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Technical Note

2012:65

Review of the Nuclear Criticality Safety of SKB's Licensing Application for a Spent Nuclear Fuel Repository in Sweden

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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

Uppdraget är ett led i SSM:s granskning av SKB:s ansökan om slutförvaring av använt kärnbränsle. Detta uppdrag avser granskning av nukleär kriticitetssäkerhet.

Författarens sammanfattning

Svensk Kärnbränslehantering AB ansökte 2011 om svenska regeringens tillstånd för en föreslagen lösning för slutförvaring av använt bränsle från svenska kärnkraftverk och en del mindre kvantiteter av annat fissilt material.

Denna Technical Note innehåller resultat från en färsk genomgång av nukleär kriticitetssäkerhet för att bedöma de övergripande förutsättningarna för om ansökan kommer att klara de formella bestämmelserna.

Ett antal frågeställningar har identifierats för vidare bearbetning. Sådana frågeställningar inkluderar säkerhetskriterier, säkerhetsmarginaler, tilllämplighetsbekräftelse av metoder samt potentiella konsekvenser av en kriticitetsolycka.

Den övergripande slutsatsen är att tillräcklig nukleär kriticitetssäkerhet kan klaras utan att orsaka oacceptable sidoeffekter (exempelvis stråldoser, användning av naturresurser, kontaminering, minskad samhällsnytta av verksamheten).

Projektinformation

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Diarienummer: SSM2012-790
Aktivitetsnummer: 3030007-4107

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

This project is part of SSM:s review of SKB:s license application for final disposal of spent nuclear fuel. The assignment concerns a review of the nuclear criticality safety.

Summary by the author

The Swedish Nuclear Fuel and Waste Management Company in 2011 applied to the Swedish government for approval of a proposed solution for disposal of used fuel from Swedish nuclear power reactors and some relatively minor quantities of other fissile material.

This Technical Note contains results of a recent nuclear criticality safety review of the overall prospects of the application being able to meet regulatory requirements.

A number of issues have been identified for further elaboration. Such issues include safety criteria, safety margins, method validation and potential criticality accident consequences.

The overall conclusion is that adequate nuclear criticality safety can be obtained without causing unacceptable side-effects (e.g. radiation doses, use of natural resources, contamination, lost benefits to society from the activity).

Project information

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Contents

1. Introduction

Before loading of a new reactor with nuclear fuel could be approved by the government, a Swedish law introduced in 1977 required an acceptable plan for the nuclear fuel after being used in the reactor.

At first, this law was complied with by signing reprocessing contracts for recovery of uranium and plutonium from the spent fuel. This law was in force until 1984, leaving establishment of an acceptable final disposal solution as the only remaining alternative. The law was merged with the Act on Nuclear Activities (1984:3).

SKBF, the predecessor of SKB, in the years 1977 and 1978 prepared two ambitious studies on final disposal of waste from reprocessing (KBS-1) and on direct disposal of the spent fuel (KBS-2). Some of the results from those studies are still applicable. In 1983 an application for start of new reactors was supported by a demonstration for final direct disposal of spent fuel (KBS-3). This was eventually approved by the licensing authorities and by the government.

SKB has in 2011 applied for approval, according to the Nuclear Activities Act (1984:3), for construction of a final repository for nuclear fuel that has been used in Swedish nuclear reactors, as well as for other associated radioactive wastes. The method is still referred to as KBS-3, even though there are some changes from the 1983 specifications.

SKB has also applied for approval, according to the Environmental Code (1998:808), for the integral solution to long-term safety and environment consideration related to the same material.

Radiation protection is concerned with protection of people and the environment from the harmful effects of ionizing radiation now or in the future,. Nuclear safety as defined by the Swedish act of nuclear activities is concerned with both prevention of errors or malfunctions that may lead to radiological accidents and prevention of illegitimate handling of nuclear materials or nuclear waste. Nuclear criticality safety takes this one step further by trying to prevent divergent fission chain reactions and thus to prevent new radiation. Radiation safety covers nuclear safety and radiation protection, as well as some other concerns.

This technical note focuses on the prospect for nuclear criticality safety in the final disposal proposed in the SKB application. This has been reviewed on request by the Swedish Radiation Safety Authority (SSM). The full application for final disposal is covered, including the Environment Impact Statement (EIS). The objective of the review is to determine the credibility of implementing the conclusions in the application and the appropriateness of the criticality safety procedures. SSM will review the specific, detailed evaluations of various scenarios at a later stage.

The criticality safety at the storage plant Clab, in operation since 1985, and at a proposed extension of Clab with an encapsulation plant, has been reviewed in a separate project, also on request by SSM. The current report covers a review of the closed copper canisters containing spent nuclear fuel, after the closure has been approved at the encapsulation facility.

The potential for failure of the canister to allow water in-leakage and/or escape of fissile material from a canister needs to be considered. As always in a criticality safety assessment, the potential human factor influence needs to be considered.

The balance between criticality safety and other considerations needs to be considered.

2. The SKB application

2.1. Application for final disposal of spent nuclear fuel

The SKB license application for final disposal of spent nuclear fuel was made on 16 March 2011. The application involves the construction, ownership and operation of the facility (including dealing with the nuclear material within the facility). In addition SKB requests that the EIS be approved.

This chapter contains extracts from and the author's interpretation of information in the SKB application.

SKB also requests that the Government stipulates some specific conditions for the license:

- Conformity with the application documents,
- SKB submittal to SSM of a construction safety report for approval
- Permission for SSM to approve changes in the reference design.

The EIS as well as the SR-Drift (Swedish for Operation) and SR-Site safety reports are documents directly supporting the license application for final disposal. In addition, there are many references that are also considered parts of the application.

The fact that the EIS shall be included in the license application, according to the Nuclear Activities Act, may require some clarification. According to the license application, Section 1.6, "SKB assumes that SSM will prepare the matter based on nuclear safety and radiation protection and leave the assessment of other impacts on the surroundings to the environmental court".

The SKB response to Chapter 2, section 5 of the Environmental Code is of interest. It requires housekeeping with raw materials and energy as well as taking advantage of possibilities for recycling and recovery. The response is included in Appendix AH to the application:

- Section 5.1.2 estimates that the total quantity of copper will amount to 45 000 tonnes. The copper will not be reusable (no reason given).
- Section 5.2.2 admits that objections have been raised against final disposal of the spent fuel since more energy can be extracted. This requires reprocessing which SKB does not consider economically or otherwise appropriate.

SKB refers to safety with a quote from the general guidelines in SSMFS 2008:21. Safety is "the ability of a final repository to prevent the dispersion of radioactive substances".

SKB also refers to the SSMFS 2008:37 risk criterion that: "the annual risk of cancer or hereditary defects from radiation doses caused by releases from the final repository may not exceed one in a million for those individuals who are exposed to the highest risks”. This is also expressed by SKB as one-hundredth of the natural background radiation in Sweden.

As SKB describes in the application, the best available technology (BAT) is referred to both in the Environmental Code chapter 2 (required by the Nuclear Activities Act) and in SSMFS 2008:37. The quoted SSM text refers to releases from the barriers.

The ALARA principle (As Low As Reasonably Achievable) with regard to economic and societal factor is quoted from SSMFS 2008:26.

SKB refers to guidelines in SSMF 2008:37 concerning the period of time to be covered by the application. Two time periods are referred to, up to a thousand years and the time thereafter. However, the risk analysis appears to be divided into two other periods: up to one hundred thousand years and the period up to one million years.

2.2. Specifications of the spent nuclear fuel

The scope of the application covers spent nuclear fuel from Swedish reactors. Most of the spent fuel comes from LWR (Light-Water Reactor) of either BWR (Boiling-Water Reactor) or PWR (Pressure-Water Reactor) types but some are from older and smaller Swedish reactors like Ågesta and R1.

In addition, due to reprocessing contracts from 1977 and 1978 (Wikdahl 2005)[1], plutonium from some reprocessed Swedish reactor fuel was exchanged with spent BWR- and PWR-MOX (Mixed OXides of uranium and plutonium) fuel from Germany. Additional plutonium from reprocessing is expected to be included in BWR MOX fuel for use at the Oskarshamn reactor site.

In common for all the fuel types is that the uranium has a low assay of ^{235}U and that the ratio of plutonium to uranium is also low. There may be small quantities of other fissile material that are not important for criticality safety.

2.3. The final disposal site and transports

Each copper canister is essentially a cylinder with 5 cm thickness, about 1 m outer diameter and 5 m outer length. Two different nodular iron inserts have been designed. Each insert essentially fills a copper canister. The BWR fuel insert has 12 positions for spent BWR fuel assemblies while the PWR insert has 4 positions for spent PWR fuel assemblies. Such inserts are also expected to be used for the other types of spent fuel to be disposed of.

This report covers the license application from the moment the copper canisters are welded tight and approved for transport at the encapsulation facility at Simpevarp.

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[1] Application quotes are: The EIS, Section 1.3: “At an early stage of the Swedish nuclear power programme” and Section 1.1: “1977 – the Stipulations Act, which stated that the spent fuel should either be reprocessed”

Transportation of the copper canisters with spent nuclear fuel from the encapsulation plant to the final disposal site is covered by the application and by this review. However, there is not yet any specific information on the transport package design to be used. It is known that the copper canisters need to be packaged inside an outer packaging to reduce the potential for damage and for additional radiation shielding.

The procedures for design and licensing of transport packages are bound by international and national regulations.

Section 2.3.3 of the application states that: “the gamma and neutron radiation is high even outside the canister”.

At the time of the application, it was estimated that about 6 000 copper canisters need to be disposed of in the rocks at Forsmark. The site will consist of tunnels going down to a depth of about 500 m where one deposit hole for each canister will be prepared. The holes and tunnels are eventually filled with bentonite clay. The copper canister, the bentonite clay and the granite rock are considered as barriers for containment of the radioactive material.

The possibility of retrieval of canisters from the repository sometime in the future is addressed in the SKB application. This is considered to “be resource-consuming but not impossible”. There is no formal requirement of making retrieval possible. It is not the intention of final disposal that deposited canisters should be retrieved. It is stated in both the SSM 2008:22 and SSM 2008:37 that any actions taken to facilitate retrieval of the waste should be analysed and reported.

Alternatives to the proposed final disposal are discussed in the application. One is that the spent fuel may be considered as a resource and not as a waste. Related to this view is the strategy (4) of long-term storage such as in Clab, waiting for other alternatives to clarify.

One group of scenarios involves future human actions that should be considered in the safety assessment.

2.4. Criticality safety in the application

SKB refers to nuclear safety in the final disposal application and this could refer to criticality safety. Section 8.1 specifies that no event during the pre-closure operations at the disposal site is so serious that it leads to criticality.

The EIS does not refer to criticality safety at all.

There are many comments on criticality safety in various documents included as appendices to the application. For convenience, to simplify an overview, most of them are referred to and many are quoted below.

2.5. Main appendix SR

2.5.1. Main appendix SR - Section 5

Section 5 is a summary of Appendix SR-Drift. Section 5.1 refers to criticality as a group of potential events. Section 5.2 states that no event leads to criticality. The same section also contains a paragraph describing the criticality safety assessment for SR-Drift and the copper canister in particular. Water is assumed to enter the canister. Burnup credit is required, in particular for PWR fuel. Special solutions may be required for a few PWR assemblies with low burnup.

2.6. Appendix SR-Drift

2.6.1. Chapter 3

Chapter 3 contains requirements and design specifications. (Reference 5 to Chapter 3 is referred to but contains similar information.)

- Section 2.1.2 gives the k_{eff} limit of 0.95 for the copper canister in all design basis scenarios in the final disposal facility.
- Section 2.2 requires that the copper canister with spent fuel is delivered to the final disposal facility with a document confirming the minimum sub-criticality margin.
- Section 4 contains legal requirements: SSMFS 2008:1 Chapter 6, paragraph 2 that criticality shall be prevented.
- Section 4.4.4 contains sub-criticality margins for the canister.
- Section 6.2.1, Design basis scenarios and acceptance criteria. Event classes are specified.
    - H1, Normal operation. H.1.1 includes all planned conditions that can be attributed to normal operation. The event frequency f is > 1 per year. Can be criticality safety related (not specifically expressed).
    - H2, with a frequency f where $10^{-2} \leq f < 1$ per year, includes events that influence criticality safety
    - H3/H4, with a frequency f where $10^{-6} \leq f < 10^{-2}$ per year, also includes events that influence criticality safety
    - Beyond-design-basis scenarios with a frequency $f < 10^{-6}$ per year (referred to as H5 for nuclear reactors) are considered too infrequent to warrant design considerations. Criticality is not mentioned.
- Section 6.2.2, Acceptance criteria are to be defined for each event class: One of the criteria is the sub-criticality margin for the canister. k_{eff} shall be < 0.95 for H1 (normal operation), H2 (mishaps) and for H3/H4 scenarios.
- Section 7, Safety function requirements include sub-section 7.1 that deals with criticality safety. It is assumed in the criticality safety assessment that the canister is damaged and filled with water. There is no credible scenario leading to damage resulting in water in-leakage. Damage to the fuel due to acceleration or retardation events must not result in a $k_{eff} > 0.95$ (with water inside).

2.6.2. Reference 1 to Chapter 3 – SKBdoc 1198253

Reference 1 contains identification of requirements for final disposal.

- SKB refers to SSMFS 2008:1 chapter 6, paragraph 2 and to SR-Drift Chapter 3 where criticality is excluded. It is also stated that the criticality safety requirements for final disposal are stricter than for the facility.
- A reference is made to SKBdoc 1188478 concerning compliance with the design criteria.

2.6.3. Reference 3 to Chapter 3 - SKBdoc 1073301

Reference 3 covers principles for safety classification in the safety assessment the operation of the repository.

- Section 1. Under operation, criticality shall be prevented.
- Section 2 contains the requirement that the final disposal facility classification shall include the canister with those internal parts required to preserve geometry such that the sub-criticality requirements are complied with.

2.6.4. Reference 4 to Chapter 3 - SKBdoc 1091152

Reference 4 in the safety assessment for the operation of the repository contains a summary of issues, identified events, consequences and event classes.

- Under the issue “General events”, criticality is identified. Potential consequences are suggested for:
    - Radiological consequences and release of radioactivity,
    - Increased person doses and
    - Influence on a barrier.
- Event classes include H2 and H3/H4
- A comment is that:
    - Criticality shall under no conditions be credible, independent on how the fuel is stored in the canister (requirement on the encapsulation facility),
    - Criticality shall not be an event that is credible in the final disposal repository.
      In the final disposal facility it shall be possible to demonstrate that events with large retardation/acceleration cannot lead to criticality

2.6.5. Chapter 6

Chapter 6 covers radioactive materials in the final disposal facility:

- In Section 3 (Source term) sub-criticality is listed, together with maximum heat generation and the maximum dose rate at the surface of canister, as providing the basis for what fuel assemblies can be loaded into a particular canister.
- Section 6 (radioactive release in the facility) informs that Chapter 8 of SR-Drift concludes that no event in classes H1-H4 is serious enough to cause criticality and a subsequent activity release from the canister.

2.6.6. Chapter 7

Chapter 7 covers radiation protection and shielding in the final disposal facility.

- Reference 4 covers transport of the copper canister to the final disposal facility in Forsmark. Section 2.4.3 informs that the transport package design to be used for the copper canister must be supported by a safety report demonstrating criticality safety.

2.6.7. Chapter 8

Chapter 8 covers safety assessment.

- Section 1.2 Methodology explains that the purpose of classification of events into frequency-based event classes with acceptable consequences is to obtain a balanced risk profile for the facility. Frequent events are acceptable with only limited consequences while less frequent events are acceptable for more severe consequences.
- Section 1.2 Methodology contains Table 1-1 Summary of acceptance criteria. For all event classes H2, H3 and H4 the criticality safety acceptance criteria are identical: $k_{eff} < 0.95$.
- Section 1.3 includes criticality as an initiating event. A criticality event may lead to radiological accidents.
- Section 1.3.1 Table 1-2 explains that a criticality event in class H2 may involve consequences related to Activity release (A), Barrier influence (B) and Radiological accident that leads to an increased personal dose. A footnote describes that the separation of criticality for event classes H2 and combined H3/H4 makes it possible to have different acceptance criteria.
- Section 1.3.4 is a summary of the criticality safety assessment for the final disposal facility. The information has been included in other texts, referred to above. The conclusion is that water in-leakage is not credible and thus not criticality.
- Section 6 (Safety evaluation) explains that adequate sub-criticality margins are assured with water inside but accounting for fuel burnup. A final sentence concludes that not all design-basis events are covered and that the safety evaluation will be updated.
- Section 7 (References) refers to SKBdoc 1193244, version 2.0 for criticality safety. Version 4.0 of that report is attached to Chapter 8 in the application.

2.6.8. Reference 5 to Chapter 8 - SKBdoc 1193244

Reference 5, updated to version 4.0, covers criticality safety calculations of disposal canisters. This is an extensive report and only a few specific points are referred to here for the initial review phase. This report is applicable to all operations from the loading of the copper canisters in the encapsulation plant until the failure of the copper canister to prevent water in-leakage in the far future during the post-closure final disposal period.

- Section 1 (Introduction) acceptance criterion: The effective neutron multiplication factor must not exceed 0.95 in the most reactive conditions when the canister is filled with water, including different kinds of uncertainties.

- Section 4. The regulatory guides referred to are listed in a later sub-chapter of this report.
- Section 4, last paragraph specifies the overall acceptance criterion for the final disposal facility. They are quoted later in this chapter of this report.
- Section 5.3. The maximum enrichment is 5 % U-235. New MOX fuel will contain 4.6% Pu_{fiss} and 0.2% U-235.
- Section 9.17 evaluates some postulated defects in the canisters. This may be related to the remaining uncertainty in the quality of the nodal iron inserts presented in another of the application documents.
- Statistical considerations are made frequently in the report.
    - Section 3, last paragraph.” If a change in a parameter in the model gives a difference in k_{eff} smaller than the statistical spread (2σ) the difference is caused by the statistical uncertainty and not by the parameter change.” The intention must be that the difference **may** be caused by the statistical uncertainty.
    - Uncertainties are sometimes specified as ± one standard deviation (σ) and sometimes as ± two σ.
    - A correction (or allowance) for an uncertainty is based on the 95/95 upper one-sided tolerance limit. This is calculated as a factor dependent on the statistical sampling multiplied by the standard deviation.
    - The largest individual uncertainty allowances found in Tables 42 and 43 appear to be between 0.02 and 0.03. The allowances are added linearly to obtain a total allowance.
- The method selected for burnup credit is tied to the U.S.A. Nuclear Regulatory Commission (NRC) and Oak Ridge National Laboratory (ORNL) guidance and recommendations. This strategy is based on the need to determine detailed information on each considered nuclide in the spent fuel.
- Validation of the methods used for criticality safety evaluation and burnup credit in particular are referred to:
    - Traditional NRC (based on ORNL recommendations) methods have been applied. No consideration of independence between benchmarks (correlated error sources) appears to have been made, see Appendix 1.
    - For validation of burnup credit, validation of the depletion method is also required. SKB refers to two proprietary reports that will be needed for the detailed review phase.
    - Validation of burnup credit methods against benchmarks based on direct measurements has not been referred to (unless covered by proprietary reports not reviewed yet).
- Section 12 References is informative. 15 different references provide a background to the report. They are not necessarily the latest issues but, when relevant, the list can be updated later.

2.7. SR-Site Main report (TR-11-01)

2.7.1. TR-11-01, Volume 1, Summary

Section S3.9, Step 8, point 5 makes it clear that combinations of scenarios need to be considered.

Section S3.11, Step 9, part 2 covers criticality in a failed canister as a source for further damage and releases. The conclusion is that criticality is not reasonably conceivable.

2.7.2. TR-11-01, Volume 1, Section 5

Section 5.3.1 covers the initial state of the canister and its handling:

- "The fuel assemblies to be encapsulated shall be selected with respect to enrichment, burnup, geometrical configuration and materials in the canister so that criticality will not occur during the handling and storage of canisters even if the canister is filled with water. The effective multiplication factor (k_{eff}) must not exceed 0.95 including uncertainties.
- Before the fuel assemblies are placed in the canister they shall be dried so that it can be justified that the allowed amount of water stated as a design premise for the canister is not exceeded. The amount of water left in any one canister shall be less than 600 g.
- Before the canister is finally sealed, the atmosphere in the insert shall be changed so that acceptable chemical conditions can be ensured. The atmosphere in canister insert shall consist of at least 90% argon."

Section 5.3.4 states: "The assemblies must not under any circumstances be encapsulated if the criticality criteria cannot be met".

Section 5.4.1 (Design premises relating to long-term safety), with a reference to SKB TR 09-22 quotes: "The spent fuel properties and geometrical arrangement in the canister should further be such that criticality is avoided if water should enter a canister."

Section 5.4.1 also contains a further specification of the requirement to prevent criticality: "The material composition of the nodular cast iron shall be: Fe > 90%, C < 4.5% and Si < 6%."

Section 5.4.3 contains a subsection on criticality with requirements on separation between the channel tubes (and thus of the fuel assemblies) in the initial state of the canister.

2.7.3. TR-11-01, Volume 1, Section 7

Section 7.4.1, Table 7-2 contains a row F3 with criticality safety statements for the intact canister and for the failed canister.

- For the intact canister criticality is neglected since there is no moderator in the canister.
- For the failed canister criticality is neglected if credit is taken for the burnup of the fuel.

2.7.4. TR-11-01, Volume 1, Section 8

Section 8.3.1, “As long as the containment is intact, the possibility of criticality is ruled out. Therefore, no safety function related to criticality is formulated for an intact canister. See further Section 8.4.”

Section 8.4.1, F3 Criticality: “The fuel properties and geometrical arrangement in the canister should be such that criticality is avoided if water should enter a defective canister, but there is no meaningful simple criterion to use for such an evaluation.”

Section 8.4.2, “Can5 Avoid fuel criticality” repeats previous conclusions.

Section 8.4.6 repeats some information in the summary Table 8-2:

- Fuel reactivity $k_{eff} < 0.95$. Established according to principles generally applied for handling of nuclear fuel, see further the Spent fuel report.
- The F3 and Can5 blocks repeat previous conclusions

2.7.5. TR-11-01, Volume 3, Section 13

Section 13.1: “Two issues related to radionuclide transport and dose calculations that can to a large degree be treated independent of the scenario or the nature of the failure mode of the canister are addressed first in this chapter:

- …
- The issue of potential criticality for a failed canister is treated in Section 13.3”

Section 13.3 is a full page discussion of criticality safety.

- “If a canister failure occurs, the issue of nuclear criticality has to be considered, since, if this occurred, it could have a strong influence on the further development of the failed canister and of repository areas in its vicinity.”
- “The possibility of nuclear criticality in the canister interior… has been dismissed in a number of studies; see e.g. the SR-Can report” TR-06-09. SKBdoc 1193244 is referred to extensively (see earlier text in this chapter).
- “In the repository, the normal spent fuel criteria for safety against criticality must apply. This means that the effective neutron multiplication factor k_{eff}, including uncertainties, must not exceed 0.95.”
- “The risk of criticality as a result of redistribution of material has been analysed by /Behrenz and Hannerz 1978/ and by /Oversby 1996, 1998/. The conclusions were that criticality outside the canister has a vanishingly small probability, requiring several highly improbable events.”
- “After the report of a possibility of criticality outside a canister by /Bowman and Venneri 1994/ that was dismissed in a review by /Van Konynenburg 1995/, several other studies have concluded that criticality in a geologic repository as a result of redistribution of fissile material is a highly unlikely event.”
- “The possibility of nuclear criticality in the vicinity of the proposed Yucca Mountain repository was explored recently by /Nicot 2008/. It was concluded that external nuclear criticality is not a concern at the proposed Yucca Mountain repository for any of the deposited waste. Some of the

waste intended for Yucca Mountain contains higher levels of fissile material than what is intended for disposal in a Swedish repository."
- "In conclusion, credit for burnup has to be taken to demonstrate that the canister remains subcritical in the repository for all reasonably conceivable scenarios (Table 2-3 in the Fuel and canister process report). The probability of criticality inside or outside the canister is considered to be negligibly small, based on the results reported in /SKBdoc 1193244/ and in /Van Konynenburg 1995, Oversby 1996, 1998, Nicot 2008/."

2.7.6. TR-11-01, Volume 3, Section 14

Section 14.4.2 Fuel:

- "According to Table 7‑2, the following fuel processes are omitted from the assessment for parts or a whole glacial cycle:
    - F3 Induced fission (criticality). …"
- *F3 Induced fission (criticality)*: "Acceptance criteria for encapsulation of fuel assemblies in canisters are defined to ensure that intact canisters are sub-critical (see Section 5.3.4). Furthermore, analyses of the potential for criticality in failed canisters as well as outside failed canisters indicate that this is highly unlikely (see Section 13.3). Therefore, omission of this process is considered justified as long as the acceptance criteria for fuel encapsulation are met."

Sections 14.5 (time beyond one million years) and 14.6.2 (analogues of repository materials and processes affecting them) refer to criticality. The natural critical reactor at Oklo in Gabon, about 2 billion years ago, is discussed. In particular the consequences, such as retainment of the spent fuel due to low mobility of uranium and stable geology, are pointed out in Section 14.5 under "Indications from natural analogues".

2.8. Other appendices to the application

2.8.1. Appendix VU – Document ID 1199888

Sections 6.3.2 and 6.3.8 (Table 6-1), refer to on-going work with solutions to the potential criticality safety problem with PWR fuel with high ^{235}U assay and low burnup.

2.8.2. Appendix PV - Report TR-10-54

Section 1.2.2, contains a chart with "Safety functions related to retardation":

- Block F3, under "Fuel – matrix and structural parts", contains, "Avoid criticality, $k_{eff} < 0.95$".
- Block Can5, under "Canister", contains "Avoid fuel criticality
    - a) Favourable geometry
    - b) Favourable material composition

2.8.3. Appendix MV - Report R-10-25

Section B1.5 discusses changes in the study SR-95. Nodal iron was selected for the inserts. This reduced the potential for criticality since the free volume available for damaged fuel was reduced, according to SKB.

2.9. Criticality safety standards selected by SKB

SKB in SKBdoc 1193244 version 4.0 refers to some standards that involve criticality safety.

"The criticality safety criteria are based on the US NRC regulatory requirements for transportation and storage of spent fuel:

- Regulatory guide 3.58 – Criticality Safety Criteria for the Handling, Storing and Transporting LWR Fuel at Fuels and Materials Facilities
- Regulatory guide 1.13 – Proposed revision 2 to Regulatory Guide 1.13 Spent Fuel Storage Facility
- NRC issued revision 2 of ISG 8 which gives recommendations concerning burnup credit of PWR fuel.
- FCSS-ISG-10 revision 2 concerns the minimum margin of subcriticality for safety of fuel cycle facilities.
- The basic criticality criteria is that the effective neutron multiplication factor should not exceed 0.95 including uncertainties and the nuclear safety analysis should include considerations of all credible normal and abnormal operating occurrences. Credit for fuel burnup may be taken."

2.10. SKB acceptance criteria

2.10.1. Pre-closure criteria

SR-Drift, Chapter 8, Reference 5 updated to version 4.0 (SKBdoc 1193244), Section 4: "The basic criticality criteria are that the effective neutron multiplication factor should not exceed 0.95 including uncertainties and the nuclear safety analysis should include considerations of all credible normal and abnormal operating occurrences. Credit for fuel burnup may be taken".

2.10.2. Post-closure criteria

SKB intends to comply with the guidance to paragraph 9 in SSMFS 2008:21 and quotes it in Appendix A to TR-11-01:

- "Particularly in the case of disposal of nuclear material, for example spent nuclear fuel, it should be shown that criticality cannot occur in the initial configuration of the nuclear material. With respect to the redistribution of the nuclear material through physical and chemical processes, which can lead to criticality, it should be shown that such redistribution is very improbable."

> ***"Handling in SR-Site:*** *See Section 13.3 and further the* ***Fuel and canister process report****, Section 2.1.3."*

Section 13.3 refers to TR-11-01. The criteria for the initial configuration (in the canister) and for redistribution of fissile material are different, as pointed out by SKB in other texts.

3. Review basis

3.1. General directions from SSM

A list of expected results from the review of criticality safety includes:

- Overall evaluation of the safety documents
- Any need for additional information
- Topics that need a more detailed consideration during the main review phase
- Completeness
- Transparency
- Traceability

A summary of the expectations of the initial SSM review is that the quality and completeness of the application shall be evaluated, with the perspective that a detailed SSM safety review can be carried out in the next phase.

3.2. Specific criticality safety directions from SSM

A purpose for the current review is to identify missing information that may be essential for criticality safety. Identification and response to requirements as well as relevant comparisons with international standards for criticality safety shall be made. The review shall evaluate whether assumptions and conclusions in analyses are reasonable. The review shall also identify whether there are issues related to criticality safety that SKB has not accounted for.

The scope of the criticality safety review includes the spent fuel in copper canisters and any potential for in-leakage of water or out-leakage of fissile material (uranium and/or plutonium in the used fuel) from the canisters,

The review shall evaluate whether the SKB method of burnup credit can be acceptable and whether SKB can apply this method correctly for controlling the sub-criticality of all canisters.

3.3. Legal structure and requirements

Detailed criticality safety criteria for Swedish operations with fissile material are not defined in the regulations. It should be discussed whether they could be more detailed in some areas (not necessarily as in the U.S.). Since the design of nuclear facilities, transport packages and final disposal requires considerable efforts and investments, the industry often prefers predictable licensing requirements, even if they are considered and intended to be conservative, over vague requirements that are open to subjective changes at any time.

The Nuclear Activities Act (1984:3) is the main legal reference. The Radiation Protection Act ((1988:220) is also essential. Other laws need to be complied with as well, e.g. the Environment Code (1998:808) and the Dangerous Goods Act (2006:263).

For transport of radioactive material, international conventions need to be complied with. They are essentially based on the IAEA model regulations TS-R-1
Ordinance (1984:14), Nuclear Activities

Ordinance (1988:293), Radiation Protection

Ordinance (2008:452), Instructions for the Swedish Radiation Safety Authority

SSM has issued a number of Regulations that apply to the transport and final disposal of spent fuel. SKB refers to such Regulations. For this review, the following Regulations are particularly important:

- SSMFS 2008:1, Safety in Nuclear Facilities
- SSMFS 2008:21, Safety in connection with the disposal of nuclear material and nuclear waste
- SSMFS 2008:37, Protection of Human Health and the Environment in Connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste

In the original Swedish language versions, there is also SSM guidance on how to interpret the Regulations.

3.4. Standards, guides, etc.

There are not many standards and guides on criticality safety directed specifically towards final disposal of spent fuel.

In the operations at Clink (the combined Clab and “Inkapsling” (encapsulation) facility), many of the normal criticality safety standards can be applied. They could also apply to some of the operations and scenarios at the final disposal facility and during the post-closure period. However, there are differences for the post-closure period that require attention.

Many criticality safety standards and guides that may be applicable to the final disposal of spent fuel are listed in the references. Some of the more recent developments are mentioned here.

The U.S. NRC Division of Spent Fuel Storage and Transportation (SFST) recently proposed revision 3 of internal staff guidance (ISG) 8. A major change is a requirement for specific validation of the method for determining depletion reactivity related to the fresh fuel reactivity. Validation against critical benchmark experiments is also required. The French HTC experiments (NUREG/CR-6979) are referred to (proprietary, with a general allowance for use within the U.S. only).

There are many ORNL reports supporting the proposed ISG-8 rev. 3. Some are listed in the references.

The nuclear industry, particularly in the U.S., during recent years has shown more interest in getting burnup credit accepted. The EPRI project on validation of depletion methods is an interesting development. It has been published, with a few conference presentations supporting its use. A number of EPRI reports are listed in the references.

TVO in Finland has presented a demonstrated procedure for creating burnup credit validation benchmarks based on cold shut-down reactivity measurements at BWRs. The validation may be applied to PWR fuel, making it even more valuable. The project needs support from the industry.

ISO, in its TC85/SC5/WG8[2] work on criticality safety standards, is considering preparing a standard on nuclear waste containing fissile material. The last pre-draft (not a formal project yet) includes final disposal of spent fuel. The development of the standard will take several years and may not be completed during the current KBS-3 licensing process.

3.5. SKB reports

Appendix 1 contains a list of SKB reports that have been reviewed with a focus on criticality safety. Since the copper canister integrity against corrosion and mechanical events must be assured, essentially all documents related to the copper canister may have relevance to criticality safety. If the copper canister can fail within the time periods considered, reports on the other barriers (bentonite clay and granite rock) will also become important.

3.6. National and international studies of final disposal

Final disposal of spent fuel and of wastes containing significant quantities of fissile material has been a hot international topic for many decades. The reviewer is aware of many of these studies but the reports have not been reviewed in relation to this initial phase. They all have in common that reasonable solutions are technically and economically considered to be achievable. Many of those studies include comments on the KBS-3 method, without challenging the safety. SKB refers to many of the studies in the application documents, see chapter 2.7.5, fifth and sixth bullets in the second list..

The U.S. has a lot of influence on criticality safety practices in the world. The last two decades, the U.S. has also been very active in producing criticality safety reports related to the Yucca Mountain Project. Very extensive post-closure criticality safety assessments have been made in the U.K. but they have not been studied for this review, Finland, Germany, France and Switzerland are examples of other countries that have carried out studies of interest. A few reports have been listed in the references.

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[2] International Standards Organisation, Technical Committee 85, SubCommittee 5, Working Group 8

There are many studies of consequences of real or potential nuclear accidents. Many of them demonstrate that limiting the radiological dose is not sufficient to obtain acceptable safety. The Fukushima accident in Japan 2011 demonstrates this on a large scale. The 1999 JCO criticality accident, also in Japan (Tokai-Mura), also demonstrated that evacuation and restrictions for a large population needs to be considered. The political decision to permanently shut-down the Barsebäck BWRs near Copenhagen also involves consideration of the seriousness of evacuation of the capital of another country, even if it did not involve any radiation doses.

A Swedish study (G. Wranglen) “Gold solves nuclear waste problem” from 1977 is of interest because it suggests a best available technique (BAT) using gold. It demonstrates the issue of safety versus other issues that require consideration according to the Nuclear Activities Act. It is referenced in chapter 7.8.

4. Results of the review

4.1. Applicable standards and guides

The SKB license application contains references to several U.S. standards and in particular U.S. NRC guides. There are others that may be useful. One area is validation, where the ANSI/ANS 8.24 standard is of particular interest. There are also two recent standards on burnup credit that may be useful, one from ANSI/ANS and one from ISO. Those standards are very different.

4.2. Criticality safety criteria

It has been somewhat complicated to find a consistent approach to criticality safety criteria for the wide range of operations and facilities covered by the SKB licensing application for final disposal. This is not so strange considering that the documentation supporting the application has been developed under many decades. Neither national nor international regulations, standards, guides nor licensing experiences demonstrate any clearly consistent and safe criteria.

4.2.1. Different criteria for different scenarios

The criticality safety criteria should probably be adapted to different types of operations and facilities. They may differ in one or more significant areas due to issues such as:

- Probability of the design-basis scenario
    - Presence of moderation (primarily water)
    - Safety sensitivity to a single parameter
- Speed of development from normal to accident conditions
    - Multiple events required for criticality?
    - Independence between events?
    - Early recognition of deviations from normal?
- Burnup credit
- Burnable absorber (gadolinium) credit

- Potential influences of the human factor
  - Water presence
  - Misloading of nuclear fuel into positions not allowed (burnup credit, gadolinium credit, enrichment controls)
  - Serious error in assessment or in calculation results
  - Abandoning adequate supervision over operations
- Required margin of safety
  - Margins in the form of control parameter values
  - K_{eff} corresponding to required margin of safety
- Potential consequences of a criticality event
  - Almost fresh fuel (highest criticality potential) implies lower radiation source from previous reactor operation
  - Fuel causing worst consequences
  - Shielding mitigates direct consequences of a criticality event
- Emergency preparedness and response
  - Criticality detection system
  - Criticality alarm system
  - Evacuation
  - How to stop the divergent chain reaction (criticality event)
  - Dose and contamination determination

4.2.2. Different criteria for different operations and facilities

The criticality safety should be discussed for at least the following operations covered by the application:

- Transport of spent fuel assemblies loaded and unloaded in water
- Storage and other operations of spent fuel in water
- Storage and other operations of spent fuel with water reliably excluded
- Transport of closed copper canister with spent fuel
- ‘Pre-closure operations with copper canister in final disposal facility
- Post-closure periods under various conditions

4.2.3. Use of k_{eff} as a safety indicator

The neutron multiplication factor k_{eff} is the inverse eigenvalue for the steady-state (time-independent) neutron transport equation. It is normally a calculated factor of the ratio between production and loss of free neutrons in a system, excluding neutron sources from events not initiated by free neutrons (e.g. spontaneous fission and alpha-neutron reactions).

A k_{eff} value in itself is not a good safety indicator of a real system or of an evaluated scenario. However, it is essential since it is a single value that accounts for many variables. Other safety indicators are often more than one for each operation. An example combination is fissile material mass, material composition and ^{235}U enrichment,

The design k_{eff} limit for each scenario should be determined after the analysis of various parameters and the probability of each scenario. If the scenario is extremely unlikely and the analysis is totally reliable, it is reasonable to accept a high k_{eff} limit. The safety margin may have a low value but still represent a very safe scenario. In another case, the sensitivity of the criticality potential to human factor influence, instrument failure or other events may be very high and the probability of such events may be difficult to predict. In such cases, the k_{eff} limit should be reduced substantially. The NRC FCSS ISG-10 contains more discussions on safety limits. Examples of high k_{eff} limits are provided below.

If the system scenario is close to the optimum conditions (materials and configurations), conservatively accounting for calculation biases, incidents, the human factor, and uncertainty allowances, a very high estimated k_{eff} value can be acceptable. A k_{eff} value of 1.000 (critical) may be acceptable if it is known that this scenario could never occur.

On the other hand, a low estimated k_{eff} value can be unacceptable for another system or scenario. There are many potential reasons for this such as large uncertainties, high sensitivity to credible incidents, high sensitivity to the human factor, fissile material properties that cause high sensitivity to changes.

Examples to the acceptance of high acceptable k_{eff} values can be found in U.S. NRC licensing procedures and guidance (e.g. NRC 10 CFR 50.68):

- For unlikely combinations of extreme incidents, such as a spent fuel storage pool where boron dilution is credited, any k_{eff} value less than 1.000 may be acceptable in the unlikely event of flooding with unborated water (10 CFR 50.68 (b)(4)).
- For dry storage of fresh fuel at nuclear reactor sites, a k_{eff} value up to 0.98 may be acceptable for the incredible scenario of optimum overall water moderation and infinite extensions of the storage (10 CFR 50.68 (b)(3)).

Application of geometrical and mass "safety factors" to reduce critical systems to safely subcritical systems have been applied both for facilities and for transport of fissile material. A safety factor of 0.80 will limit the fissile mass to 80 % of the critical mass. Depending on the fissile material and other constituents in the system, the k_{eff} value can vary from more than 0.99 to less than 0.95. A system with 80 wt.% of the critical mass with high k_{eff} would normally be safer than a system with 80 wt.% of the critical mass with low k_{eff} value because it is much less sensitive to changes.

The IAEA transport regulations TS-R-1 2009 have several examples of specified limit specifications where the maximum k_{eff} is around 1.000 or even above (e.g. inherently safe materials with uranium containing limited ^{235}U assays in paragraphs 417(b) and (c)). They are acceptable because the specified materials under optimum conditions have been agreed to not being credible.

The NRC FCSS ISG-10 Rev. 0 is a good start for establishing subcritical margins and safety margins. It is referenced by SKB (probably a draft version).

4.2.4. Observable parameters as safety indicators

Since a single credible variation in a safety parameter is not allowed to lead to a criticality event, there is usually more than one safety parameter for each operation. There are many examples of singe-parameter controls, e.g. mass, volume, sphere radius, cylinder radius, slab thickness, fissile nuclide concentration (e.g. ^{235}U enrichment, ratio to neutron absorbers) and moderation. However, even for those “single-parameter” controls, there are other controls as well, such as spacing from fissile materials in other operations, containment of the fissile material in the intended containments, etc.

The safety parameters that are essential for each operation should be clearly specified and controlled, using easily observable methods.

In the case of the copper canister in the SKB application for final disposal of spent fuel, there are several surviving safety controls (e.g. moderation, burnup and geometry), until the canister fails. After that, there is no reliable safety control even if there may still be significant barriers to a criticality event.

For the intact copper canister, some of the safety parameters that SKB accounts for are:

- Lack of moderation with a maximum of 600 g of water per canister
- Limits on the initial (fresh fuel) assay of ^{235}U in uranium
- Limits on the minimum burnup for some fuel assemblies
- Limiting geometry specifications of each fuel assembly, allowing some damage
- Separation of fuel assemblies within each canister
- Observation of potential damage to each canister or its contents during all operations until it is covered by bentonite clay.

4.2.5. Consideration of uncertainty allowances

Essentially all regulations, standards and guides require consideration of uncertainties. A common approach in criticality safety is to apply conservative bounding values for parameters (e.g. optimum moderation), to convert tolerances to normal distribution uncertainties and to consider other uncertainties as normally distributed uncertainties.

A combined uncertainty can then be determined by taking the square root of the sum of variances (squares of the standard deviations). The real value should be within a range of ± two standard deviations with a confidence level of about 95/95 (probability and confidence). If the range ± three standard deviations is considered, the confidence level changes to about 99/99.

Uncertainty allowances are commonly made in criticality safety evaluations by adding two or three standard deviations to the calculated and bias-corrected (e.g. due to validation of the calculation method) k_{eff} value. This consideration is made under the assumption that the combined uncertainties approach a normal probability distribution. The actual confidence level depends on the quality of the statistical data (e.g. sampling). The factors two and three are examples of the concept “coverage factor”.

It has become more common, in particular in the U.S., to assign a fixed one-sided upper confidence level, often 95/95 as the uncertainty allowance. This has been applied by SKB, leading to coverage factors between 1.7 and 2.1.

The margin between the estimated k_{eff} value and criticality can be specified as a number of uncertainty standard deviations. This can be translated into a one-sided confidence level and thus a probability for criticality.

The larger the uncertainty is and the smaller the coverage factor is, the more likely a criticality event becomes. This must be accounted for when the limiting value of k_{eff} is determined.

In the current SKB application (Table 42 in SKBdoc 1193244), some of the uncertainty allowances are large, more than 0.02 in k_{eff}. SKB also refers to NRC guides for the treatment of uncertainties and safety margins.

If a calculated k_{eff} value, accounting for method biases, of a normal condition scenario is 0.890 and the total uncertainty standard deviation is 0.035, a coverage factor of 1.7 would result in an uncertainty allowance of 0.0595 or a total k_{eff} value of 0.9495, which is usually accepted. If the coverage factor 3 is applied, the total k_{eff} value becomes 0.995. The probability for criticality is in the order of 1 in 1000. This is not acceptable for a normal condition scenario.

In the past, Swedish license holders for Clab and for the fuel fabrication plant have been requested to limit the total standard deviation to 0.01 or to treat the uncertainty allowance with other methods than the coverage factor. For Clab, this has meant that the total uncertainty allowance has been based on a linear addition of small uncertainty allowances, rather than by the traditional square root of the sum (Table 42 in SKBdoc 1193244 essentially builds on the previous criteria). This reduces the probability for criticality substantially.

The NRC approach, e.g. as applied in the approval of the MOX Fabrication Fabrication Facility (NRC 2010), even though considerable improvements are suggested in NRC FCSS ISG-10, should not be accepted as sufficient for the final disposal operations. A major issue is the validation of criticality safety calculation methods.

4.2.6. Multiple events required to make criticality credible

Traditionally, the double contingency principle (DCP) from the U.S. is a recommended (not required) method for assuring that a single credible event does not lead to criticality. Basically, it requires at least two unlikely, independent and concurrent changes in process conditions before a criticality accident is possible.

In Europe, the DCP is well known and often used. However, it is used as a minimum requirement. In Sweden, there are not so many facilities handling fissile material in forms where many process conditions are expected to change concurrently.

The fuel fabrication plant is the most obvious example in Sweden. The criticality safety design of the fuel fabrication plant is based on a requirement (approval letters for CLAB by Statens Kärnkraftinspektion (SKI, now SSM), 1989-07-10 and 1992-03-13)[3] that two unlikely, independent and concurrent incidents don’t lead to criticality. The source of the safety philosophy at the Swedish fuel fabrication plant appears to be based on practices in the U.K. in the 1960’s or early 1970’s. That is the time when they were introduced at the fuel fabrication plant.

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[3] From SKB information to SKI, attachment to letter of 2004-12-28, preparing for meeting in 2005-02-04. The SKI sources have not yet been found.

The fuel fabrication philosophy sounds stricter than the DCP. However, the actual implementation of the DCP in the U.S. often builds on additional conservative assumptions that may compensate for the differences in the specifications.

Experience has shown that the requirement for no criticality during two unlikely, independent and concurrent events has been justified. This is particularly true for the facility for “wet” conversion of uranium fluoride to uranium dioxide. The presence of fissile material solutions under normal conditions makes criticality a realistic hazard. The many different types of operations and human interactions made predictions of probabilities difficult during the initial licensing process.

Spent fuel handling and storage may be less complicated, in particular when dry. The long experience that SKB has with Clab makes estimations of probabilities easier. However, burnup credit is a new complication. Since the copper canister will never be intentionally flooded with water, moderation control is credible. This is unlike the handling of the packages used for transport of spent fuel from the reactor sites to Clab.

4.3. Validation of criticality safety calculation methods

Validation of calculation methods (computer codes and nuclear data) for criticality safety is an essential responsibility for the designer of an operation involving fissile material. Validation is preferably based on benchmark experiments, usually critical.

A reasonably reliable source of benchmarks can be found in the ICSBEP Handbook.. For validation of burnup credit methods, additional benchmarks are required.

4.3.1. Standard for validation of calculation methods

As mentioned earlier, the quite recent ANSI/ANS 8.24 standard on validation, not referred to by SKB in the application, appears to be useful for the review of the SKB safety assessment.

4.3.2. Benchmarks and applications

For a specific “application” (here in the meaning of the scenario to be evaluated), the author has the opinion that at least one highly similar, reliable and low-uncertainty benchmark should be found to validate the evaluation. If such a benchmark is not available, use of other methods may be acceptable, as long as uncertainties are appropriately accounted for.

4.3.3. Similarity between benchmarks and applications

Traditionally, benchmarks have been selected because they have one or more parameters that are similar to the application. There are even examples of critical experiments being designed with such similarity in mind.

A common problem with the use of such benchmarks is that the k_{eff} sensitivity to the parameter may be high in the application but very low in the benchmark. Good agreement between calculation results for benchmarks with the experiment-based benchmark results would not assure good agreement between the calculated result for an application and the real result for the application.

During the last ten years, more reliable methods of determination of the similarity between an application and a benchmark have been established. In particular, the SCALE software package now includes several sequences in the TSUNAMI family based on sensitivity and uncertainty techniques.

SKB has selected a number of benchmarks that appear to be similar to the intended applications in the final disposal operations. The more in-depth review to follow this initial review should apply the more recent methods available, e.g. TSUNAMI, to verify the similarity between benchmarks and applications.

4.3.4. Independent benchmarks.

To treat the benchmark calculation results statistically, a large number of independent benchmarks should all be available. It is quite obvious that many of the SKBdoc 1193244 Appendix 1 benchmarks are not independent of each other.

The problem with independence of error sources is referred to in the ANSI/ANS 8.24 standard (not referenced in the SKB application) and in the NRC/FCSS ISG 10.

The ANSI/ANS 8.24 standard and the NRC FCSS ISG-10 have no suggestions for how to deal with benchmarks that are not independent. A simple solution is to select one of the benchmarks and to reject the others. A better solution may be to evaluate all the correlated (dependent) benchmarks and to apply statistical methods (e.g. regression) to reduce the random variations and to avoid outliers in the benchmarks. After that a single benchmark with similar characteristics as the application may be selected.

4.3.5. Positive biases in k_{eff} calculation method results

A positive bias is here defined as an over-estimation of the calculated results compared with the experiment-based benchmark results. A bias is normally defined for each benchmark calculation as the calculated value minus the experiment-based benchmark vale. The average bias for a group of calculations of similar and independent benchmarks is used as a representative bias for the application.

The U.S. NRC has been strict on the recommendation that a positive bias in the k_{eff} calculation method result should not be accounted for (NRC Regulatory Guide 3.71).

There may be some justification for the approach of neglecting positive biases. However, there may be a non-conservative total effect for several reasons:

- The best available technique/data may result in a quite high positive bias. If this can’t be accounted for, the designer would obtain a solution that is not competitive with solutions from other designers. The economic consequences could be severe for some applications. The author believes that the designer is thus encouraged to retain older, more inaccurate[4] and incomplete techniques/data that produce negative biases.

- A positive bias can have been incorrectly determined. It seems conservative to account for this by avoiding a negative bias correction. However, the same argument should apply for a zero or negative bias. The correct bias should perhaps be much more negative, justifying a larger positive bias correction. An example:
    - Method 1 (old and difficult to use correctly): An estimated negative bias of -0.01 is perhaps really -0.03.
    - Method 2 (modern and user-friendly): A conservatively estimated positive bias of +0.01 is perhaps really +0.03.
    - It should be obvious that it is better to use method 2. Allowance for a positive +0.01 bias in Method 2 is much more conservative than allowance for a negative bias of -0.01 in method 1. NRC (and possibly others) strongly encourages the use of method 1.

4.4. Burnup credit

4.4.1. SKB method for burnup credit

SKB intends to apply burnup credit to the copper canister during and after loading it with spent fuel. SKB has also indicated that burnup credit may be applied, when considered appropriate, for some other operations in Clink. For this reason, burnup credit as a general control method, and in particular as it has been implemented by SKB in the current licensing application, needs to be carefully reviewed.

The current licensing application does not cover use of burnup credit in Clab, where BA credit is applied. The encapsulation facility will apply both burnup credit and BA credit, possibly in the same pool.

The method selected by SKB is based on U.S. NRC and ORNL developments (sponsored by NRC). They have been applied in the U.S. and the SKB implementation appears to be in agreement with the NRC intentions before 2012. There are now new, stricter NRC requirements for depletion method validation. A draft NRC internal guide (ISG) has been released for public comment. SKB will be expected to respond to this.

4.4.2. Some earlier experience with burnup credit in Sweden

Burnup credit was applied already in the 1970’s and 1980’s for the international transport of spent research reactor (Studsvik R2) fuel in a Swedish package design, validated by the U.S. competent authority[5]. The fuel depletion calculations were simpler since the fresh fuel contained uranium with over 90 wt.% ^{235}U. The critical mass in a transport package was experimentally determined to be about 2845 g ^{235}U,

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[4] Inaccuracies are normal and acceptable if they are appropriately accounted for.

[5] “Radioactive Materials Package Design Certificate USA/6032/B(M)FT, Revision 8, Endorsement of Swedish Competent Authority Certificate S/23/B(M)F”, US Department of Transportation, 1 March 1985.

the ^{235}U mass limit per package was 2276 g (80 % of the critical mass) and the mass of twelve fresh normal fuel assemblies was 3000 g ^{235}U.

The actual safety design circumstances were similar to the SKB copper canister with PWR fuel. Since the loading (in Studsvik) and the unloading (at Savannah River Site, U.S.) of the fuel were made in pure water, criticality due to misloading was a real possibility.

4.4.3. OECD/NEA studies on spent fuel and on burnup credit

The U.S. Department of Energy (DOE), responsible for handling the spent fuel issue in the U.S., in the late 1970's proposed an OECD/NEA study for transport of spent fuel. An initial study[6] was carried out in 1980-1981 with fresh fuel in typical packages designed for spent fuel.

Sweden participated in the mentioned study with three different contributions. One was with the Studsvik reactor physics code CASMO, together with a 2D diffusion theory code. A second contribution was made with the ASEA-Atom reactor physics code PHOENIX together with the ORNL Monte Carlo code KENO. The third contribution was with the first version of SCALE, including KENO.

Even though this first OECD/NEA international study did not consider burnup credit, some of the methods were designed for reactor depletion, k_{eff} and reactivity calculations. In fact, the use of PHOENIX to generate homogenized cross-sections for KENO has been used for criticality safety design since the 1970's and this combination is still applied.

In the first OECD/NEA study on burnup credit[7], starting in 1991, Studsvik (Sweden) participated with CASMO to demonstrate its depletion capabilities. Unfortunately, the OECD/NEA studies have focused on nuclide compositions rather than on k_{eff} and reactivities. The use of lumped fission products in CASMO made full participation in the study difficult. The use of lumped fission products would be appropriate for burnup credit since it is the integral effect of all nuclides (macroscopic cross sections) that needs to be determined.

The OECD/NEA studies of burnup credit have always focused on the nuclide composition path, rather than on the reactivity path. A major reason is that the measurements and critical experiments required to develop and validate reactor depletion methods have not been publicly available.

The OECD/NEA studies on burnup credit have demonstrated the capabilities of many calculation methods. They have also demonstrated many potential problems with burnup credit that may not have been understood without the focus on specific issues.

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[6] "Standard Problem Exercise on Criticality Codes for Spent Fuel Transport Containers", CSNI Report No. 71, OECD/NEA, Published by Oak Ridge National Laboratory, May 1982.

[7] OECD/NEA Burnup Credit Criticality Benchmark Result of Phase-1A", NEA/NSC/DOC(93)22, OECD/NEA, Published by JAERI, January 1994.

4.4.4. IAEA burnup credit workshops

IAEA has 1997, 2000, 2002, 2005, 2009 and 2013 arranged workshops on burnup credit. The main purpose has been to present, compile and discuss international experience in burnup credit. The workshops have helped participants to establish burnup credit as a safe and economical control of spent fuel criticality safety.

4.4.5. Earlier SKB studies on burnup credit

SKB has for a long time been open about its interest in evaluating burnup credit for Clab and other operations involving spent fuel.

The PHOENIX/KENO combination was used in the late 1980's to study potential burnup credit for the design of compact canisters in Clab[8]. The resulting report is indirectly referenced by SKB in the application for final disposal. The study was also presented at an ANS meeting in 1990[9]. SKB chose to base the compact canister design on boron absorption, probably due to the licensing uncertainty related to burnup credit.

SKB has presented their ideas on burnup credit implementation in informal meetings with SKI since the 1980's. As mentioned above, SKB has also presented such ideas at an ANS meeting in 1990 and at the IAEA workshops mentioned above.

SKB has also published several reports on burnup credit for copper canisters. Most of them are referenced in the current license application and in associated references.

4.4.6. Standards and guides

During the last years, there has been considerable international progress made in the development of burnup credit standards and guides. ANSI/ANS, ISO, NRC and DIN are examples.

NRC/SFST is currently revising its internal guide ISG-8 to rev. 3 (a draft has been published). NRC has sponsored many ORNL studies on different aspects of burnup credit. NRC has also sponsored use (in the U.S. only) of the French HTC validation benchmarks for spent fuel.

4.4.7. Validation of depletion and burnup credit methods

SKBdoc 1193244 refers to some proprietary reports[10] for the validation of depletion calculation methods. The validation data may be proprietary but the approach should be described in an open document. It is not possible to review the adequacy of the validation without access to this information. SKB has specified that the reports used for validation are available to SSM for review.

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[8] "Burnup credit in nuclear criticality safety analysis of CLAB", ABB Atom report UR 89-478, Draft 1989, Final report 1991 referenced by SKB in Clink application.

[9] H. Forsström, L. Agrenius, S. Helmersson, "Burnup Credit in the Central Storage Facility for Spent Fuel in Sweden", TANS-1990, 62, 327, November 1990

[10] Ringhals 2007-10-19, 1960160/1.1 and OKG 2008-05-26, reg nr 2008-14670.

NRC has become much stricter on validation of depletion methods. The soon to be formally released ISG 8 Rev. 3 requires validation against specific measurement benchmarks. SCALE 6.1 will be acceptable but only with the use of the French HTC benchmarks for support. They are currently not for general use outside the U.S.

A development that appears to be more efficient is the nuclear industry involvement in generating validation benchmarks. EPRI has for many years studied burnup credit, initially often published only for members or at a considerable cost. However, most reports appear to have been published eventually without cost.

Recently EPRI sponsored Studsvik (U.S.) to develop depletion benchmarks based on power reactivity measurements and adjustments of CASMO calculation results to the measured results. The benchmarks as well as an implementation using SCALE 6.1 (including input examples) have been published by EPRI (report id: 1022909). This development is interesting since it uses direct validation of overall reactivities, rather than taking the complicated way of determination and validation of individual nuclide data.

TVO (Finland) has recently been working on simplifying the cold shut-down margin measurements made at each BWR twice a year. Preliminary results have been presented at international meetings (Ranta-aho 2011) and appear very promising for validation of burnup credit. They appear to be even more direct than the EPRI benchmarks. As a commercial company, it is not obvious that TVO would publish such benchmarks. It is clear that nuclear power operators could develop really solid benchmarks, if motivated to do so.

4.4.8. Verification of spent fuel characteristics

Verification of correct selection and positioning of fuel assemblies for transport and storage applies to all criticality safety controls. However, burnup credit application can be more demanding, in particular if a serious mistake can lead directly to criticality.

The spent fuel characteristics include initial assay of ^{235}U in the uranium, initial plutonium contents in MOX fuel, actual fuel design, burnup of various axial sections of the fuel, presence of burnable and other absorbers during reactor operation, reactor operating conditions such as power level, moderator temperature, shut-down periods, cooling time, etc. Observed damage to the fuel, including geometry variations, needs to be within specified tolerances.

The issue of verifying important aspects of the fuel characteristics needs serious consideration. The IAEA transport regulations TS-R-1 (2009, paragraph 674(b)) require measurements before transport to verify the fuel composition. This would be covered during the encapsulation operations.

The quality of reactor records for each fuel assembly is important.

The possibilities for misloading fuel into positions that are not intended for that fuel need to be evaluated.

The author finds it essential that the benefits of measurements should be balanced against potential dose increases to personnel at the encapsulation facility as well as other consequences.

4.5. Burnable absorber credit

Fresh BWR fuel contains a varying number of fuel rods with varying contents of the neutron absorber gadolinium. During the first cycle of operation, most of this gadolinium is “burned” (depleted) into nuclides with much lower neutron absorption cross sections. Gadolinium is referred to as a burnable absorber (BA).

The advantage of a BA is that the maximum k_{eff} is reduced, compared with fuel without BA. The BA is initially depleted (reactivity increase) faster than the reactivity loss due to the net effect of uranium transmutation (primarily build-up of plutonium and depletion of ^{235}U). The k_{eff} value for a system containing slightly depleted fuel may increase substantially compared with a system with fresh fuel.

Gadolinium (or BA) credit has been applied at Swedish power reactor storage pools since the early 1980’s and at Clab since 1995.

The SKB license application for expansion of Clab with an encapsulation plant is based on continued use of BA credit. This covers the Clab facility and some operations in the encapsulation facility. BA credit will not be used for the copper canister or later steps in the final disposal operations.

The SKB licensing application for the extended facility with Clab and of the proposed encapsulation plant is not subject to this review. This applies also to BA credit.

4.6. Event classes, barriers, defence in depth, risks

It is not very clear how the SSM and SKB specifications of event classes, barriers, defence in depth and maximum acceptable risk based on a maximum radiation dose involve criticality safety.

An event in the unused class H5 (rest risk) has a frequency $f < 10^{-6}$ per year. A postulated criticality event appears to fit in this category. Is it the intention that any combination of accidents within classes H1/H2/H3 and H4 with a frequency of $f > 10^{-6}$ per year shall be sub-critical?

With a frequency f of 10^{-6} per year, what are the potential consequences of a criticality event? This will of course vary enormously, depending on the scenario. The frequency f of $<10^{-6}$ per year for a criticality event may be compared to the maximum acceptable risk for damage to a representative individual in the most exposed group after closure of a repository, as specified in §5 of SSMFS 2008:37.

A frequency f of 10^{-6} per year for a criticality event due to a specific scenario may be reasonable but the ALARA principle should also be applied. The total probability for a criticality event due to any scenario requires addition of the probabilities for all scenarios.

Some discussion or analysis by SKB of potential criticality consequences for a number of selected scenarios appear to be useful or even necessary.

4.7. Early failure of a copper canister – Unacceptable

The author has obtained the impression from the application documents that SKB has assumed that a criticality event in a copper canister is unacceptable, at least for several thousand years. This is consistent with guidance on probabilities in SSMFS 2008:21: “it should be shown that criticality cannot occur in the initial configuration of the nuclear material. With respect to the redistribution of the nuclear material through physical and chemical processes, which can lead to criticality, it should be shown that such a redistribution is very improbable”. A criticality event requires failure of a copper canister to prevent water in-leakage.

Since failure of a copper canister is a central issue for radioactive material escape from the canister, it has been thoroughly analysed by SKB. It appears to the author based on information from some reviews[11] of the SKB evaluation of copper canister corrosion as if early (within the first few thousands of years) corrosion can’t be excluded at this time.

If the copper canister corrosion could be so fast, the author assumes that criticality can’t be excluded without further evaluation, in particular of misloading and other human factor influences. Design changes may be required. In that case, there are at least two options to demonstrate criticality safety:

- Improve the corrosion barriers in the canister. SKB has estimated that increased copper thickness from 5 cm to 10 cm may improve the situation (e.g. TR-11-01 p. 763).
- Evaluate the criticality potential of a failed copper canister with water in-leakage and the potential consequences of criticality. The direct radiation should be easy to evaluate. The indirect consequences leading to reductions in other barriers may be more difficult to establish.

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[11] E.g. “Begäran om komplettering av ansökan om slutförvaring av använt kärnbränsle och kärnavfall” SSM letter to SKB 2012-02-14

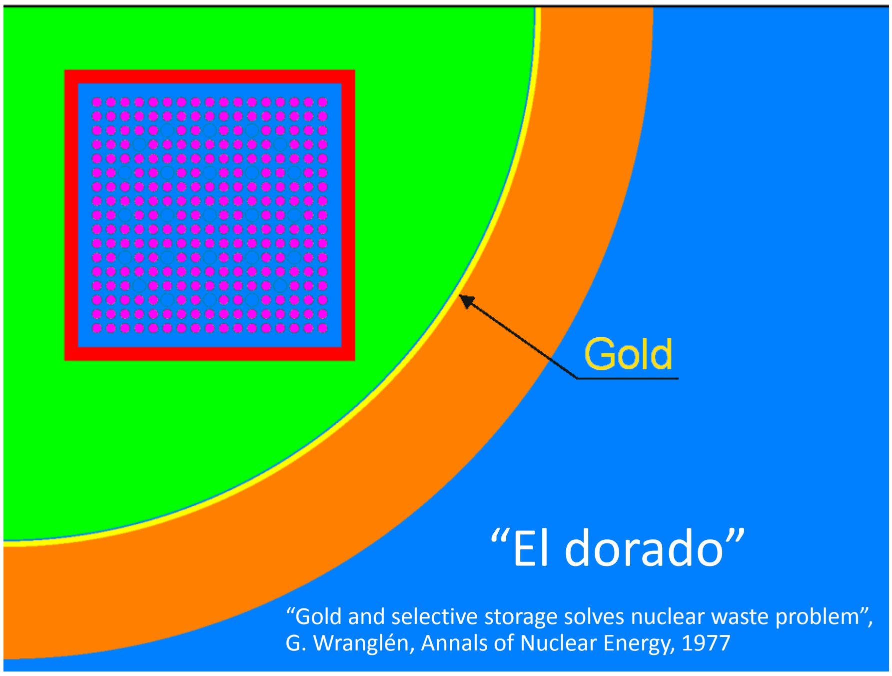

Figure 1: A 2D radial quarter-view of a copper canister, improved with a thin shell of gold.

4.8. Conservation of natural resources, recycling

Considering the lack of detailed regulations and SSM directives for criticality safety, it is necessary to base the review on the Nuclear Activities Act, the primary legislation covering criticality safety.

The Nuclear Activities Act requires consideration of the Environment Code, chapter 2 paragraph 5. This appears to be very relevant for the SKB application and the natural resources uranium, plutonium (transmuted uranium) and copper.

According to the author and many criticality safety specialists, the most important element in criticality safety is not calculations or technical barriers but consideration of the human factor. This conclusion is based on experience from criticality accidents and has influenced criticality safety regulations, standards, guides, etc.

Today, the spent fuel appears to the author as not being considered as economically valuable. It seems very likely that this will change in the not too distant future, in particular if the cost of the final disposal is considered.

The copper in the 6 000 canisters has a considerable economic value today. Where the limit for conflict with the Environment Code lies today is not known. It depends on the alternatives and on the consequences of a failed canister. The ALARA principle is of interest in determining priorities.

Criticality is considered to be unacceptable during the first ten thousand years or so (this perception by the author is described elsewhere in the Note). It is a potential consequence if the copper canister fails. Other radioactive material containment barriers may be influenced by the same event (canister failure leading to criticality).

SKB has already discussed the safety improvement by increasing the copper thickness from 5 cm to 10 cm. Another option may be to add some corrosion-resistant material to the copper canister. A potential material is a thin layer of gold, as suggested in a late 1970's journal article (G. Wranglén 1978). The author is not suggesting that such a solution is recommended, only that the use of natural resources and criticality safety (human factor influence and the ALARA principle) are related.
It appears as if the Nuclear Activities Act requires SKB to justify the use of natural resources and lack of recycling against the perceived benefits. This may have been done, but during this brief initial review such information has not been found.

SKB has assumed in the application that SSM focuses on nuclear safety and radiation protection and leaves other aspects of the EIS (Environment Impact Statement) to the Environment Court. This appears to be in conflict with the Nuclear Activities Act and does not appear to be reasonable. SSM should evaluate the benefits of the proposed solutions, consider the use of natural resources and recycling as well as to consider alternatives requiring less of those resources and improved recycling.

The response to the suggestions in this subchapter may already be available in the licensing application or in its references. If so, it should be clearer since it is a key issue. The reason for including the suggestions here is that the best available technology (BAT) principle cannot be applied without consideration of the Environment Code.

4.9. Incentives for retrieval of materials, consequences

The application covers intentional retrieval of the spent fuel and admits that it is possible but would be a complicated procedure requiring considerable time and cost. Here, the value of the copper is of interest. Whatever society is ruling, it would be aware of any action to retrieve the canisters or materials from them. It would be of international concern related to non-proliferation. The radiation safety awareness, and probably the ambition level, is expected to be adequate for a society that wants to retrieve the spent fuel. SKB may have covered the safety issue of spent fuel retrieval adequately.

The author has some questions concerning retrieval of copper as a primary incentive. A society that is interested in the copper but not in the spent fuel may act accordingly.

- Can the copper be retrieved without transporting the canisters to the surface?
- If the canisters are transported to the surface, is it possible that the spent fuel will be dumped without adequate safety measures?

Since failure of some of the copper canisters is assumed by SKB and such a scenario is not fully evaluated, the author assumes that it can eventually lead to criticality. The potential consequences are relevant even for this criticality safety review. However, other aspects than criticality appear to be more threatening.

The conclusion is that intentional copper retrieval and potential consequences should be discussed in the SKB licensing application and in the EIS.

5. Main review findings

The SKB licensing application for final disposal of spent fuel has been reviewed, with a focus on criticality safety during the steps following encapsulation of the spent fuel in copper canisters. Main review findings are:

- An overall evaluation of the safety documents leads to the conclusion that the criticality risk (probability and consequences) can be reduced to any level required by SSM, using the safety documents and specified intentions as a basis.
- The safety documents need to be expanded in some areas and revised in other areas to comply with modern standards and guides on criticality safety. This is achievable during the in-depth review of the licensing application, expected to follow the initial review by SSM.
- The issue of criticality safety criteria should be clarified by SSM. The results may involve some need for revision of the SKB safety documents but are not expected to change the results and conclusions significantly. This clarification should be achieved in the early phase of the in-depth review.
- The potential consequences of a criticality event should be clarified by SKB. In particular the early failure of a copper canister is assumed to be unacceptable. This is not due to direct radiation but to consequential influences on other barriers. There are valuable descriptions and references to potential effects of criticality (e.g. Oklo and U.S. studies) but the direct link to the SKB licensing application operations is not obvious. This clarification should be achieved in the early phase of the in-depth review.
- The concepts of barriers, defence-in-depth, event classes and maximum acceptable risk level appear to be based on containment of radioactive substances. Preventing radiation from occurring through criticality safety does not appear to fit within the current definition of the mentioned concepts. SSM and SKB should consider this issue. This clarification should be achieved in the early phase of the in-depth review.
- Validation of criticality safety calculation methods is an area that has been found to be weak both in Sweden and internationally. After most of the SKB criticality safety reports were prepared, new standards and guides have become available. They help to solve some of the validation issues.
- The issue of burnup credit is not new in general but its large-scale implementation for LWR spent fuel will be new for Sweden. The criteria and implementation needs to be discussed and evaluated thoroughly.
- There are two independent criticality safety control methods that each prevents criticality for sealed copper canisters:
    - Lack of water or other significant moderation in the canister
    - If water enters the canister, proper implementation of burnup credit (including adequate consideration of the human factor

during the loading operations at the Clink facility) will prevent criticality as long as the fuel and inserts are basically intact.

- It is reasonable for the Environmental Impact Statement (EIS) to be more specific on criticality safety and potential consequences of a criticality event during various operations. The risk may be low due to specific actions and circumstances but the potential hazard is there.
- The use of best available technology requires consideration of the Environmental Code, Section 2, paragraph 5. The benefits need to justify the significant value of natural resources and loss of recycling. SSM is expected to provide such information, according to the Nuclear Activities Act.
- The issue of transparency appears to be somewhat weak regarding the consequences of criticality in post-closure operation and in the consideration of use of natural resources against benefits.
- The traceability of criticality safety assessments and of the associated references appears to be very good. As mentioned above, descriptions of the consequences of a criticality event under various operations and the potential for intentional retrieval of copper are difficult to find.
- Considering an integrated view of all issues related to the SKB final disposal application, it appears questionable to the author that the copper canisters will be disposed of at all and very unlikely that they will not be retrieved within a thousand years. SKB has discussed alternatives. Experience in Sweden since 1977 and in other countries show that seriously intended plans can be abandoned. Retrieval of copper from the final disposal site may lead to radiation safety consequences, including criticality.
- The author gets the perception that SSM and SKB (perhaps as a consequence of SSM requirements) focus on radioactive material escape and radiation doses[12]. The perception is primarily based on the use of the risk concept as being based on radiation doses. This may be sufficient for the period after the disposal is left unattended and without adequate control[13]. Before that, it appears to the author as if some consideration has been missing. This also applies to international transport regulations for radioactive material. Contamination of large land or sea areas or volumes is in itself a serious accident even if evacuation reduces the radiation doses to zero. Criticality may be one of the sources for such contamination. Evacuation may in itself be a much larger risk than the radiation. The consequences of a criticality accident can be lethal without any escape of radioactive material.

6. Recommendations to SSM

6.1. Criticality safety criteria

Criticality safety is often a lethal threat to individuals close to the event. This is of course serious but there are overall consequence limitations that may not apply to

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[12] E.g. SSMFS 2008:37, §2: risk is defined as the product of probability of receiving a dose and the consequences of that dose.

[13] E.g. SSMFS 2008:21, §7 and §9 and the corresponding guidance texts.

other nuclear accidents or to radiological accidents. Most criticality safety standards and guides are prepared for such criticality accidents.

In the case of final disposal, SKB has indicated (a perception by the author based on reading the application documents) that a criticality could cause serious secondary effects, like further damage to the copper canister and to reduced efficiency of other barriers to containment of the radioactive material. SSM is recommended to oversee current criticality safety criteria for different types of operations. This should preferably be done before the in-depth criticality safety review.

6.2. Validation of calculation methods

This is an issue that may be included under criteria but it is specified separately here.

Statistical evaluation of calculation method results requires consideration of dependence between benchmarks to be reliable. This does not appear to be the case with the SKB validation (SKBdoc 1193244). Recent standards and guides refer to this issue.

There are also other areas related to general validation of calculation methods that would benefit by some clarification from SSM. Use of sensitivity/uncertainty methods to determine similarity between evaluated scenarios (applications) and benchmarks is one such area.

The acceptability of a well-supported negative bias correction (for a positive bias) is another area. It is not accepted by NRC and leads to use of inferior methods without any actual safety benefit, just a false sense of safety.

Validation of burnup credit calculation methods may be particularly important for the in-depth review. SKBdoc 1193244 refers to some proprietary reports[14] that were not reviewed in this initial phase. In the past, subjective engineering judgment has been used to validate depletion (burnup) calculation methods both in Sweden and in the U.S. This is not acceptable to NRC anymore, as evident from recent conferences and in particular from () NRC SFST ISG-8 Rev. 3 (NRC 2012).

SSM should determine internally how to deal with validation in general and with burnup credit in particular. For the Clab facility, additional validation and review of the BA credit calculation methods should also be considered. These efforts should preferably be started before the in-depth review of the SKB licensing applications.

6.3. Criticality safety related to radiation safety

Criticality safety is normally (prevention) a nuclear safety area, not a radiological protection area. If a criticality event occurs, it will become a radiological protection concern. In particular for the final disposal, criticality may also be a trigger for a release of a much larger source term than generated by the criticality event itself.

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[14] Ringhals 2007-10-19, 1960160/1.1 and OKG 2008-05-26, reg nr 2008-14670.

Reading the Acts, Ordinances and SSM Regulations, it appears to be clear that criticality safety is a recognized safety threat but the specifications and directives are not so clear. Some of the concepts such as barrier, defense-in-depth, event classes and risk are not easy to connect to criticality safety. Additional guidance may be a wise move.

6.4. Potential consequences of a criticality event

The consequences of a criticality event may be lethal but they may also be insignificant. In emergency preparedness and response, such information is essential. Justification of the use of significant quantities of natural resources (e.g. copper) requires benefits in the reduction of potential consequences of failed copper canisters. Prevention of criticality is expressly stated by SKB as one such benefit.

SSM is recommended to request from SKB some evaluations of potential criticality scenarios that are specific to a selected number of operations.

6.5. The Environment Impact Statement (EIS)

SKB should be requested to update the EIS to mention criticality as a potential safety hazard. The Nuclear Activities Act (5 b §) also requires SSM to consider the use of natural resources and recycling of materials when safety is evaluated.

An SKB assumption in the licensing application (Section 1.6) is that SSM only looks at nuclear safety and radiation protection while other areas are left to the Environment Court.

The author suggests that SSM should provide to the Environment Court the potential benefits from using the suggested natural resources and the lack of recycling. The Environment Court may be encouraged to express some limits on natural resources that are reasonable for this licensing application. This may later be used by SSM and SKB to determine best available techniques, with appropriate consideration of the Environment Code.

7. References

7.1. Laws and regulations

Nuclear Activities Act (1984:3), Modified 28 February 2011

Ordinance (2008:452) with instructions for the Swedish Radiation Safety Authority, updated up to SFS 2011:315

Ordinance (2008:14) on Nuclear Activities, updated up to SFS 2011:315

Radiation Protection Act (1988:220), Modified 21 October 2010

Ordinance (1988:293) on Radiation Protection, Modified 28 December 2009

SSMFS 2008:1, ”The Swedish Radiation Safety Authority’s Regulations concerning Safety in Nuclear Facilities”, consolidated version, updated up to SSMFS 2011:3, full validity from 1 November 2012.

SSMFS 2008:21, ”The Swedish Radiation Safety Authority’s regulations concerning safety in connection with the disposal of nuclear material and nuclear waste”, 30 January 2009.

SSMFS 2008:37, ”The Swedish Radiation Safety Authority’s Regulations Concerning the Protection of Human Health and the Environment in Connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste”, 30 January 2009.

Act (2006:263) on Transport of Dangerous Goods, 6 April 2006

IAEA TS-R-1, ”Regulations for the Safe Transport of Radioactive Material”, 2012 Edition (to be published in 2012). This is a model regulation.

7.2. Standards and guides

ANS/ANSI-8.24-2007, ”validation of neutron transport methods for nuclear criticality safety calculations”

ANSI/ANS-8.27-2008, “Burnup Credit for LWR Fuel”, American Nuclear Society

ANS/ANSI-8.1-1998(R2007), ”Nuclear criticality safety in operations with fissionable material outside reactors”

ANS/ANSI-8.10-1983(R2005), “Criteria for nuclear criticality safety controls in operations with shielding and confinement”

DIN 25472, “Kritikalitätssicherheit bei der Endlagerung ausgedienter Kernbrennstoffe”, 2011-02-21.

ISO 27468:2011, “Nuclear criticality safety – Evaluation of systems containing PWR UOX fuels – Bounding burnup credit approach”

ISO 27467:2009, “Nuclear criticality safety – Analysis of a postulated criticality accident”

ISO 11320:2011, “Nuclear criticality safety–Emergency preparedness and response”

ISO 14943:2011, “Nuclear fuel technology – Administrative criteria related to nuclear criticality safety”

NRC Regulatory Guide 3.71, “Nuclear Crticality Safety Standards for Fuels and Material Facilities”, December 2010

NRC FCSS Division Interim Staff Guidance ISG-10 Rev. 0, “Justification for Minimum Margin of Subcriticality for Safety”, June 2006

NRC SFST Division, ISG-8 Rev. 3, ”Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks”, September 2012.

7.3. Some SKB criticality safety application references

P. Behrenz, K. Hannerz, “Criticality in a spent fuel repository in wet crystalline rock”, KBS TR 108, ASEA-ATOM, 1978-05-30

C. D. Bowman, “Underground Supercriticality from Plutonium and Other Fissile Material”, LA-UR-94-4022A, Los Alamos 1994

V. O. Oversby, “Oklo: Des reacteurs nucleaires fossils (Oklo: The fossil nuclear reactors). Physics study (R Naudet, CEA), Translation of chapter 6, 13, and conclusions, SKB TR 96-14, September 1996

V. O. Oversby, “Criticality in a high level waste repository – A review of some important factors and an assessment of the lessons that can be learned from the Oklo reactors”, SKB TR 96-07, June 1996.

V. O. Oversby, “Criticality in a Repository for Spent Fuel: Lessons from Oklo”, Mat. Res. Soc. Symp. Proc. Vol. 506, 1998.

R. A. Van Konynenburg (compiler), ”Comments on the Draft Paper “Underground Supercriticality from Plutonium and Other Fissile Material” written by C. D. Bowman and F. Venneri (LANL)”, UCRL-ID-120990, 5 May 1995.

7.4. References to SKB canister criticality safety report

This criticality safety report, a reference to Appendix SR-Drift (Swedish) Chapter 8, contains 15 references on various criticality safety issues. All 15 references are available but the list is not repeated here.

7.5. A selection of NUREG/ORNL Reports

G. Radulescu, I. C. Gauld, “An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Isotopic Composition Predictions”, NUREG/CR-7108 (ORNL/TM-2011/509), U.S. NRC and ORNL, April 2012.

D. E. Mueller, J. M. Scaglione, J. C. Wagner, and W. J. Marshall, “An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Criticality (k_{eff}) Predictions”, NUREG/CR-7109 (ORNL/TM-2011/514), U.S. NRC and ORNL, April 2012.

D. E. Mueller, K. R. Elam, P. B. Fox, “Evaluation of the French Haut Taux de Combustion (HTC) Critical Experiment Data, NUREG/CR-6979 (ORNL/TM-2007/083), U.S. NRC and ORNL, September 2008.

G. Radulescu, D. E. Mueller, and J. C. Wagner, “Sensitivity and Uncertainty Analysis of Commercial Reactor Criticals for Burnup Credit”, NUREG/CR-6951 (ORNL/TM-2006/87), U.S. NRC and ORNL, September 2008.

"Estimating the Probability of Misload in a Spent Fuel Cask", U.S. NRC and ORNL, June 2011.

J. C. Wagner, "Criticality Analysis of Assembly Misload in a PWR Burnup Credit Cask", NUREG/CR-6955 (ORNL/TM-2004/52), U.S. NRC and ORNL, January 2008.

NRC, "Final Safety Evaluation Report for the License Application To Possess and Use Radioactive Material at the Mixed Oxide Fuel Fabrication Facility in Aiken, SC", Docket No. 70-3098, December 2010.

7.6. A selection of EPRI reports and presentations

Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty, EPRI, Palo Alto, CA, 2011. 1022909.

Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation, EPRI, Palo Alto, CA, 2012, 1025203.

R. Ferrer, J. Rhodes, K. Smith, "CASMO5/TSUNAMI-3D Spent Nuclear Fuel Reactivity Uncertainty Analysis", PHYSOR 2012, Knoxville, April 2012.

D. Lancaster, A. Machiels, "Benefits of the Delta K of Depletion Benchmarks for Burnup Credit Validation", PHYSOR 2012, Knoxville, April 2012.

Burnup Credit – Contribution to the Analysis of the Yankee Rowe Radiochemical Assays, EPRI, Palo Alto, CA, 2011. 1022910.

Feasibility of Direct Disposal of Dual-Purpose Canisters Options for Assuring Criticality Control, EPRI, Palo Alto, CA. 2008, 1016629.

Burnup Credit Methodology: Spent Nuclear Fuel Transportation Applications. EPRI, Palo Alto, CA, 2010, 1021050.

Program on Technology Innovation: Yucca Mountain Post-Closure Criticality – 2007 Progress Report, EPRI, Palo Alto, CA, 2007, 1015128.

Burnup Credit—Technical Basis for Spent-Fuel Burnup Verification, EPRI, Palo Alto, CA, 2003. 1003418.

7.7. A selection of Yucca Mountain reports

“Screening Analysis of Criticality Features, Events, and Processes for License Application”, ANL-DS0-NU-000001 Rev 00, February 2008, Yucca Mountain Project.

“CSNF Loading Curve Sensitivity Analysis”, ANL-EBS-NU-000010 Rev 00, February 2008, Yucca Mountain Project.

“Blue Ribbon Commission on America’s Nuclear Future”, Report to the Secretary of Energy, January 2012

“Technical Evaluation Report on the Content of the U.S. Department of Energy’s Yucca Mountain Repository License Application – Postclosure Volume: Repository Safety After permanent Closure”, NRC, 2011

7.8. Other references

Gösta Wranglén, “Gold and selective storage solves nuclear waste problem”, Annals of Nuclear Energy, Vol. 4, pp 527-528, 1977.

A. Ranta-aho, “Modeling of BWR Cold Critical Measurements with CASMO-4E/ MCNP5 – Combined Validation Approach”, ICNC 2011, Edinburgh, October 2011.

Carl-Erik Wikdahl, “MOX-bränsle i svenska kärnreaktorer”, Analysgruppen vid KSU, Faktablad nummer 40, December 2005

”International Handbook of Evaluated Criticality Safety Benchmark Experiments”, NEA/NSC/DOC(1995)3, OECD, September 2011. Referred to as the ICSBEP Handbook (International Criticality Safety Benchmark Evaluation Project).

APPENDIX 1

Coverage of SKB reports

Table A1:1

Reviewed report	Reviewed sections	Comments
Application for final disposal	All	Application + all appendices
SR-Drift (Swedish)	All	Appendix to application
SR-Site - TR-11-01	All	Appendix to application
Miljökonsekvensbeskrivning	All	Appendix to application
R-10-25	All	Appendix MV to application
TR-09-22	All	Appendix to application
TR-10-12	All	Appendix to application
TR-10-13	All	Appendix to application
TR-10-14	All	Appendix to application
TR-10-45	All	Appendix to application
TR-10-46	All	Appendix to application
TR-10-52	All	Appendix to application
TR-10-53	All	Appendix to application
TR-10-54	All	Appendix PV to application
1193244 v. 4.0	All	SR-Drift Chapter 8 reference

APPENDIX 2

Suggested needs for complementary information from SKB

1. Criticality safety criteria should be discussed with SSM.
2. The two validation reports related to burnup credit in SKBdoc are needed for in-depth review. SKB should consider presenting the principles for the validation in an open document.
3. The references to criticality safety standards and guides should be updated and more recent standards and guides should be considered.
4. The validation technique for the calculation method is not statistically sound. Consideration of dependence between benchmarks is required.
5. SKB should present evaluations of potential criticality accident consequences that are typical for some specific scenarios that represent final disposal operations. This is necessary for emergency preparedness in some operations and for understanding the importance of copper canister integrity in the final disposal site,
6. The Environment Impact Statement (EIS) should refer to criticality as a potential hazard in itself and as a source for release of radioactive material. The definition of neutron radiation should be modified to acknowledge that such radiation needs to be considered after reactor operation.
7. The EIS should express the benefits of using large quantities of copper and balance this against the use of natural resources and lack of recycling. This may apply to the spent fuel as well.
8. Intentional retrieval of copper from the final disposal site should be discussed in the EIS or, if dismissed, such conclusions should be justified.

APPENDIX 3

Suggested review topics for SSM

1. It is essential that a consistent and durable set of criticality safety criteria is prepared by SSM to support the review and to give SKB adequate time to prepare for compliance with such criteria.
2. Make sure that the most recent standards and guides, as well as experience from international studies, are used to support the review.
3. Validation of calculation methods is an area that needs improvement.
4. Sensitivity and uncertainty analysis methods (e.g. SCALE/TSUNAMI) should be applied to confirm similarity between benchmarks and applications (specific evaluation scenarios)
5. Experience from wet and dry handling, storage and transport of spent fuel both in Sweden and internationally should be considered.
6. Burnup credit can be a very complicated issue that requires considerable review efforts. This depends on the final specifications for the encapsulation plant. SSM should prepare for licensing of burnup credit with the goal of setting a model for potential future applications of burnup credit (e.g. in Clab).
7. Emergency preparedness and response as well as other considerations rely on a reasonable understanding of potential consequences of criticality events during various operations.

2012:65

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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