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Technical Note

2012:34

Review of FEP Handling in the SR-Site Safety Assessment: Initial Review Phase

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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 i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Syftet med detta projekt är att granska SKB's hantering av FEPs ("Features"= egenskaper, "Events"=händelser, "Processes"= processer) i säkerhetsanalysen SR-Site, vilken finns dokumenterad i en digital databas och i "FEP"- rapporten för SR-Site (SKB TR-10-45). SSM behöver bli förvissad om att SKB's metod för hantering av FEPs är försvarbar och att metoden har använts på ett grundligt och systematiskt sätt.

Författarnas sammanfattning

Den 16 Mars 2011 skickade Svensk Kärnbränslehantering AB in en ansökan för tillstånd att uppföra en inkapslingsanläggning för använt kärnbränsle i Oskarshamn samt ett slutförvar för använt kärnbränsle vid Forsmark. SKB's ansökan granskas för närvarande vid Strålsäkerhetsmyndigheten (SSM) samt vid Mark- och miljödomstolen vid Nacka tingsrätt. SSM genomför sin granskning av SKB's säkerhetsanalys i flera faser. För närvarande genomförs den inledande granskningsfasen, vars syfte är att identifiera behov av kompletterande information och förtydliganden från SKB. Denna rapport innehåller en granskning av SKB's metodik för hantering av FEPs ("Features"= egenskaper, "Events"=händelser, "Processes"= processer) i SKB:s säkerhetsanalys SR-Site.

SKB's analys och hantering av FEPs inkluderar etablerandet av SR-Sites FEP databas, vilken inkluderar SR-Sites FEP katalog vilken innehåller alla FEPs som beaktats i säkerhetsanalysen. Utvecklingen av FEP databasen som baseras på en systematisk metodik har följt en iterativ process som pågått i många år. SKB har genomfört kontroller för att försäkra sig om att det genomförda arbetet är konsekvent i förhållande till motsvarande databaser som utvecklats i andra länder. SKB:s arbete inger förtroende att ett brett urval av faktorer som kan påverka slutförvaret över relevanta tidsskalor har beaktats i säkerhetsanalysen SR-Site.

SKB:s metod för att dokumentera olika FEP i FEP-databasen skiljer sig i förhållande till den som använts i många andra länders slutförvarsprogram. Det är mera typiskt att inkludera mera fullständiga beskrivningar av FEPs samt detaljerade motiveringar till varför en viss FEP inte är relevant för säkerhetsanalysen alternativt hur den annars har hanterats i säkerhetsanalysen. Beskriviningen av FEP och dess hantering är i SKB:s databas generellt minimal med viss inkonsekvens i angreppssättet. Det finns exempel där informationen om FEP endast är skissartad, ofullständig eller inkonsekvent i förhållande till den detaljerade informationen i övriga delar av säkerhetsanalysen. En fullständig förståelse av hanteringen av FEP i SKB:s säkerhetsanalys kan endast fås i andra dokument. För att förenkla sådana kontroller samt FEP granskning och FEP revision borde SKB i sin FEP databas införa digitala länkar till relevanta delar av säkerhetsanalysen.

Denna granskning har på ett generellt plan visat att FEPs som SKB har inkluderat i sin säkerhetsanalys är spårbara via tillgängliga SKB rapporter som t.ex. SR-Sites processrapporter. FEPs som har bedömts sakna betydelse för säkerheten är dock i vissa fall otillräckligt diskuterade. Detta betyder att motiv för att utesluta FEPs har inte presenterats på ett utförligt och konsekvent sätt. Denna slutsats baseras på stick-prov som genomförts. Detta borde vara ett tema för ytterligare systematisk och mera detaljerad granskning under huvudgranskningsfasen.

Projektinformation

Kontaktperson på SSM: Bo Strömberg
Diarienummer ramavtal: SSM2011-4244
Diarienummer avrop: SSM2011-4547
Aktivitetsnummer: 3030007-4027

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) 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 on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of this project is to review SKB's FEP handling methodology in SR-Site, which has been documented in a digital database and in the FEP report for the safety assessment SR-Site (SKB TR-10-45). SSM need to be ensured that SKB's method for handling of FEP's is defensible and that the method has been implemented in a thorough and systematic manner.

Summary by the authors

On 16th March 2011 the Swedish Nuclear Fuel and Waste Management Company, SKB, submitted applications for licences to construct a spent nuclear fuel encapsulation facility in Oskarshamn and a repository for final disposal of the encapsulated fuel in Forsmark. SKB's applications are currently being reviewed by the Swedish Radiation Safety Authority, SSM, and the Land and Environmental Court in Nacka. SSM is undertaking a phased review of the safety assessment. Currently, an Initial Review Phase is being undertaken, where the overall objective is to identify requirements for complementary information and clarifications from SKB. This report provides a review of SKB's methodology for handling FEPs (features, events and processes) in SR-Site.

SKB's analysis and handling of FEPs has included the establishment of the SR-Site FEP Database, including the SR-Site FEP catalogue that contains all FEPs that are considered in the safety assessment. The development of the FEP Database has followed an iterative process over many years using a systematic methodology. SKB has undertaken checks to ensure consistency with FEP databases developed in other countries. SKB's approach builds confidence that the broad range of different factors that could influence the performance of the repository over timescales of concern has been considered in the SR-Site safety assessment.

SKB's approach to documenting FEPs in the FEP database is different to that taken in many other radioactive waste management programmes. It is more typical for fuller descriptions of FEPs to be provided with more detailed descriptions of why the FEP is not significant to the safety assessment or otherwise how the FEP has been addressed in the safety assessment. The descriptions of FEPs and FEP handling in the SKB FEP Database are generally minimalistic with some inconsistency in approach. For example, there are cases in which information on FEPs is sketchy, incomplete or inconsistent with the detailed discussion in the safety assessment reports. A full understanding of the treatment of FEPs in SKB's safety assessment can only be achieved by consulting the supporting documents. Incorporation of automatic links in the electronic SKB FEP Database to the relevant sections of the safety assessment documentation would have facilitated this process and aided FEP audits and reviews.

In general, the review has found that FEPs that SKB has included in the safety assessment are traceable through supporting reports such as the SR-Site Process Reports. However, FEPs that have been judged to have negligible impact on the safety assessment are in some cases discussed inadequately. That is, the justifications for their exclusion have not been presented consistently and comprehensively. This finding is apparent from the FEP spot-checks and should be the subject of further systematic and comprehensive review in the Main Review Phase.

Project information

Contact person at SSM: Bo Strömberg
Framework agreement number: SSM2011-4244
Call-off request number: SSM2011-4547
Activity number: 3030007-4027

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Review of FEP Handling in the SR-Site Safety Assessment: Initial Review Phase

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Contents

1. Introduction

1.1. Background

On 16th March 2011 the Swedish Nuclear Fuel and Waste Management Company, SKB, submitted applications for licences to construct a spent nuclear fuel encapsulation facility in Oskarshamn and a repository for final disposal of the encapsulated fuel in Forsmark. SKB's applications are currently being reviewed by the Swedish Radiation Safety Authority, SSM, and the Land and Environmental Court in Nacka. SSM's review is concerned with nuclear safety and radiation protection in the facilities in accordance with the Nuclear Activities Act. The Land and Environmental Court's review is concerned with compliance with the Environmental Code.

The SR-Site safety assessment for the spent fuel repository is an important component of SKB's licence application and is a focus of SSM's review. SSM is undertaking a phased review of the safety assessment involving an Acceptance Review, an Initial Review and a Main Review. Currently, the Initial Review Phase is being undertaken, where the overall objective is to identify requirements for complementary information and clarifications from SKB. In order to meet this objective, the review is aiming to achieve broad coverage of the SR-Site safety assessment and its supporting references. On completion of the Initial Review Phase, SSM will determine if the quality and comprehensiveness of the safety assessment is sufficient to warrant more detailed review in the Main Review Phase. The Main Review Phase will consist of a number of review tasks defined to address the uncertain and/or safety critical issues identified in the Initial Review Phase as requiring more comprehensive review. The Main Review Phase will be iterative and will continue until the issues raised have been resolved.

Due to the large scope and scientific breadth of the safety assessment, SSM has arranged for external experts to provide support in its review of the safety assessment. To this end, Galson Sciences Ltd (GSL) has been awarded a framework agreement with SSM concerned with undertaking quality assurance (QA) reviews of the SR-Site safety assessment. Under this framework agreement, GSL has been contracted to review SKB's methodology for handling FEPs (features, events and processes) in SR-Site and to make a number of spot-checks to ensure that the documentation of FEPs is sufficient for its purpose. This Technical Note documents the results of this review of FEPs in support of SSM's Initial Review of SR-Site.

1.2. Objective

The objective of the task is to review SKB's methodology for handling FEPs in SR-Site in order to make judgments regarding the sufficiency of SKB's approach and identify any areas of weakness in the methodology.

1.3. Approach

This review assignment has considered the discussion of FEPs in the SR-Site Main Report (SKB, 2011). However, as part of the SR-Site safety assessment documentation, SKB has provided a report dedicated to describing how FEPs have been treated in the safety assessment (SKB, 2010a). The FEP Report is accompanied by the SKB FEP Database (on a CD supplied with the FEP Report and downloadable from SKB's website). The FEP Database includes the SR-Site FEP Catalogue, which comprises information on all FEPs considered in the SR-Site safety assessment. Therefore, the review has centred on the FEP Report and FEP Database in order to gain an understanding of, and comment on, how FEPs have been handled in the safety assessment. However, the FEP Report and FEP Database do not include detailed information on FEPs. Instead, references are provided to supporting documents that describe how FEPs are treated, such as the process reports that discuss the post-closure behaviour of different components of the repository barrier system. Therefore, supporting documents have been consulted as part of the FEPs review.

It is not intended or feasible to review the treatment of every FEP in the database in detail in the Initial Review Phase. Instead, the review has involved a few spot-checks of FEPs in order to gain an understanding of the level of consistency in the treatment of FEPs in the FEP Database and the associated documentation, and to make judgments on whether the treatment of FEPs is sufficient for purpose and that the required information is available in a traceable and transparent format. Note that the review does not address scientific details in the FEP descriptions, because such details are the subject of separate technical review assignments.

1.4. Structure

Section 2 of this Technical Note sets out the main review findings. Section 3 provides recommendations regarding the sufficiency of SKB's handling of FEPs and identifies areas of weakness in the methodology. Also, in Section 3, proposals are provided regarding the complementary information and clarifications that are required from SKB in order to address the areas of weakness in the FEP methodology.

The Technical Note also includes three appendices. The first appendix records the SKB reports that have been reviewed in this work; the second appendix summarises the proposed requests for complementary information from SKB; and the third appendix lists proposed topics for further review in the Main Review Phase.

2. Main Review Findings

2.1. Development of the FEP Database

The processing of FEPs is presented as the first main step in SKB's approach to producing the SR-Site safety assessment (SKB, 2011, §2.5 and Figure 2-2). This step involves identifying all of the factors to be considered in the safety assessment analysis. SKB's approach to identifying such factors has involved an analysis of the FEPs that could influence the long-term safety of a geological disposal facility for spent fuel. It is important that this step is comprehensive and systematic, and that decisions regarding the treatment of different factors are justified, checked and properly documented. This review has focused on these quality assurance (QA) aspects of SKB's FEP analysis.

SKB's analysis and handling of FEPs has included the establishment of the SR-Site FEP Database, including the SR-Site FEP catalogue that contains all FEPs that are considered in the SR-Site safety assessment. The FEP Database has its roots in work done by SKB in the 1990s to construct interaction matrices that show interdependencies between FEPs relevant to the post-closure performance of a repository for spent nuclear fuel. The interaction matrices were constructed using the Rock Engineering System (RES) approach, whereby the main variables of the system are listed along the leading diagonal of a square matrix and interactions between the variables are given in the off-diagonal elements. Interaction matrices were developed for the buffer, near-field and far-field of the repository. These interaction matrices were presented as part of the SR 97 safety assessment (SKB, 1999a).

Also, for the SR 97 safety assessment, the interaction matrices formed the basis of the identification of processes and variables relevant to the post-closure performance of a repository. Descriptions of the processes and process diagrams illustrating interactions between processes and variables were presented by SKB (1999b). SKB (1999b) represents the first version of a process report for a KBS-3 repository and its development involved the work of many SKB staff and contractors.

The contents of the SR 97 Process Report were incorporated into a database for the SR-Can safety assessment to produce the first SKB FEP Database (SKB, 2006). The format of the database was intended to facilitate a systematic analysis of FEPs and documentation of the FEP analysis. The SR-Can FEP Database and process reports formed the basis of the SR-Site FEP Database and process reports.

SKB has approached QA of the SR-Site FEP Database by ensuring that the preparation of process descriptions and the development and handling of the SKB FEP Database were done by experts according to QA instructions. The instructions for developing process descriptions (SKB, 2008a) aimed to ensure that system component variables and processes are defined and reviewed by experts and that interactions between processes and variables are documented.

The process of developing the SKB FEP Database included auditing the database against FEPs in the NEA's International FEP Database. This auditing aimed to ensure that the FEP Database is based on a comprehensive consideration of all factors relevant to the long-term safety of a spent fuel repository. The audits were undertaken by experts according to QA instructions that required checking that all

Project FEPs contained in the NEA's International FEP Database had been considered in the SKB FEP Database (SKB, 2008b).

The experts were also required to map the FEPs in the SR-Site FEP Database to the buffer, near-field and far-field interaction matrices developed in the SR 97 safety assessment (SKB, 2008b).

The results of this FEP analysis and auditing were documented in the SR-Site FEP Report (SKB, 2010a) and in the series of SR-Site process and production reports.

In summary, although FEP processing is presented as the first step in SKB's approach to producing the SR-Site safety assessment, the development of the FEP Database has followed an iterative process over many years using a systematic methodology. Checks have been undertaken to ensure consistency with FEP databases developed in other countries and to check for consistency with the original interaction matrices developed using the RES approach in the SR 97 safety assessment. SKB's approach builds confidence that the broad range of different factors that could influence the performance of the repository over timescales of concern have been considered in the SR-Site safety assessment. However, a number of issues have been identified in the review of the FEP Database and related reports, as discussed in the following sections.

2.2. Scope of SKB's FEP Audits

SKB has audited the FEP Database against FEPs in the NEA's International FEP Database. One concern with this process is that the national (or project) FEP databases included in the NEA International FEP database were developed some ten to twenty years ago, with the most recent inclusion being SKI's FEP encyclopaedia, which was produced in 2002. Spent fuel disposal programmes in many countries have advanced significantly in this time and there may be lessons to be learnt from any more recent FEP analyses conducted in these programmes. Examples of FEP analyses that are not included in the International FEP Database are as follows:

- JNC (2000): a report on high level waste (HLW) disposal in Japan, which includes a FEP analysis.
- Nagra (2002): a report on FEP management in support of a safety assessment for the disposal of spent fuel, vitrified HLW and long-lived intermediate-level waste in Switzerland.
- Mazurek *et al.* (2003): a FEP catalogue for radioactive waste disposal in clay host rocks.
- Hwang *et al*. (2006): a FEP analysis in support of an assessment of HLW disposal in Korea.
- Miller and Nuria (2007): a FEP analysis for spent fuel disposal in Finland.
- SNL (2008): a FEP analysis for the planned Yucca Mountain repository in the US.
- ONDRAF/NIRAS (2009): a safety assessment methodology report in support of radioactive waste disposal in Belgium, which includes a FEP discussion.

- Freeze and Swift (2010): a FEP analysis for performance assessments in the US.
- Blink *et al*. (2010): a FEP analysis for spent fuel disposal in the US.
- SNL (2011): an assessment of the disposal of HLW in granite in the US, which includes a FEP analysis.
- NWMO (2011): a FEP analysis in support of an assessment of low and intermediate level waste disposal in Canada.

Of course, some of these FEP analyses were published at the time of, or shortly after, the preparation of the SR-Site safety assessment. However, some demonstration of awareness of the approaches being undertaken in the above-noted programmes and a process for responding to any significant developments in FEP analyses would further build confidence that best available methods and understanding were being used.

The reviewers acknowledge that, given the comprehensiveness of the FEP databases developed in the 1990s and the involvement of international experts from different disposal programmes in the compilation of the NEA FEP list, it is unlikely that many new FEPs have been identified in more recent work, but approaches to FEP presentation and treatment may have progressed. SKB should provide information on how it maintains an awareness of work on the description and treatment of FEPs being undertaken internationally.

2.3. QA Instructions for Process Descriptions

Parts of the QA instruction for developing process descriptions (SKB, 2008a) are stated as not being applicable to the development of descriptions of biosphere processes. Although the biosphere synthesis report (SKB, 2010b) and biosphere process report (SKB, 2010c) describe the use of an interaction matrix approach to identifying biosphere processes and identifies the project experts involved in the work in the Biosphere Project, it is not clear from the QA instructions whether SKB followed a formal QA process in establishing and checking the biosphere process list and process descriptions. Information on the QA process for developing biosphere FEPs should be provided.

2.4. Mapping of FEPs to SR 97 Interaction Matrices

FEPs in the SR-Site FEP Database have been mapped to interaction matrices developed in the SR 97 safety assessment. However, the mapping is incomplete, as acknowledged by SKB in reporting its required checks on the content of the FEP Database (SKB, 2010a, Appendix 1 and Sections 2.3.4 and 3.2). The FEP report does not explain why or in what way the mapping is incomplete. Spot-checks of the mapping have led to the following observations:

- **FEP Bu07 Piping/erosion**. The interaction matrix mapping pages include fields entitled ‘Addressed how?’, ‘Not addressed because’ and ‘Comments’. FEP Bu07 has been mapped to buffer and near-field interactions, but in each case for 'Addressed how?' it is stated simply that 'Fracturing is discussed'. The relevance of this entry to the treatment of piping and erosion is not explained and there are no references to its treatment in SR-Site.

- **FEP F07 Structural evolution of fuel matrix**. FEP F07 has been mapped to buffer and near-field interactions, but no information is given regarding how this interaction is addressed in SR-Site. The interaction matrix mapping pages include fields relating to quality assurance checking. The entry for FEP F07 has not been checked and is marked as requiring further revision.

- **FEP F17 Radionuclide transport**. FEP F17 has been mapped to several near-field interactions, but no information is given regarding how this interaction is addressed in SR-Site and the entry has not been checked and is marked as requiring further revision.

- **FEP Bu24 Speciation of radionuclides**. FEP Bu24 has been mapped to interaction *09.14d Dissolution of radioactive gas*, which is reasonable because it is noted that dissolved gases are treated as aqueous species, but surprisingly the FEP has not been mapped to interaction *09.14a Dissolution/precipitation in the near-field*.

- **External FEPs**. No external FEPs, such as future human actions FEPs, have been mapped to SR 97 matrix interactions, although this may be because such FEPs were not considered when the interaction matrices were originally developed.

In general, the entries relating to how the interactions have been addressed in SR-Site simply note that the interaction is 'mentioned', 'described' or 'considered' with no further details or references to how or where this has been done.

In conclusion, the mapping of SR-Site FEPs to SR 97 interactions is clearly incomplete and gives an impression of a lack of thoroughness in approach. However, the mapping does not appear to have a significant role in the safety assessment and, as such, the deficiencies in the mapping do not weaken the safety assessment.

2.5. FEP Audit against the International FEP Database

Appendices 3 to 10 of the FEP Report (SKB, 2010a) present the results of the audit of each SR-Site FEP against the Project FEPs contained in the NEA International FEP database. The mapping of the Initial State FEPs (Appendix 3) does not appear to have been checked because the relevant fields have not been completed. Also, the mapping of FEP *Ge10 Erosion/sedimentation in fractures* (Appendix 8) does not appear to have been checked. These omissions are also apparent in the electronic FEP Database.

Almost all of the recording, checking and revision of FEP mappings to NEA FEPs is dated December 2010, with the checking and revision having been done by Kristina Skagius. According to the FEP Report (SKB, 2010a, Section 2.3.3) the recording date indicates the date at which the final information was imported into the database. However, given that the report was published in December 2010, it is unclear what the dates shown in the appendices represent, but the impression is given that most of the FEP recording, checking and revision work was done in December 2010.

SKB should provide completed QA records of the FEP audit.

2.6. FEP Categories

There is some minor confusion in the classification of FEPs. The FEPs are initially classified as being 'initial state', 'internal processes', 'external', 'assessment methodology' or 'irrelevant' FEPs in the FEP Report (SKB, 2010a, Section 1.1 and Figure 2-3) as reproduced in Figure 2.1. The treatment of the 'initial state' classification is confusing, because FEPs in this classification are divided into two groups (SKB, 2010a, Section 4.2) with one group related to the reference initial state and the other group related to deviations from the reference initial state. The FEPs related to the reference initial state are included in the group of FEPs called 'variable' FEPs and the FEPs related to deviations from the reference initial state are defined as 'initial state' FEPs. It would have been clearer throughout if the latter group had been called, say, 'initial state deviation' FEPs. Also, it would have been helpful if the 'variable' FEP category had been identified in SKB (2010a, Figure 2-3).

The category of FEPs called 'site-specific factors' is introduced in the FEP Report (SKB, 2010a, Section 5.7) and in the FEP Database. This FEP category is not discussed in the overview of FEP processing in SKB (2010a, Section 2.2) or in SKB (2010a, Figure 2-3) that shows the handling of FEPs in SR-Site. The figure should also indicate a connection between the external FEPs box and the geosphere process report (SKB, 2010d) for geosphere FEPs.

Lists of the different categories of FEPs are presented in SKB (2010a, Section 5). SKB (2010a, Table 5-1) lists the initial state FEPs, but references to where these FEPs are considered in SR-Site have not been provided, which hinders traceability of FEP treatment through the safety assessment documentation. However, information on the treatment of initial state FEPs is provided in FEP records in the electronic FEP Database.

SKB (2010a, Figure 2-3) and associated discussion should be revised to correctly reflect the FEP processing procedure, FEP categories and links to process reports.

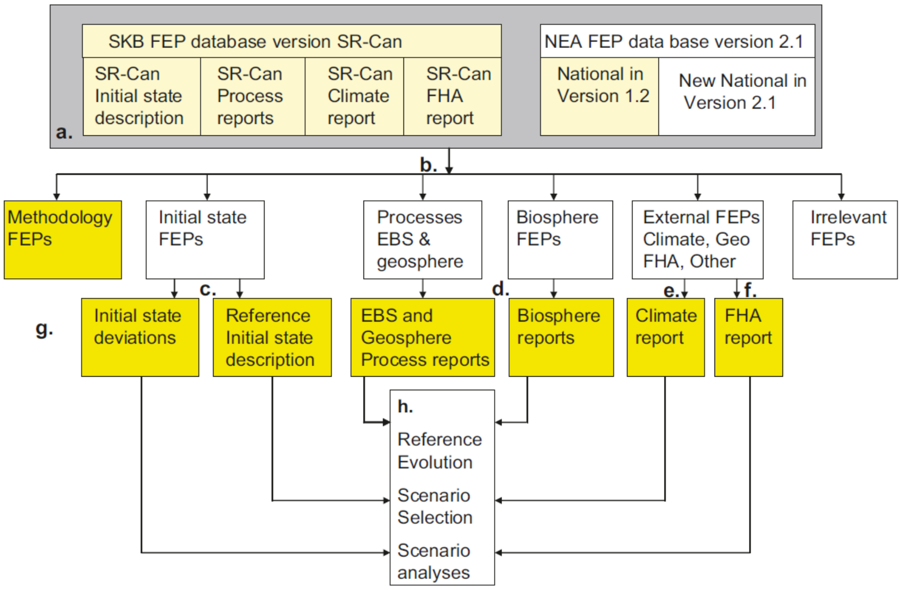

Figure 2.1: Diagram showing handling of FEPs (SKB, 2010a, Figure 2-3). Variables and site-factor FEPs are not shown and the external FEPs box should show a connection to the Geosphere Process report.

2.7. Excluded FEPs

A number of Project FEPs included in the NEA International FEP database have been determined to be irrelevant to the KBS-3 disposal concept. Generally, this approach appears reasonable, although in some cases the exclusion is questionable. For example:

- Project FEP *K 1.23 Radiolysis* has been determined to be irrelevant. However, the FEP is concerned with radiolysis of water and should be mapped to FEP *Bu20 Radiolysis of porewater*. Presumably the FEP has been excluded because a glass wasteform is mentioned in the discussion of the FEP, but this is not significant to the actual process of concern.

- Project FEP *E SFR-22 Changes in radionuclide inventory* has been excluded, but the FEP could reasonably be mapped to SKB FEP *F01 radioactive decay*.

However, the exclusion or otherwise of such FEPs does not affect the scope of the SR-Site FEP catalogue, because the FEPs are captured in other Project FEP lists and are correctly mapped to FEPs in the SKB FEP Database.

2.8. FEP Documentation in the FEP Catalogue

The FEP Catalogue includes fields for presenting each FEP's 'Description/Definition' and its 'Handling in SR-Site'. There is inconsistency in the type of material presented in the FEP Catalogue. In most cases the entries are very brief and supporting references need to be consulted to gain a full understanding of the FEP and how it has been treated. For example, spot checks on FEPs have revealed:

- FEP *F01 Radioactive decay*. The handling of this FEP in SR-Site is described as ‘Thermal model’ for the intact canister and simply ‘COMP23’ for the failed canister.

- FEP *F14 Speciation of radionuclides, colloid formation*. The handling of this FEP in SR-Site is described as ‘Not relevant’ for the intact canister and ‘COMP23’ for the failed canister.

- FEP *Cli04 Climate system - Climate in Sweden and Forsmark*. This FEP is described simply as ‘Present-day climate in Sweden and at Forsmark’ and regarding handling in SR-Site it is described as the ‘[b]asis for identification of climate-related issues relevant to the long-term safety of a KBS-3 repository’.

- FEPs *Cli05 Climate related issues – development of permafrost, Cli06 Climate related issues - ice-sheet dynamics* and *Cli07 Climate related issues - ice-sheet hydrology*. These FEPs have far more detailed descriptions and discussions of how the FEPs have been addressed, including modelling and analogue studies.

- The FEP Catalogue records do not include discussions of how the biosphere component FEPs *CompBio01* to *CompBio15* are addressed in SR-Site.

SKB’s approach to documenting FEPs in the FEP database is different to that taken in many other radioactive waste management programmes. As exemplified in the Project FEP entries in the NEA FEP Database, it is more typical for fuller descriptions of FEPs to be provided with more detailed descriptions of why the FEP is not significant to the safety assessment or otherwise how the FEP has been addressed in the safety assessment. The descriptions of FEPs and FEP handling in the SKB FEP Database are generally minimalistic and are inconsistent in approach. A full understanding of the treatment of FEPs in SKB’s safety assessment can only be achieved by consulting the supporting documents. Incorporation of automatic links in the SKB FEP Database to the relevant sections of the safety assessment documentation would have facilitated this process and aided FEP audits and reviews. Note that FEP numbers are not retained in the supporting documents, which slightly reduces traceability.

2.9. Process Diagrams and Influence Tables

The SKB FEP Database includes process diagrams that provide a useful visual indication of the coupling between processes and variables in each system component and influence tables that provide brief information on what these couplings are and how they are treated in the safety assessment. However, the references need to be consulted to fully understand the couplings. The influence tables are reproduced in the process reports, with more detailed discussion of the processes and variables.

Also, process diagrams and influence tables are not available for all FEPs. For example, there is no process diagram or influence table for FEP *C15 Radionuclide* *transport* or for several of the Backfill FEPs related to radionuclide transport (e.g., BfT19, BfT20, BfT21, BfT22) (see Figures 2.2 and 2.3). These process diagrams and influence tables should be provided.

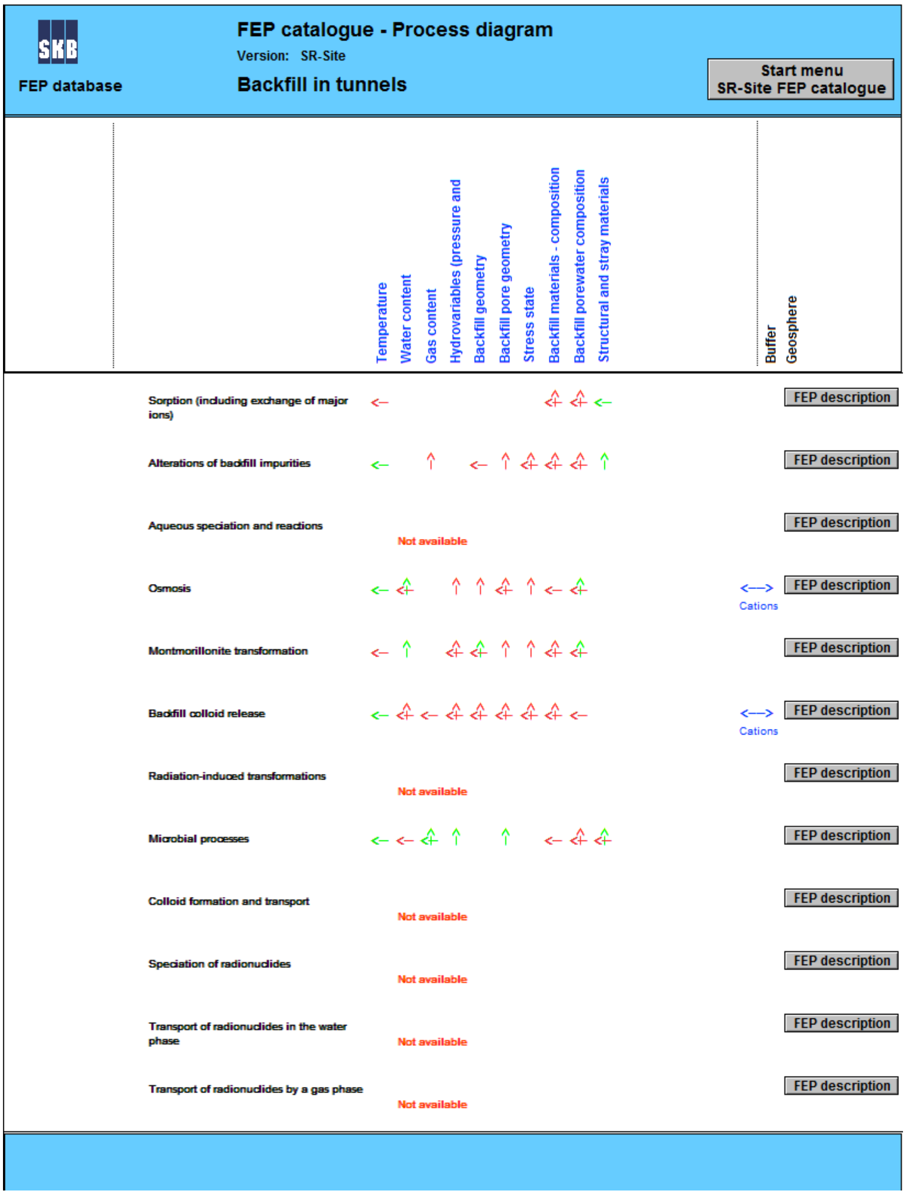

Figure 2.2: Extract from the SKB FEP Database indicating missing Process Diagrams.

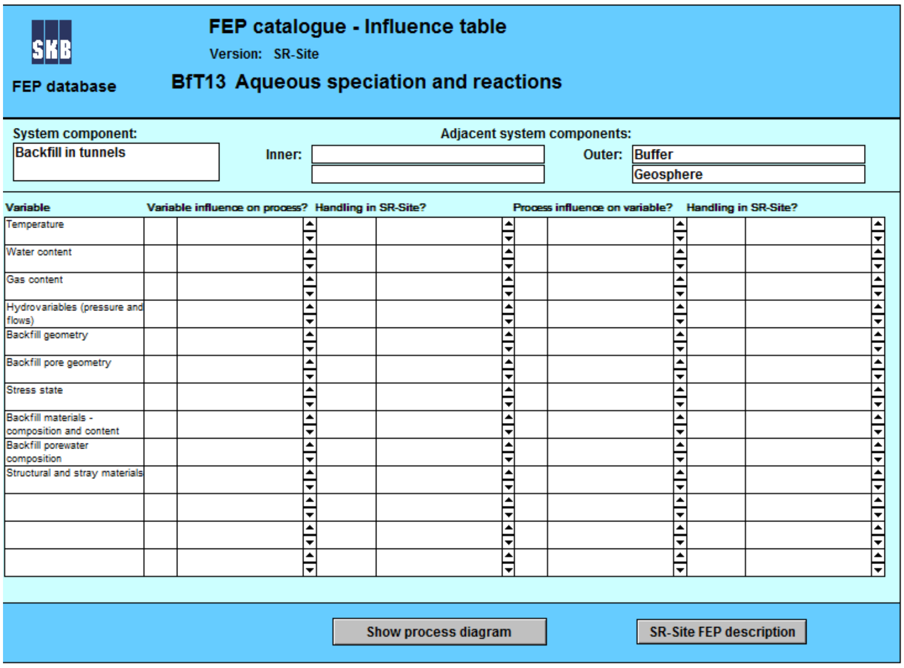

Figure 2.3: Extract from the SKB FEP Database indicating an Influence Table that has not been completed.

2.10. AMF Charts and Tables

The assessment model flow charts (AMFs) and AMF Tables in the SKB FEP Database provide helpful links to models used to assess different processes. However, there are some inconsistencies with regard to the models described and discussed in the AMF Tables. For example, with regard to the modelling activity *Groundwater composition over glacial cycle* in the AMF chart, linked FEPs *Ge03 Groundwater flow*, *Ge11 Advective transport/mixing of dissolved species* and *Ge12 Diffusive transport of dissolved species in fractures and rock matrix* refer only to the use of Darcy Tools. However, the AMF Table indicates that PhreeqC was used. A similar issue arises for the modelling activity *Oxygen penetration during glacial period*, where PhreeqC, PHAST and analytical expressions are indicated as having been used rather than Darcy Tools. The references for these modelling activities are not reflected in the FEP Catalogue. This finding indicates that some FEP descriptions may not be consistent or up-to-date with all of the analyses in which they are addressed. The AMFs and AMF Tables should be updated such that they are consistent with the actual treatment of FEPs.

2.11. FEP Spot Checks

It is not feasible to review the treatment of every FEP in the database in detail in the Initial Review Phase. Instead, the review has included detailed spot-checks of a few FEPs in order to gain an understanding of the level of consistency in the treatment of FEPs in the FEP Database and the associated documentation, and to make judgments on whether the treatment of FEPs is sufficient for purpose and that the required information is available in a traceable and transparent format. The following sub-sections provide the results of these FEP spot-checks.

2.11.1. F03 Induced Fission (Criticality)

The description of FEP F03 in the FEP Catalogue of the SKB FEP Database states that the FEP refers to the possibility for induced fission and criticality inside the canister. Regarding handling of the FEP in the SR-Site safety assessment, it is stated that criticality in an intact canister is neglected because an insufficient amount of moderator would be present for criticality and that criticality in a failed canister can be neglected if credit is taken for fuel burn-up in the reactor. Reference is made to the Fuel and Canister Process Report (SKB, 2010e, Sections 1.6 and 2.1.3) for the detailed discussion of the FEP. A very minor inconsistency is that the discussion of FEP F03 in the relevant process table of the SKB FEP Database refers to the discussion of criticality in the Main Report (SKB, 2011, Section 13.3) rather than the Fuel and Canister Process Report, although the Main Report does refer to the Fuel and Canister Process Report.

FEP F03 does not appear to cover the possibility of criticality outside a failed canister and there is no FEP in the SKB FEP Database that relates directly to such a criticality event. However, the mapping of Project FEPs in the NEA International FEP Database has resulted in the linking of many FEPs that do cover criticality outside the canister to FEP F03. In the discussion of how linked FEPs have been treated, it is stated that criticality outside the canister "can be excluded" for a KBS-3 repository. However, no discussion of why such criticality can be excluded is given or cited. The scope of FEP F03 should be broadened or a separate FEP should be introduced that covers criticality outside the canister, and reference should be made to arguments that support the judgment that such criticality can be excluded.

SKB (2011, Section 13.3) and SKB (2010e, Section 2.1.3) refer to Agrenius (2010) and the main report of the SR-Can safety assessment for discussion of how the criticality FEP is addressed in the SR-Site safety assessment. Note that Agrenius (2010) is listed in the safety assessment as an unpublished document (SKB, 2011, Section 16). However, the document was found to be available from SKB's website.

Agrenius (2010) and the discussion in SKB (2010e, Section 2.1.3) do support the judgment that, based on consideration of burn-up, criticality would not occur in a failed canister. Note that Agrenius (2010) does discuss the fact that the reactivity of spent fuel may increase in the long term (on a timescale of 10,000 years) as a result of the decay of neutron absorbers ^{241}Am and ^{240}Pu. However, this issue is not discussed in the Fuel and Canister Process Report.

The issue of criticality outside a canister is discussed in SKB (2010e, Section 2.1.3), with references to work by Behrenz and Hannerz (1978), Oversby (1996;1998) and work on the proposed Yucca Mountain repository in the US to support the view that the possibility of criticality outside the canister is small. However, the arguments that support this judgment are not presented and the supporting documents would need to be consulted to gain a full understanding of why criticality outside a canister is considered unlikely. Note that the engineered and natural barrier system and post-closure conditions in the proposed Yucca Mountain repository would be substantially different to those of the KBS-3 concept and therefore the applicability of the Yucca Mountain work to the Swedish concept is questionable.

The arguments that support judgments on the probability of criticality outside a canister should be presented in the context of the KBS-3 repository concept. Also, SKB (2010e, Section 2.1.3) does not discuss the potential consequences of criticality in terms of direct radiological impacts, impacts on the barrier system or long term radiological impacts. A discussion of the potential consequences of criticality would build confidence in the understanding of repository post-closure criticality issues. Also, SSM should consider the acceptability of the safety case's reliance on burn-up credit and disposability requirements on substantiation of spent fuel properties.

2.11.2. C11 Corrosion of Copper Canister

The FEP Catalogue provides only a very brief description of FEP C11 and how it is handled in the SR-Site safety assessment. It is stated that copper corrosion is not relevant for a failed canister. Short statements are provided to indicate how corrosion of an intact canister is handled, and it can be gleaned that:

- Copper corrosion is modelled based on mass balance and transport capacity considerations and not reaction rates.
- Sulphide in the buffer and backfill is modelled. Microbially generated sulphide in the buffer is bounded by the supply of nutrients.
- All initial oxygen in the buffer is assumed to corrode copper, neglecting consumption by buffer pyrite and rock. Initial oxygen in the tunnel backfill is consumed by the host rock and by microbes. There is integrated handling of rock, backfill and buffer conditions for potentially intruding oxygen.
- Pitting corrosion associated with oxygen is described as uneven general corrosion.
- Corrosion due to radiation results in negligible corrosion depths.
- Chloride assisted corrosion is neglected if pH > 4 and $[Cl^-] < 2M$.
- Corrosion effects on cold worked material are neglected due to small consequences.
- Corrosion by water is modelled as a 'what-if case'.

Thus, only a loose understanding of the handling of copper corrosion can be gained from the FEP Catalogue entry for FEP C11.

More information on the treatment of copper corrosion is provided in the descriptions of how linked NEA Project FEPs are addressed or not in the safety assessment (SKB FEP Database and SKB, 2010a, Appendix 5). From this discussion the following additional information may be derived:

- Uniform corrosion is controlled by the supply of sulphide in the buffer and backfill in the long term. During the aerobic period pitting and stress corrosion cracking could occur.
- A hole in the copper canister could be closed due to clogging by iron corrosion products but this is not addressed because the probability of clogging cannot be assessed.
- The consequences of radiolytically generated corrosive gases are discussed.

- Changes in groundwater salinity are considered.

- The gap between the copper and iron is closed quickly by copper creep.

- Bacterial activity in the bentonite barrier is "considered and dismissed", although this is most likely a typographical error because the effects of bacterial activity are included.

- The effects of temperature on the transport of corrodants are of limited importance.

- The effect of temperature on copper corrosion can be neglected.

- Corrosion caused by fission products is negligible. All the iodine in a canister can corrode less 100 g of Cu.

- Changes in groundwater chemistry caused by the construction are of negligible importance for long-term corrosion.

More information can be found in the process influence diagram and table for FEP C11:

- There is a complex dependence of copper corrosion on temperature but this is neglected because corrosion is modelled using transport control and mass balance.

- Corrosion products are formed but their growth is too slow to create additional pressure on the canister, although there is no detailed discussion to support this view.

In summary, only a sketchy understanding of the treatment of copper corrosion can be obtained from different components of the SKB FEP Database and FEP Report and the cited SR-Site reports must be consulted to gain a clearer understanding of how the copper corrosion FEP has been handled in the safety assessment. The FEP Catalogue entry for FEP C11 refers to the Fuel and Canister Process Report (SKB, 2010e, Sections 1.10 and 3.5.4), whereas the relevant process table in the FEP Catalogue refers to the Main Report (SKB, 2011, Sections 10.3.13 and 10.4.9).

In general, more detailed information can be found on each aspect of copper corrosion identified in the FEP Catalogue. However, the reviewers observe that:

- In the Main Report (SKB, 2011, p418) and the Fuel and Canister Process Report (SKB, 2010e, p102) it is stated that copper corrosion processes would only be marginally affected by the changes in temperature expected in the repository. SKB (2010e, p108) notes that localised corrosion is affected by temperature and the degree of corrosion should decrease as temperature decreases. However, there is no detailed discussion of the sensitivity of corrosion processes to temperature and there are no references to such discussion.

- There appears to be no discussion of the potential for clogging of a hole in the copper canister from iron corrosion products. Some discussion of this process and any experiments being undertaken that could support its understanding would be beneficial, because it could support arguments regarding the cautious treatment of the effects of canister corrosion in the safety assessment.

- The SR Site safety assessment reports do not discuss the potential for fission products to affect copper corrosion if released from fuel assemblies in the canister. There is no support for the statement in the FEP catalogue that iodine in a canister can corrode less than 100 g of Cu.

2.11.3. Oth01 Meteorite Impact

The meteorite impact FEP entry in the FEP Catalogue states that the FEP has been excluded from further analysis. It is argued that it is demonstrably extremely unlikely that a meteorite large enough to damage the repository will impact in the vicinity of the repository footprint and that the direct effects of such an impact would be much more severe than its possible radiological consequences.

The FEP catalogue entry has no references to discussions or arguments to support these assertions. However, a more detailed justification for excluding meteorite impact, including references to supporting documents can be found in the FEP Report (SKB, 2010a, Section 4.3.4). The discussion also refers to the handling of meteorite impact in Project FEP databases contained in the NEA International FEP Database. The inclusion of a FEP discussion in the FEP Report is unusual, because no other FEPs are dealt with in this way in the FEP Report. However, although there is a lack of connection from the FEP Catalogue to the FEP Report, the basis of the exclusion argument is reasonable.

2.11.4. Bu07 Piping/erosion

The FEP Catalogue describes FEP Bu07 as piping in the bentonite, formation of a channel and a continuing water flow and erosion of soft bentonite gel. The discussion in the FEP Catalogue of how FEP Bu07 is handled in the SR-Site safety assessment is cursory and refers only to the situation when the canister is intact. It is stated that a model study is undertaken to address the FEP for the thermal period and that the FEP is not relevant in the long-term after saturation and the thermal period, and it is not relevant to scenarios involving earthquakes. Reference is given to the Buffer, Backfill and Closure Process Report (SKB, 2010f, Sections 2.2.4 and 3.3.4) and the Main Report (SKB, 2011, Section 7.4.3).

The discussion of FEP of linkages to NEA Project FEPs provides a little more information on FEP handling. It is stated that piping can lead to increased hydraulic conductivity and pathways in the buffer.

A more detailed description is provided in SKB (2010f, Section 3.3.4), which covers the current understanding of the process and experimental work to further develop that understanding.

3. Recommendations to SSM

The development of the FEP Database has followed an iterative process over many years using a systematic methodology. SKB has undertaken checks to ensure consistency with FEP databases developed in other countries. SKB's approach builds confidence that the broad range of different factors that could influence the performance of the repository over timescales of concern has been considered in the SR-Site safety assessment.

SKB's approach to documenting FEPs in the FEP database is different to that taken in many other radioactive waste management programmes. It is more typical for fuller descriptions of FEPs to be provided with more detailed descriptions of why the FEP is not significant to the safety assessment or otherwise how the FEP has been addressed in the safety assessment. The descriptions of FEPs and FEP handling in the SKB FEP Database are generally minimalistic with some inconsistency in approach. For example, there are cases in which information on FEPs is sketchy, incomplete or inconsistent with the detailed discussion in the safety assessment reports. A full understanding of the treatment of FEPs in SKB's safety assessment can only be achieved by consulting the supporting documents. Incorporation of automatic links in the electronic SKB FEP Database to the relevant sections of the safety assessment documentation would have facilitated this process and aided FEP audits and reviews.

In general, the review has found that FEPs that SKB has included in the safety assessment are traceable through supporting reports such as the SR-Site Process Reports (although this review has not considered technical issues regarding FEP treatment). However, FEPs that have been judged to have negligible impact on the safety assessment are in some cases discussed inadequately. That is, the justifications for their exclusion have not been presented consistently and comprehensively. This finding is apparent from the FEP spot-checks. For example, arguments to support the view that criticality in the repository would be unlikely or insignificant are not presented in sufficient detail to justify exclusion from the safety assessment. Also, a number of corrosion-related factors have been excluded without sufficient justification (e.g. temperature effects, effects of corrosive fission products).

This initial review has concluded that, rather than undertake further reviews of FEPs included in the safety assessment, in the Main Review phase SSM should review in more detail and more comprehensively the decisions made by SKB to exclude FEPs (or certain components of FEPs) from the safety assessment. That is, a systematic review of each FEP, including the information available in the linked NEA Project FEP databases, should be undertaken to identify aspects of FEPs that have been excluded from the safety assessment and to determine if the exclusion is reasonable and does not undermine confidence in the safety assessment.

Other specific issues raised by the review of the FEP Database may be summarised as follows:

- The FEP audits were undertaken against information on national FEP databases published ten to twenty years ago. There may be lessons to be learnt from any more recent FEP analyses conducted in such radioactive waste management programmes.

- It is not clear from the QA instructions if SKB followed a formal QA process in establishing and checking the biosphere process list and process descriptions.

- The mapping of SR-Site FEPs to SR 97 interactions is incomplete, but it is unclear what purpose the mapping actually serves in the safety assessment.

- QA records of the mapping of FEPs to NEA Project FEPs are incomplete.

- Process diagrams and influence tables are not available for all FEPs.

It is accepted that some of these issues are minor and are not significant to the reliability of the safety assessment, other than to reduce confidence in the thoroughness of the applied methodology.

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APPENDIX 1

Coverage of SKB reports

Report sections considered in this review are listed in the table below.

Table A:1

Reviewed report	Reviewed sections	Comments
TR-11-01, Long-term safety for the final repository for spent nuclear fuel at Forsmark, Main report of the SR-Site Project	Sections 1-3, 5, 7, 8, 13.3, 13.5, 10.3, 10.4	
TR-10-45, FEP Report for the Safety Assessment SR-Site	Entire	
Digital SKB SR-Site FEP database	Entire	All components and features of the database were examined to understand the methodology and selected FEPs were reviewed in detail
R-10-37, Components, Processes and Interactions in the Biosphere	Section 4	
TR-10-46, Fuel and Canister Process Report for the Safety Assessment SR-Site	Sections 1, 2.1.3, 3.5.4	
Public Report 1193244, Criticality Safety Calculations of Disposal Canisters	Entire	
KBS TR 108, Criticality in a Spent Fuel Repository in Wet Crystalline Rock	Summary	
KBS TR 108, Criticality in a Spent Fuel Repository in Wet Crystalline Rock	Summary	
1082127, Instruction for Developing Process Descriptions in SR-Site and SR-Can.	Entire	
1082126, Instruction for Development and Handling of the SKB FEP Database – Version SR-Site.	Entire	

TR-10-47, Buffer, Backfill and Closure Process Report for the Safety Assessment SR-Site	Sections 2.2.4, 3.3.4	
TR-99-20, SR 97 – Identification and Structuring of Process	Entire	Report consulted to understand original basis for FEP methodology
TR-99-07, SR 97 Process in the Repository Evolution	Section 2	Report consulted to understand original basis for FEP methodology

APPENDIX 2

Suggested needs for complementary information from SKB

The list below records suggested questions to SKB for clarification and complementary information as identified during this review.

1. SKB has audited its FEP Database against FEP databases that were developed some ten to twenty years ago. SKB should provide information on how it maintains an awareness of more recent and on-going work that is being undertaken by other organisations and internationally and incorporates such developments into its FEP analysis.
2. SKB should provide information on the QA process for establishing and checking the biosphere process list and process descriptions.
3. The FEP Report (SKB, 2010a) shows incomplete QA records of the FEP audit for some FEPs. SKB should confirm that the FEP audit was checked for all FEPs.
4. SKB should provide detailed justifications to support the view that criticality in the repository (including outside the canister) would be unlikely and that the effects of criticality would be insignificant.
5. SKB should provide detailed justifications to support the view that temperature effects and the effects of corrosive fission products and the effects would not be significant for copper corrosion.

APPENDIX 3

Suggested review topics for SSM

The list below records recommendations for issues requiring more detailed review in the SSM Main Review Phase:

1. In general, the review has found that FEPs that SKB has included in the safety assessment are traceable through supporting reports such as the SR-Site Process Reports. However, FEPs that have been judged to have negligible impact on the safety assessment are in some cases discussed inadequately and sometimes only in the electronic FEP Database. Thus, rather than undertake further reviews of FEPs included in the safety assessment, in the Main Review phase SSM should review in more detail and more comprehensively the decisions made by SKB to exclude FEPs (or certain components of FEPs) from the safety assessment. That is, a systematic review of each FEP, including the information available in the linked NEA Project FEP databases, should be undertaken to identify aspects of FEPs that have been excluded from the safety assessment and to determine if the exclusion is reasonable and does not undermine confidence in the safety assessment.

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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 270 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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