungum	NORSAR
Neil	Chapman	MCM Consulting
Conrad	Lindholm	NORSAR
James	McCalpin	GEO-HAZ
Ki-Bok	Min	Seoul National University
Goodluck	Ofoegbu	Southwest Research Institute
Ove	Stephansson	Steph Rock Consulting
Sven	Tirén	Geosigma
Pål	Andersson	SSM
Björn	Brickstad	SSM
Mike	Egan	SSM
Peter	Ekström	SSM
Mikael	Kjellberg	SSM
Flavio	Lanaro	SSM
Jan	Linder	SSM
Georg	Lindgren	SSM
Jinsong	Liu	SSM
Maria	Nordén	SSM
Lena	Sonnerfelt	SSM
Bo	Strömborg	SSM
Rickard	Sundberg	SSM
Shulan	Xu	SSM







2014:22

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 315 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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