X-XX-XX

Month and year

Post-closure safety for the final repository   
for spent nuclear fuel at Forsmark

Fuel and canister process report,  
FSAR version

Svensk Kärnbränslehantering AB

*Keywords:* Abbbbbbbbcccccc, Xxxxxxxx, Yyyyyy

This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

Data in SKB’s database can be changed for different reasons. Minor changes in SKB’s database will not necessarily result in a revised report. Data revisions may also be presented as supplements, available at www.skb.se.

This report is published on www.skb.se.

© 2024 Svensk Kärnbränslehantering AB

Summary

If there is a Summary, it is placed directly after the title page or directly after the preface.

Sammanfattning

Summary in Swedish.

Content

[1 Introduction 5](#_Toc195186547)

[1.1 General aspects for the system component(s) in this report 5](#_Toc195186548)

[1.2 Structure for process description 5](#_Toc195186549)

[1.2.1 Description 5](#_Toc195186550)

[1.2.2 Dependencies between process and variables 6](#_Toc195186551)

[1.2.3 Natural and anthropogenic analogues 7](#_Toc195186552)

[1.2.4 Boundary conditions 7](#_Toc195186553)

[1.2.5 Model- and experimental studies 7](#_Toc195186554)

[1.2.6 Time perspective 7](#_Toc195186555)

[1.2.7 Impact on safety functions 7](#_Toc195186556)

[1.2.8 Handling of the process in the assessments of post-closure safety 8](#_Toc195186557)

[1.2.9 Handling of uncertainties in the FSAR 9](#_Toc195186558)

[1.3 Initial state of the fuel in PSAR 9](#_Toc195186559)

[1.3.1 General 9](#_Toc195186560)

[1.3.2 Fuel types 10](#_Toc195186561)

[1.3.3 Structure of the fuel assemblies 11](#_Toc195186562)

[1.3.4 Description of fuel structure and radionuclide distribution in the structure 12](#_Toc195186563)

[1.4 Definition of fuel variables 15](#_Toc195186564)

[1.5 Summary of handling of fuel processes in the PSAR 16](#_Toc195186565)

[1.6 Initial state of the canister in the PSAR 16](#_Toc195186566)

[1.6.1 Description of cast iron insert and copper canister 16](#_Toc195186567)

[1.7 Canister performance and safety 20](#_Toc195186568)

[1.8 Definition of canister variables 21](#_Toc195186569)

[1.9 Summary of handling of canister processes in the PSAR 21](#_Toc195186570)

[2 Fuel processes 25](#_Toc195186571)

[2.1 Radiation related processes 25](#_Toc195186572)

[2.1.1 Radioactive decay 25](#_Toc195186573)

[2.1.2 Radiation attenuation/heat generation 25](#_Toc195186574)

[2.2 Thermal processes 26](#_Toc195186575)

[2.2.1 Heat transport 26](#_Toc195186576)

[2.3 Hydraulic processes 27](#_Toc195186577)

[2.3.1 Water and gas transport in the canister, boiling/condensation 27](#_Toc195186578)

[2.4 Mechanical processes 27](#_Toc195186579)

[2.4.1 Mechanical cladding failure 27](#_Toc195186580)

[2.4.2 Structural evolution of the fuel matrix 28](#_Toc195186581)

[2.5 Chemical processes 28](#_Toc195186582)

[2.5.1 Advection and diffusion 29](#_Toc195186583)

[2.5.2 Residual gas radiolysis/acid formation 29](#_Toc195186584)

[2.5.3 Water radiolysis 30](#_Toc195186585)

[2.5.4 Metal corrosion 30](#_Toc195186586)

[2.5.5 Fuel dissolution 31](#_Toc195186587)

[2.5.6 Dissolution of the gap inventory 32](#_Toc195186588)

[2.5.7 Speciation of radionuclides, colloid formation 32](#_Toc195186589)

[2.5.8 Helium production 33](#_Toc195186590)

[2.5.9 Chemical alteration of the fuel matrix 33](#_Toc195186591)

[2.6 Radionuclide transport 34](#_Toc195186592)

[3 Canister processes 36](#_Toc195186593)

[3.1 Radiation related processes 36](#_Toc195186594)

[3.1.1 Radiation attenuation/heat generation 36](#_Toc195186595)

[3.2 Thermal processes 36](#_Toc195186596)

[3.2.1 2.2.1 Heat transport 36](#_Toc195186597)

[3.3 Hydraulic processes 37](#_Toc195186598)

[3.3.1 Water and gas transport in the canister, boiling/condensation 37](#_Toc195186599)

[3.4 Mechanical processes 38](#_Toc195186600)

[3.4.1 Introduction 38](#_Toc195186601)

[3.4.2 Deformation of cast iron insert 38](#_Toc195186602)

[3.4.3 Deformation of copper shell from external pressure 38](#_Toc195186603)

[3.4.4 Thermal expansion 39](#_Toc195186604)

[3.4.5 Deformation from internal corrosion products 39](#_Toc195186605)

[3.4.6 Radiation effects 40](#_Toc195186606)

[3.4.7 Hydrogen embrittlement of copper 41](#_Toc195186607)

[3.5 Chemical processes 41](#_Toc195186608)

[3.5.1 Corrosion of cast iron insert 41](#_Toc195186609)

[3.5.2 Galvanic corrosion 42](#_Toc195186610)

[3.5.3 Stress corrosion cracking of cast iron insert 43](#_Toc195186611)

[3.5.4 Corrosion of copper canister 50](#_Toc195186612)

[3.5.5 Stress corrosion cracking of the copper canister 50](#_Toc195186613)

[3.5.6 Earth currents – stray current corrosion 51](#_Toc195186614)

[3.5.7 Deposition of salts on the canister surface 52](#_Toc195186615)

[3.6 Radionuclide transport 55](#_Toc195186616)

[4 References 56](#_Toc195186617)

[5 Appendix A or 1 – Heading 1 in appendix is included in table of content 57](#_Toc195186618)

[5.1 Heading 2 in appendix is not included in table of content 57](#_Toc195186619)

[5.1.1 Heading 3 in appendix is not included in content 57](#_Toc195186620)

# Introduction

***Svart text*** *nedan är den text som föreslås vara med i ett inledande kapitel i alla tre Processrapporterna, samt i huvudrapporten (texten är tänkt att kunna vara identisk i alla rapporter, förutom sista avsnittet om ’systemkomponent-specifika aspekter’).*

***Lila svensk text*** *nedan syftar till att ge konkreta råd till skribenter/redaktörer, dels för att hjälpa dem och dels för att vi i slutänden ska få en ökad samstämmighet mellan Processrapporterna (och FEP-katalogen). Denna text ska inte vara med i Processrapporterna.*

After Heading 1 follows Body text (Times New Roman 10.5 p).

## General aspects for the system component(s) in this report

***General aspects for the system component(s) addressed in this report***

Aspects relevant for describing dependencies between process and variables, the handling of processes in the assessment, and sometimes also the description of processes, will differ between different system components. In this section, the aspects **relevant for the specific report are discussed**, including:

*Time periods*: Over what time periods is the process relevant for the system evolution? In e.g., the case of the buffer, relevant time periods might be related to the saturation of the clay materials and the resaturation of the rock, why the geosphere relevant time periods might be related to when different climate domains occur.

*The special cases of a failed canister and of earthquakes altering deposition hole or tunnel geometry*: These special cases imply altered conditions that could influence many processes in particular for the fuel, the canister, the buffer and the backfill and they therefore need to be discussed separately. During the several thousands of years after deposition when temperate conditions are likely to prevail, canister failures are not expected and earthquakes of a magnitude that could affect the deposition hole or tunnel geometry are very unlikely, meaning that these special cases may not be relevant for many “early” processes.

By documenting the relevance of the process for applicable time periods, or intact or failed canisters, the process system can be simplified by omitting the process when it is not relevant.

***Till skribent/redaktör:***

Detta är ett nytt avsnitt, och är lämpligt att placera just innan avsnittet som beskriver mallen för processdokumentationen

Det är dock ingen ny information som behöver tas fram. Det som ska stå här fanns oftast tidigare under *Handling in the assessment*. Anledningen att flytta det till eget avsnitt är att de aspekter som ska beaktas och hur de delas upp kommer att skilja mellan de olika processrapporterna samt att uppdelningen är generell för hela processdokumentationen, inte bara för hur processer hanteras i analysen.

## Structure for process description

### Description

Stress corrosion cracking (SCC) of metals requires a combination of tensile stresses, a specific chemical environment and a susceptible material. Unfavourable combinations of these conditions can lead to the initiation and propagation of local cracks through the matrix over a period of time. Radiolysis on residual quantities of air and moisture within a canister can produce nitric acid (nitrate) as well as ammonia, which both are stress corrosion cracking agents for carbon steel. Also oxidising conditions (or more precisely an oxide film), as well as (at least) a water film on the metal surface are required.

The first paragraph under this heading should be a brief introduction of the process and put into context of the safety assessment. This text will be identical to the description for the corresponding internal process in the FSAR SFK FEP catalogue.

***Till skribent/redaktör:***

Syftet med det **inledande** stycket är att ge en kort introduktion, ’inflygning’ till processen som ger läsaren en snabb överblick. På förslag ligger att detta stycke i rapporten kommer presenteras i en ruta. Paragrafen bör innehålla en kort beskrivning av vad processen är, och sätta in den i rätt kontext (för en del väldigt breda processer, tex advektion, behövs något om vad som inkluderas i processen och vilka begränsningar som den har).

En tanke med denna inledande text är att den även ska passa som beskrivning för motsvarande interna process i FEP-katalogen. Denna inledande text ska därför inte innehålla några litteratur- eller kors-referenser, samt inte heller komplicerad formatering (dvs i möjligaste mån ska den undvika matematiska symboler, grekiska alfabetet, upphöjt till, nersänkt till, osv). Ett riktmärke på omfånget är att det inledande stycket inte överstiger ca 100 ord.

Syftet med **resten** av beskrivningen i detta avsnitt är att:

* ge relevant underlag till beskrivning/analys av referensutvecklingen och analys av scenarier
* ge relevant underlag till valet av hur processen hanteras i analysen (utan att gå in på hanteringen)

Den generella beskrivningen behöver således inte innehålla all tillgänglig vetenskaplig information om vår processförståelse, dvs den behöver inte vara av ’skolboks-karaktär’.

För att ge läsaren en bakgrund till varför processen är inkluderad i rapporten är det bra om det i början av 'resten av beskrivningen’ beskrivs kort, bara nån mening eller två, om vilken/vilka säkerhetsfunktioner processen påverkar (mer detaljer om detta kommer sedan i avsnitt 1.2.7).

### Dependencies between process and variables

For each system component, a set of physical variables that defines the state of the system is specified. For each process identified, a table is presented under this heading with documentation of how the process is influenced by the variables and how the process influences the variables. In addition, the handling of each influence in the FSAR is indicated in the table.

Influences between processes and variables and handling of influences may vary depending on aspects related to e.g., climate domains, saturation state of the clay materials, and whether the canister is intact or failed. Which aspects to consider when producing the ‘influence table’, for the system component(s) addressed in this report, is discussed in Section **Fel! Hittar inte referenskälla.** above.

Where an influence is present but not included in the analyses, a justification for the exclusion is provided in the table. Several reasons for excluding an existing influence for further analyses can be distinguished, such as:

* The influence has a minor intrinsic significance.
* The influence has a minor significance compared with other influences acting simultaneously.
* The influence can be subsumed into another influence (without necessarily judging which is the more significant).

***Till skribent/redaktör:***

Arbetet med att uppdatera influenstabellerna är tänkt att med fördel genomföras i Excelfilerna framtagna för uppdatering av FEP-katalogen. Om detta arbetssätt är det bästa kommer visa sig när vi börjar med arbetet.

Ambitionen är att tabellerna i FEP-databasen och i Processrapporterna ska vara identiska. Det planeras att ta fram skript som skapar Word-tabeller till processrapporterna direkt från informationen i Excel-filerna.

### Natural and anthropogenic analogues

If relevant, natural and anthropogenic analogues that contribute to the present understanding of the process are documented under this heading.

***Till skribent/redaktör:***

Behövs det några ytterligare förtydliganden för detta avsnitt?

### Boundary conditions

The boundary conditions for the process are discussed. These refer to the boundaries of the relevant system component the process occurs in. For example, for processes internal to the buffer, the boundaries are the buffer interfaces with the canister, the walls of the deposition hole, the backfill, and the bottom plate in the deposition hole.

The processes for which boundary conditions need to be described are, in general, related to transport of material or energy across the boundaries. For example, for chemical processes occurring within a system component, like illitisation in the buffer, the discussion of boundary conditions relates to the boundary conditions of the relevant transport processes occurring in the buffer, i.e., advection, diffusion, and heat transfer.

***Till skribent/redaktör:***

Behövs det några ytterligare förtydliganden för detta avsnitt?

### Model- and experimental studies

Model and experimental studies of the process are summarised. For many processes, this documentation constitutes the major source of information.

***Till skribent/redaktör:***

Behövs det några ytterligare förtydliganden för detta avsnitt?

### Time perspective

The time scale or time scales on which the process occurs are documented, if such time scales can be defined.

***Till skribent/redaktör:***

Dessa tidsskalor behöver definieras på förhand och synkroniseras inom respektive rapport samt, där tillämpligt, mellan rapporter så att uppsättningen och användningen blir identiska där den ska vara det. Notera att för en del processer är tidsskalorna knutna till att vissa förhållanden uppfylls, som tex att vatten har trängt in i kapseln.

### Impact on safety functions

In this section, the potential relevance for post-closure safety is discussed. Focus is on if the process may directly affect any safety function (and safety function indicators) for containment and/or retardation, or if the process may affect safety in a more indirect way (i.e., if it is coupled to another process that directly affect a safety function).

***Till skribent/redaktör:***

Detta är ett nytt avsnitt. I tidigare rapporter har de olika processernas påverkan på säkerhetsfunktioner och indikatorer diskuterats på lite olika ställen, tex i avsnitten *Handling in the assessment*, *Description* eller *Uncertainties*. För en del processer har detta inte diskuterats alls. Dock har alla tre processrapporter dedikerade avsnitt om systemdelarnas övergripande roll för säkerheten (*canister/buffer/geosphere performance and safety*) inklusive tabeller med säkerhetsfunktioner och indikatorer.

Tanken med detta nya avsnitt är att för varje process diskutera dess relevans för säkerheten efter förslutning – främst dess påverkan på säkerhetsfunktioner och indikatorer (om sådan existerar). Dvs, det som tidigare stått på lite olika ställen samlas här. Ett hjälpmedel till vad som ska skrivas i detta avsnitt är den mappning av vilka säkerhetsfunktioner som påverkas av FEPs (arbete som kommer göras under 2025 i samband med framtagandet av uppdaterad FEP-katalog).

Det kommer att finnas processer som inte direkt har en påverkan på säkerhetsfunktioner och säkerhetsfunktionsindikatorer. I dessa fall kan tex följande argumentering föras under detta avsnitt:

* Processen har inte någon direkt påverkan på någon säkerhetsfunktion, men att den har en koppling till någon annan process som har det, och bör därmed vidare beaktas i analysen.
* Processen har inte någon direkt påverkan på någon säkerhetsfunktion, och har inte eller någon koppling till en annan process som har det, och dra slutsatsen att denna process inte är viktig för säkerheten (se tex texten om jordströmmar i PR-geosfär, avsnitt 5.14.7 – den texten skulle i princip kunna skrivas in i detta nya avsnitt, sen under ’handling…’ kan det bara konstateras att den inte behöver vidare beaktas i säkerhetsanalysen).

### Handling of the process in the assessments of post-closure safety

#### Handling in the FSAR

All processes addressed in this report are in fact included and handled in the FSAR. The description of identified processes relevant to the long-term evolution of the system, i.e., this report, constitutes step 4 in the methodology of the post-closure safety assessment in the FSAR (see Main report, Chapter 2).

The aim of this section is to describe how a process is handled in the FSAR, especially in the analysis of the reference evolution (step 7) and analyses of selected scenarios (step 9).

For some processes, the process understanding gained during the discussions under previous headings may lead to the conclusion that its potential impact on post-closure safety is so small that there is no need to further handle it in the FSAR. In those cases, the argumentation is given here.

For many processes, the handling will vary depending on aspects related to e.g., the prevailing climate domain, the saturation state of the clay materials, or if the canister is intact or failed. Which aspects to consider when discussing the handling in the FSAR, for the system component(s) addressed in this report, is discussed above in Section **Fel! Hittar inte referenskälla.**.

In addition, the following two aspects of how the process is handled are relevant to discuss for all processes; no prescribed format for the documentation is given here, this may vary from process to process:

* *Boundary conditions*: How are the boundary conditions handled? Are e.g., spatially and temporally varying chemical and hydraulic conditions considered?
* *Influences and couplings to other processes*: The handling of the influences documented according to the above description is discussed as are couplings to other processes within the system component.

#### Changes in handling since the PSAR

Brief statement if the handling of the process in the FSAR is the same as it was handled in the PSAR, or if it differs. If the handling differs, key differences should be given, preferably in a bullet list.

***Till skribent/redaktör:***

I förra analysen benämndes detta avsnitt ’*Handling in the PSAR*’. För att underlätta för läsare och granskare kommer det i FSAR att delas upp i två underavsnitt – först ett avsnitt som beskriver hanteringen av processen i FSAR, sen ett kort avsnitt som ger information om hanteringen har ändrats sen PSAR eller inte.

Det nya underavsnittet, ’*Changes in handling since the PSAR*’, är tillagt för att underlätta för läsare och granskare.

Då ingen signifikant ändring i hanteringen har gjorts kan det till exempel konstaterats nåt i stil med: ”*Text above has been updated, but the handling of the process is the same in the FSAR as in the PSAR*”. Då signifikanta ändringar i hanteringen har gjorts, tex om en ny modell har använts, ska huvuddragen i ändringarna kort summeras här.

### Handling of uncertainties in the FSAR

Given the adopted handling of each process in the FSAR, the handling of different types of uncertainties associated with the process is summarised.

*Uncertainties in mechanistic understanding*: The uncertainty in the general understanding of the process is discussed based on the available documentation and with the aim of answering the question: Are the basic scientific mechanisms governing the process included and understood to a level necessary for the adopted handling? Alternative models are sometimes used to illustrate this type of uncertainty.

*Model simplification uncertainties*: In most cases, the quantitative representation of a process contains simplifications. These may result in a significant source of uncertainty in the description of the system evolution. Alternative models or alternative approaches to simplification for a particular conceptual model are sometimes used to illustrate this type of uncertainty.

*Input data uncertainties*: The set of input data necessary to quantify the process for the suggested handling is documented. The further treatment of important input data and input data uncertainties is described in the **Data report**, to which reference is made if relevant.

## Initial state of the fuel in PSAR

The following is an overview description of the initial state of the fuel, i.e. its state at the time of deposition. Most of the information is taken from the Spent fuel report (SKB 2021a), which can be considered an update of a previous report (SKB 2010d).

### General

This repository sub-system comprises the spent fuel and the cavity in the canister. The total quantity of spent fuel obtained from the Swedish nuclear reactors will depend on operating time, energy output and fuel burnup. The existing reactors in Sweden are light water reactors of both boiling water (BWR) and pressurized water (PWR) types. The fuel quantities presented here are based on SKB’s scenario for the operation of the nuclear power plants. The maximum enrichment is set to 5 % and the burnup is limited to 60 MWd/kgU for the PWR and BWR uranium oxide (UOX) fuel and 50 MWd/kgHM for the BWR mixed uranium-plutonium oxide (MOX) fuel. It is assumed that the last reactor will be taken out of operation in 2045.

### Fuel types

Several types of fuel will be emplaced in the repository. The major portion of the fuel to be deposited is UOX fuel from PWR and BWR reactors. There will also be small amounts (three used fuel elements) of BWR MOX fuel, spent heavy water reactor fuel from the decommissioned Ågesta reactor, and German MOX assemblies (from an exchange project involving reprocessing waste) as well as fuel residues from Studsvik. Since SR-Site, a decision has been taken that all fuel with failed cladding will be handled separately. Thus, special containers with failed fuel are also part of the full spent fuel inventory. The total amount of spent fuel and the total number of fuel elements are given in Table 1‑1SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 .

Differences between different fuel types are important for criticality assessments.

To allow for these quantities, the safety assessment assumes a total of 3 982 BWR canisters and 1 707 PWR canisters, in total 5 689 canisters with regular spent fuel corresponding to ca 13 000 tonnes of fuel. In addition there will be a small number of canisters with fuel residues and containers with failed fuel (ie fuel with failed cladding).

Table 1‑1. Amount of spent fuel and number of fuel elements. From the Spent fuel report (SKB 2021a).

| Fuel type | Number in interim storage (31 December 2015) | Total number for the assumed scenario (includes prognosis) | Total initial weight for the assumed scenario (tonnes of U or HM) |
| --- | --- | --- | --- |
| BWR assemblies (incl. 3 BWR MOX) | 28 931 | 47 314 | 8 367.5 |
| PWR assemblies | 3 834 | 6 793 | 3 125 |
| Fuel assemblies from Ågesta | 222 (1 unirradiated) | 222 (1 unirradiated) | 20 |
| Fuel residues in protection boxes from Studsvik | 20 | approximately 37 | 4 |
| Swap MOX assemblies (BWR) | 184 | 184 | 14.1 |
| Swap MOX assemblies (PWR) | 33 | 33 | 8.4 |

Burnups of regular fuel are expected to vary from about 15 MWd/kgU up to 60 MWd/kgU, with distributions as indicated in Table 1‑2SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 .

Table 1‑2. Statistical data for burnup of Swedish spent fuel. From the Spent fuel report (SKB 2021a).

|  | Burnup (MWd/kgU) | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| Fuel | Average | Median | 1st Quartile | 3rd Quartile | Min | Max |
| BWR produced | 36.0 | 38.8 | 31.4 | 41.9 | 5.4 | 50.0 |
| BWR prognosis | 44.7 | 48.0 | 48.0 | 48.0 | 11.3 | 50.0 |
| BWR total | 39.4 | 41.5 | 34.6 | 48.0 | 5.4 | 50.0 |
| PWR produced | 42.6 | 44 | 40.1 | 46.6 | 14.3 | 57.8 |
| PWR prognosis | 49.9 | 52.4 | 50.8 | 53.5 | 17.0 | 56.2 |
| PWR total | 45.8 | 47.3 | 41.9 | 52.4 | 14.3 | 57.8 |

### Structure of the fuel assemblies

Nuclear fuel, here exemplified by Svea 96 BWR fuel, consists of cylindrical pellets of uranium dioxide. The pellets are 11 mm high and have a diameter of 8 mm. They are stacked in approximately 4-metre-long cladding tubes of Zircaloy, a durable zirconium alloy. The tubes are sealed with welds and bundled together into fuel assemblies. Each assembly contains 96 cladding tubes. The fuel assembly also contains components made of the nickel alloys Inconel and Incoloy, and of stainless steel. Pellets in a cladding tube and a fuel assembly are shown in Figure 1‑1SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 . Aspects of importance in the safety assessment, for example the geometrical arrangements and dimensions of the fuel cladding tubes are, as a rule, handled sufficiently pessimistically in analyses of radionuclide release and transport that differences between different fuel types are irrelevant.

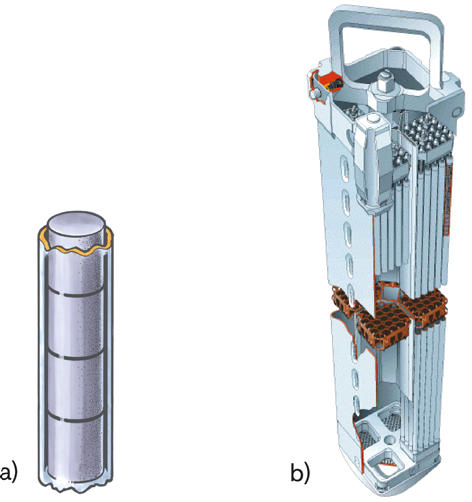


Figure 1‑1. a) Cylindrical fuel pellets in cladding tubes of Zircaloy. The pellets have a diameter of approximately one centimetre. b) Fuel assembly of type Svea 96. The assembly consists of 96 fuel tubes and has a height of approximately 4 metres.

### Description of fuel structure and radionuclide distribution in the structure

#### Fuel

The nuclear fuel consists of very nearly stoichiometric uranium dioxide in the form of cylindrical pellets. The size of the pellets varies between different fuel types, but is on the order of 1 cm in diameter and 1 cm in length. The grain size is normally in the range of a few µm to about ten µm. The uranium in the present fuel has been enriched in the isotope U-235 from the naturally occurring concentration of 0.7 % up to 3.6 % in BWR fuel (4.2 % in gadolinium-bearing fuel) and 4.46 % in PWR fuel. In the future, the enrichment will be increased to 5 %.

The fuel typically develops a power of 15 to 25 kW per metre of fuel rod during operation, which corresponds to a centre temperature in the fuel pellet of 800 to 1 200 °C. After use in the reactor, the fuel contains 2–6 % fission products, depending on the burnup, and approximately 1 % higher actinides formed by neutron capture and radioactive decay. The average burnup for Swedish nuclear fuel is currently (December 2015) 36 MWd/kgU for BWR fuel and 43 MWd/kgU for PWR fuel. Since the beginning of 1970, the burnup of nuclear fuel has gradually increased. The future average burnup of spent fuel to be deposited in the repository is estimated to 44.7MWd/kgU for BWR fuel and 49.9 MWd/kgU for PWR fuel (see Table 1‑2SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 ).

The increase of the fuel burnup leads to the formation of the high burnup structure (HBS) in the outer region of the fuel pellet (rim), which consists of small grains of submicron size and a high concentration of pores, 1 to 2 micrometres in size. The rim thickness increases with burnup and at an average burnup of 50 MWd/kgU, it is ca. 50 µm thick. One of the primary driving forces behind HBS formation is the significantly higher burnup experienced by the pellet periphery due to Pu-239 build-up by neutron capture in U-238, followed by its fission (Rondinella and Wiss 2010).

The majority of the fission products and the higher actinides are present in solid solution within the uranium dioxide matrix. Besides the chemical alteration of the uranium dioxide this entails, the fuel has also been altered physically during operation in the reactor. For example, significant cracking has occurred.

#### Enrichment of radionuclides on the pellet surface

In the case of fuel that has been irradiated at a relatively low temperature, the radial variation in grain size and porosity is small, with moderate grain growth in the centre of the pellet. An exception to this rule is the sharp increase in porosity in the pellet rim. To a depth of a few µm on the rim of the pellet, the porosity is several times higher than inside the fuel. This rim zone also deviates in microstructure from the rest of the pellet in that the original grains have been subdivided into many smaller grains. The reason for this lies in local variations in the fission rate across the diameter of the fuel.

Self-shielding in the fuel leads to a radial variation in the frequency of U-235 fissions, but more importantly, increased formation and fission of plutonium isotopes, in the rim of the fuel pellet. The result is increased burnup and alpha activity at the periphery of the fuel pellets. The increased burnup is also accompanied by a higher content of fission products. This surface layer can have a burnup up to 2.5 times the average (Matzke and Spino 1997), as well as more than four times the average alpha activity (Forsyth 1995).

#### Radionuclides in the fuel-clad gap

During irradiation in the reactor, a fraction of the radionuclide inventory will have segregated either to the gap between the fuel and the cladding or to the grain boundaries in the fuel. Of these radionuclides, the behaviour of the fission gases is best known. A number of studies of fission gas release (FGR) have been published over the years. The behaviour of other potentially segregated radionuclides is far less well known. This is of concern because these radionuclides will be released more rapidly than the radionuclides that are embedded in the fuel’s UO2 matrix. The fractions of some of the radionuclides that are incompatible with the UO2 matrix, and thus present in the fuel/cladding gap, are generally considered to be comparable to the fission gas release to the fuel/cladding gap as measured in gas release testing of fuel rods (Johnson and Tait 1997, Johnson and McGinnes 2002, Werme et al. 2004, Johnson et al. 2004, Ferry et al. 2008). This is due to the relatively high high diffusion coefficients for some of the volatile elements, such as I and Cs, at the elevated, in-reactor temperatures. At these temperatures, a fraction of these radionuclides will diffuse to the grain boundaries and then to gap, due to the expected similar behaviour as the fission gases (Johnson et al. 2012). Considering this, and since there are far more data available on fission gas release than on the release from the matrix of other radionuclides, it is of interest to discuss the fission gas release even though the fission gases are of little concern for a long-term safety assessment. Fission gas release is more strongly correlated to the linear power rating than to the burnup of the fuel (Kamimura 1992). Up to about the year 2000, the operating conditions were such that the linear power rating was kept relatively low and the fission gas release minimised. Up to a burnup of about 40 MWd/kgU, the fission gas releases are typically less than one percent (see e.g. Werme et al. 2004, Johnson et al. 2004). In SR-Can (SKB 2006), the fuel was assumed to have a burnup of 38 MWd/kgU. At that time, about 75 % of the Swedish fuel inventory had a burnup of less than 40 MWd/kgU and the number of fuel elements with an average burnup exceeding 50 MWd/kgU was very small. As of June 2005, only 45 fuel elements had a burnup exceeding 50 MWd/kgU. As of December 2015, the number had increased to ca 300. At the time of writing (2019) the number is 577.

It was previously observed, at the time of the SR-Site safety assessment, that for the interval 40 to 50 MWd/kgU, the fission gas release is generally below 1.5 % for PWR fuel, while for BWR fuel it can go as high as 5 % with an average in the range of 2.5 %. As was mentioned earlier, a high linear power rating is expected to increase the FGR. Now, some Swedish reactors have been uprated and as a consequence, the linear power rating is increased and higher FGR is expected. Therefore, for the SR-Site assessment, FGR was calculated for burnups up to 60 MWd/kgU for typical equilibrium cores for Swedish BWR (Oldberg 2009) and PWR reactors (Nordström 2009).

For the PSAR, more experimental data are available for fuels with a burnup above 50 MWd/kgU. Johnson et al. (2012) presents and discusses data from PWR fuel with burnups between ca 58 and 75 MWd/kgU. The measured fission gas releases of these fuels display a significant variation, with the highest values (ca 20 % or more) originating from fuel that had experienced a very high linear power rating (ca 300 W/cm). For other fuels, with a linear power rating between 200 and 230 W/cm, the fission gas release varies between ca 1 and 5 %. These data highlight the importance of the linear power rating in the determination of the FGR and, by extension, the so-called Instant Release Fraction (IRF) of some radionuclides. In the EU-project First Nuclides, both BWR and PWR fuels with high burnup were studied (Lemmens et al. 2017). The PWR fuels had a burnup of 50–63 MWd/kgU and a linear power rating of 136–306 W/cm (both values rod average). The BWR fuels had a burnup of 42–59 MWd/kgU and a linear power rating of 143–217 W/cm (both values rod average). The PWR fuels had a measured FGR of 2–26 %, while the BWR values are lower, between 1.4 and 3.9 %. It should be noted that the higher PWR values are from a MOX fuel, while the lowest FGR value come from a Cr+Al-doped fuel. Two main conclusions from the First-Nuclides project are 1) that the IRFs of I and Cs are generally below the FGR-values, and 2) there is a positive correlation between the IRFs of I and Cs with linear power ratings above 200 W/cm (Lemmens et al. 2017).

There are relatively few systematic studies of the release of segregated radionuclides other than fission gases from fuel. Only one very comprehensive study has been published (Stroes-Gascoyne 1996). In that publication, the rapid releases of Cs-137, Sr-90, Tc-99, I-129 and C-14 from CANDU fuel were reported. For light water reactor (LWR) fuel, there were far less data available (see e.g. Forsyth and Werme 1992, Gray et al. 1992, Gray 1999, Johnson et al. 2004, 2005, Roudil et al. 2007), but the amount of available data has now increased (Johnson et al. 2012, Kienzler et al. 2017, Lemmens et al. 2017). The inventory of C-14 and Cl-36 in spent fuel originates from neutron activation of impurities (N, Cl), and a fraction of these are also found in the gap. Very few leaching data are available for Cl-36, but this very mobile radionuclide is expected to diffuse rapidly a gas in the reactor, and a large fraction is therefore expected to found in the gap. There is some leaching data for C-14 which is used to estimate the gap inventory (e.g. Johnson et al. 2005).

Based on these studies, it was apparent that the fission gas release and the rapid release of some segregated radionuclides are correlated. This seems to be true for most LWR fuel (Johnson and McGinnes 2002, Lemmens et al. 2017).

Thus, for some radionuclides such as Cs and I, the IRF can be determined based on a correlation with FGR, while for others such as Mo, Tc, Se the relationship seems to be more complex (Werme et al. 2004, Johnson et al. 2004). Mo and Tc are non-volatile at all fuel operating temperatures, so release from UO2 doesn’t occur through volatilisation, but through phase segregation. Therefore, additional leaching data from spent fuels are required to establish the IRF of some radionuclides. One radionuclide of special interest is Se-79. The leaching behaviour and the chemical state of Se in the UO2 matrix were studied in the First Nuclides project. It was found that the observed very low fractional release of Se (e.g. Johnson et al. 2012) is likely due to the direct chemical bonding of Se to U atoms as a Se(II) (selenide) ion, probably replacing oxygen in the cubic UO2 lattice (Curti et al. 2015).

As was mentioned by Curti et al. (2015), the calculation of oxygen potential can be used as a first means to evaluate the chemical state of fission products in spent nuclear fuel. This method was utilised by Curti and Kulik (2020) for conventional and Cr-doped UO2 fuels. The results show that oxygen potentials in spent Cr-doped fuel are similar to conventional spent UO2 fuels and thus indicates that the Cr-doping should not significantly affect the chemical state of fission products in the spent fuel.

#### Radionuclide segregation to grain boundaries

In addition to the release of gaseous fission products, other elements that are incompatible with the structure of the uranium dioxide are also segregated to form separate phases. Light water reactor fuel contains inclusions of metal alloys of Mo-Tc-Ru-Rh-Pd (4d metals), known as ε-phases. In standard LWR fuel with average burnup between 40 and 50 MWd/kgU, these particles can be up to micrometres in size and observable by optical microscopy (Forsyth 1995). The fraction of 4d metals, which Forsyth was able to determine by optical microscopy (particles larger than 0.5 µm), corresponded to only 1 % of their calculated total inventory in the fuel. By electron microscopy, it has been possible to determine that ε-phases also occur in the size range 1 to 100 nm (Thomas and Guenther 1989). When fuel is dissolved in nitric acid, the 4d metals form an insoluble residue. By analysing these residues, Forsyth concluded that at least 80 % of the residues consisted of ε-particles. The particle size distribution depends on the temperature at which the fuel operated and can, therefore, vary between fuel samples. A more recent and thorough description of the occurrence of the metal aggregates is given by Spahiu and Evins (2013).

Besides these known segregations, the possibility that other fission products have segregated to the grain boundaries in the uranium dioxide has been discussed. For CANDU fuel, which is irradiated with higher linear power density (20–55 kW/m) than light water reactor fuel, it has been established by photoelectron spectroscopy that Cs, Rb, Te and Ba are present in the grain boundaries, often with high surface enrichments (Hocking et al. 1994). Gray et al. (1992) determined the grain boundary inventory of Cs in light water reactor fuel to be less than 1 %. The values of gap and grain boundary inventories for Tc and Sr were near their detection limits at less than 0.2 % of their total inventory. An Auger spectroscopy study on fuels with moderate burnup and low fission gas release showed no detectable amounts of Cs, Sr and Tc (Thomas et al. 1992). On a PWR fuel with extremely high fission gas release (18 %; equivalent fuel was also included in the study by Gray et al. (1992), ε-phases were found with high surface concentrations of Cs, Te and Pd (Thomas et al. 1992)). This observation was interpreted as indicating that Cs and other fission products are mainly associated with the ε-phases and, thereby only indirectly with the grain boundaries that contain them. However, considering the similar diffusion coefficients of I, Cs and fission gases, one could argue that fission gas bubbles found in grain boundaries also contain some I and Cs. The implications of this for the IRF is not yet clear since the pores appear to be closed (Roudil et al. 2007), and recent studies indicate a limited contribution from the grain boundaries on the IRF (Roth et al. 2019).

The question of Sr segregation and the differences between Sr and U release from spent fuel in leaching experiments at Studsvik has been discussed extensively. Werme and Forsyth (1988) offer the hypothesis that most of the Sr released comes from selective leaching of cracks and grain boundaries. Attempts have been made to determine grain boundary inventories by microprobe analysis in a fuel with a burnup of 37 MWd/kg U (linear power rating < 20 kW/m) that had been subjected to controlled power ramping to 43 kW/m in the Studsvik R2 reactor (Forsyth et al. 1988). The rod had an appreciable release of Kr and Xe, as well as redistribution of Cs to the fuel-clad gap during the power increase. Sharp concentration gradients within the individual grains could be observed for Xe and Cs, but not for Nd. In the case of Sr, the concentrations were far too close to the detection limit to yield reliable data. Subsequently, a fuel with a burnup of 44–48 MWd/kgU (linear power density < 15 kW/m), was subjected to a similar power ramping to a peak of 43 kW/m (Forsyth et al. 1994). In a corrosion experiment a significant increase, compared to the reference samples, in the release of Cs and Rb was observed, and some increase for Ba and Tc as well as possibly also for Mo. No significant redistribution of Sr was found. In a recent study of up to 5 years fuel leaching under aerobic conditions (Roth et al. 2019) the fractional release rates of Sr are about one order of magnitude higher than the U release rates, indicating that Sr originates not only from matrix dissolution, but also from leaching of segregated oxide phases (grey phases).

New data for Sr release indicates that, for BWR fuel with FGR between ca 1 and 5 %, less than 0.1 % of the Sr inventory is released during 1 year of leaching in aerated conditions (Zwicky et al. 2011, Roth 2015).

The studies presented above thus suggest that there is still some uncertainty concerning the significance of the grain boundary inventory of different radionuclides and that this likely relates to both type and irradiation history of the fuel.

More information regarding IRF values for radionuclides found in the gap and grain boundaries is given in the PSAR Data report (SKB 2022d).

## Definition of fuel variables

The spent fuel is described by the variables in Table 1‑4, which together characterise the spent fuel in a suitable manner for the safety assessment. The description applies not only to the spent fuel itself, but also to the cavities in the canister.

The fuel and the cavity in the canister are characterised with respect to radiation by the intensity of α, β, γ and neutron radiation and thermally by the temperature. Hydraulically, it is necessary to characterise the cavity only if the copper canister should be damaged and water should enter. The cavity is then characterised by water flows and water pressures as well as by gas flows and gas pressures, which are jointly termed hydro-variables. Mechanically, the fuel is characterised by stresses in the materials, and chemically by the material composition of the fuel matrix and metal parts, as well as by the radionuclide inventory. The gas composition and, if water enters the canister, the water composition are also relevant for the description.

Table 1‑3. Variables for fuel/cavity in the canister.

| Variable | Definition |
| --- | --- |
| Radiation intensity | Intensity of alpha, beta, gamma and neutron radiation as a function of time and space in the fuel assembly. |
| Temperature | Temperature as a function of time and space in the fuel assembly. |
| Hydro-variables  (pressure and flow) | Flows, volumes and pressures of water and gas as a function of time and space in the cavities in the fuel and canister. |
| Fuel geometry | Geometric dimensions of all components of the fuel assembly, such as fuel pellets and Zircaloy cladding. Also includes the detailed geometry, including cracking, of the fuel pellets. |
| Mechanical stresses | Mechanical stresses as a function of time and space in the fuel assembly. |
| Radionuclide inventory | Occurrence of radionuclides as a function of time and space in the different parts of the fuel assembly. The distribution of the radionuclides between the pellet matrix and surface is also described here. |
| Material composition | The materials of which the different components in the fuel assembly are composed, excluding radionuclides. |
| Water composition | Composition of water (including any radionuclides and dissolved gases) in the fuel and canister cavities. |
| Gas composition | Composition of gas (including any radionuclides) in the fuel and canister cavities. |

## Summary of handling of fuel processes in the PSAR

Table 1‑4SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 summaries the handlingof fuel processes in the PSAR, as suggested in this report. In the table, the process is either “mapped” to a model by which it will be quantified or associated with a brief verbal description of how it will be handled.

## Initial state of the canister in the PSAR

The following is an overview description of the initial state of the canister, i.e. its state at the time of deposition. Additional information is given in Pers and Sturek (2021).

### Description of cast iron insert and copper canister

The disposal canister for the spent nuclear fuel consists of an outer 5 cm thick copper shell with an insert made from nodular cast iron. The copper shell will act as the corrosion barrier in the repository, while the insert will provide the necessary stability to the whole package when exposed to the different mechanical loads that it may encounter during the one million year time period considered in the safety assessment. The reference design and outer dimensions for the disposal canister are shown in Figure 1‑2SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 . As shown in the figure, the insert contains individual channels for each fuel element. For BWR fuel, there are 12 channels in each insert, while for PWR fuel there will be only 4 channels. Figure 1‑3SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 SEQ Figur \\* ARABIC \s 1 shows the cross section of the BWR and PWR inserts respectively.

The copper in the canister shell is oxygen free phosphorus doped (Cu-OFP) and will fulfil the specifications in EN 1976:1988 for the grade Cu-OFE (UNS10100) with the following additional requirements: 30–100 wt.ppm phosphorus, < 0.6 wt.ppm hydrogen, < 12 wt.ppm sulfur and < 5 wt.ppm oxygen.

The material for nodular cast iron will fulfil the requirements in EN 1563:1997, grade EN‑GJS‑400‑15U regarding mechanical properties. The materials composition is as specified in the old Swedish standard SS140717 since EN 1563 does not have a material specification. As additional requirements, the following have been specified: < 0.05 % Cu, < 6 % C, < 4 % Si and > 90% Fe.

A summary of the weight for both the BWR and PWR versions of the canister is given in Table 1‑5SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 (Pers and Sturek 2021).

Table 1‑4. Process table for the fuel describing how fuel processes will be handled in different time frames and in the special case of failed canisters. Green fields denote processes that are neglected or irrelevant for the time period of concern. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition.

| Process | Intact canister | Failed canister |
| --- | --- | --- |
| F1  Radioactive decay | Thermal model | COMP23 |
| F2  Radiation attenuation/heat generation | Radiation attenuation: Initial radiation levels given in the SKB (2010d).  Heat generation: Included in integrated modelling of thermal evolution. | Neglected when releases occur after period of elevated temperatures. |
| F3 Induced fission (criticality) | Neglected since there will be insufficient amounts of moderator inside the canister prior to failure. | Neglected since the probability is negligibly small if credit is taken for the burn-up of the fuel. |
| F4 Heat transport | Included in integrated modelling of thermal evolution. | Neglected when releases occur after period of elevated temperatures. |
| F5 Water and gas transport in canister cavity, boiling/condensation | Not relevant | Description in Section 2.3.1, integrated with other relevant processes yielding simplified, pessimistic assumptions on retardation in failed canister depending on failure mode. |
| F6  Mechanical cladding failure | Not relevant | Pessimistic assumption |
| F7 Structural evolution of fuel matrix | Not relevant | Negligible for the fuel types and burn-up relevant for the PSAR. |
| F8 Advection and diffusion | Not relevant | Description in Section 2.3.1, integrated with other relevant processes yielding simplified, pessimistic assumptions on retardation in failed canister depending on failure mode. |
| F9 Residual gas radiolysis/acid formation | Neglected since only small amounts of corrodants are produced. | Not relevant |
| F10 Water radiolysis | Neglected | Neglected except for fuel dissolution, see that process. |
| F11 Metal corrosion | Not relevant | Modelled in COMP23 |
| F12 Fuel dissolution | Not relevant | Modelled as constant, pessimistic dissolution rate in COMP23. |
| F13 Dissolution of gap inventory | Not relevant | Pessimistic, instantaneous |
| F14 Speciation of radionuclides, colloid formation | Not relevant | COMP23 |
| F15 Helium production | Neglected since the amount of helium produced will not increase the pressure inside the canister enough to affect its mechanical stability. | Not relevant |
| F16 Chemical alteration of the fuel matrix | Not relevant | Neglected since it is not deemed to increase the dissolution rate of the fuel. |
| F17 Radionuclide transport | Not relevant | COMP23 |

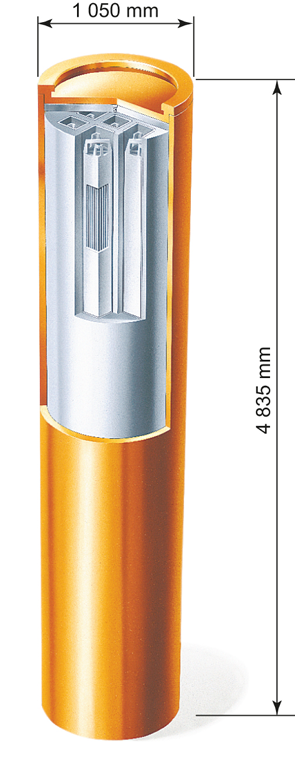


Figure 1‑2. The reference design with a corrosion resistant outer copper shell and a load-bearing insert of nodular cast iron.

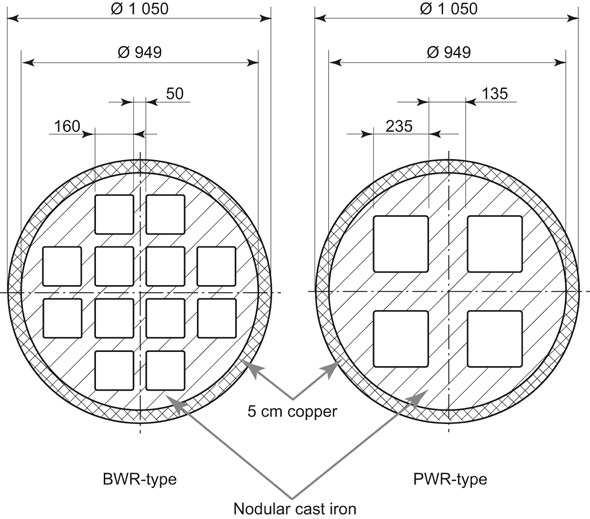


Figure 1‑3. Dimensions (in mm) of the cross section of the BWR and PWR inserts.

Table 1‑5. Weight of canisters.

|  | Weight (kg) | |
| --- | --- | --- |
| BWR-canister | PWR-canister |
| Insert with lid | 13 700 | 16 400 |
| Copper shell | 7 500 | 7 500 |
| Canister without fuel | 21 200 | 23 900 |

## Canister performance and safety

A safety function is defined qualitatively as a role through which a repository component contributes to safety. In order to evaluate the canister’s performance in the safety assessment, a number of so-called function indicators and criteria that should be fulfilled over time, have been formulated. A safety function indicator is a measurable or calculable property of a repository component that indicates to what extent a safety function is fulfilled. The safety function indicator criterion is a quantitative limit such that if the corresponding function indicator fulfils the criterion, its safety function is fulfilled. For a more elaborate discussion, see the PSAR Post-closure safety report (SKB 2022a). A summary of the canister safety function indicators and safety function indicator criteria relating to the containment potential of the canister is presented in Table 1‑6SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 .

Table 1‑6. Summary of canister safety function indicators and the criteria they should fulfil.

| Function | Indicator and criterion | Rationale |
| --- | --- | --- |
| Provide corrosion barrier | Copper thickness > 0 | As long as the copper thickness is larger than zero, containment is complete and no releases occur. |
| Withstand isostatic load | Load < 50 MPa (requirement on buffer and rock).  Copper shell resilient to creep deformation during isostatic load.  Hydrogen content low. | The evaluation of the design and manufacturing procedures for the ensemble of deposited reference canisters led to the conclusion that the canisters will fulfil the design premise of withstanding an isostatic load of 50 MPa (Pers and Sturek 2021).  The copper shell shall maintain its ductile properties for all relevant isostatic loads in the repository. No quantitative indicator is formulated for this function. Rather, for all relevant isostatic loads, creep phenomena need to be evaluated. In this evaluation, all phenomena that may affect the long-term ductility of the copper material, must also be considered. One such phenomenon concerns potential hydrogen embrittlement. Therefore, a dedicated safety function related to the hydrogen content of the copper material is also introduced. |
| Withstand shear load | No specific safety function indicator criterion for the canister relating to shear movements is formulated. Rather the set of conditions included in the design premises are used as criteria for further analyses.  Copper shell sufficiently ductile after shear load.  Hydrogen content low. | The evaluation of the design and manufacturing procedures for the ensemble of deposited reference canisters led to the conclusion that the canister will fulfil the following design premise: “*The copper shell shall remain tight and the canister shall maintain its ability to resist loads for 5 cm rock displacements at all angles and a rate of 1 m/s, exerted on the canister by a buffer with an unconfined compressive strength at failure lower than 4 MPa at a deformation rate of 0.8 %/min.*” (Pers and Sturek 2021).  No quantitative indicator is formulated for this function. Rather, for all relevant shear loads, creep phenomena need to be evaluated. As for isostatic loads, all phenomena that may affect the long-term ductility of the copper material, must also be considered when evaluating this safety function. One such phenomenon concerns potential hydrogen embrittlement. Therefore, as for the isostatic load, a dedicated safety function related to the hydrogen content of the copper material is also introduced. |

## Definition of canister variables

The canister is decribed by the variables in Table 1‑7SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 SEQ Tabell \\* ARABIC \s 1 , which, together, characterise the cast iron insert and the copper shell in a suitable manner for the safety assessment.

The fuel and the cavity in the canister are characterised with respect to radiation by the intensity of gamma and neutron radiation and thermally by the temperature. Mechanically, the canister is characterised by stresses in the materials, and chemically by the material composition of the cast iron insert and copper shell.

Table 1‑7. Variables for the cast iron insert and copper shell.

| Variable | Definition |
| --- | --- |
| Radiation intensity | Intensity of gamma and neutron radiation as a function of time and space in the cast iron insert and copper shell. |
| Temperature | Temperature as a function of time and space in the cast iron insert and copper shell. |
| Canister geometry | Geometric dimensions of all components of the cast iron insert and copper shell. |
| Material composition | The detailed composition of the materials used for the cast iron insert and copper shell. Depending on the process, the emphasis may be on the chemical composition or on the physical microstructure. This variable also includes corrosion products of cast iron and of copper. |
| Mechanical stresses | Mechanical stresses as a function of time and space in the cast iron insert and copper shell. |

## Summary of handling of canister processes in the PSAR

Table 1‑9 summaries the handling of canister processes in the PSAR, as suggested in this report. In the table, the process is either “mapped” to a model by which it will be quantified or associated with a brief verbal description of how it will be handled.

Table 1‑9. Process table for the canister describing how canister processes will be handled in different time frames and in the special case of failed canisters. Green fields denote processes that are neglected or irrelevant for the time period of concern. Red fields denote processes that are quantified by modelling in the safety assessment. Orange fields denote processes that are neglected subject to a specified condition.

| Process | Intact canister | Failed canister |
| --- | --- | --- |
| C1 Radiation attenuation/heat generation | Radiation attenuation: Initial radiation levels given in SKB (2010d).  Heat generation: Included in integrated modelling of thermal evolution. | Neglected when releases occur after period of elevated temperatures. |
| C2  Heat transport | Included in integrated modelling of thermal evolution. | Neglected when releases occur after period of elevated temperatures. |
| C3 Deformation of cast iron insert | Isostatic and shear loads modelled in design analysis of canister (Jonsson et al. 2018). (Uneven loads from uneven swelling of the buffer and lack of straightness of the deposition hole included).  Considered as cause for failure when isostatic or shear loads on canister exceed design premises loads. | Description in Section 3.4.2, integrated with other relevant processes yielding simplified, pessimistic assumptions on retardation of radionuclide transport in failed canister depending on failure mode. |
| C4 Deformation of copper canister from external pressure | Isostatic and shear loads modelled in design analysis of canister (Jonsson et al. 2018). (Uneven loads from uneven swelling of the bufferand lack of straightness of the deposition hole as well as creep in copper included).  Considered as cause for failure when isostatic or shear loads on canister exceed design premises loads. | Neglected |
| C5 Thermal expansion (both cast iron insert and copper canister) | Neglected since the thermal expansion will cause negligible strains in the materials. | Neglected |
| C6 Deformation from internal corrosion products | Not relevant | Description in Section 3.4.5, and in Section 2.3.1 integrated with other relevant processes yielding simplified, pessimistic assumptions on retardation in failed canister depending on failure mode. |
| C7 Radiation effects | Neglected based on the specified limit on Cu content for the insert. (Cu impurities promote radiation damage.) Radiation effect on the copper shell neglected due to negligable changes in the material. | Neglected |
| C8 Corrosion of cast iron insert | Neglected due to limited amount of water giving negligible corrosion effects. | Description in Section 3.5.1, and in Section 2.3.1 integrated with other relevant processes yielding simplified, pessimistic assumptions on retardation in failed canister depending on failure mode. |
| C9 Galvanic corrosion | Not relevant | Neglected, as influence of galvanic corrosion under oxygen-free, reducing conditions lies within the margins of error for the corrosion rate of the iron insert. |
| C10 Stress corrosion cracking of cast iron insert | Neglected since stress corrosion cracking is considered unlikely and even if it occurred it would have no consequences for stability of the insert. | Neglected |
| C11 Corrosion of copper canister | Generally, corrosion is modelled based on mass balance (entrapped O2) and transport capacity considerations (H2S(g) and HS−(aq)) whereas reaction rates are disregarded.  Sulfide from pyrite in buffer and backfill modelled based on transport capacity.  Microbially generated sulfide in buffer (after buffer loss) and backfill, pessimistically bounded by supply of nutrients for microbes.  Entrapped O2 in buffer and backfill: Pessimistically assumed that all O2 corrodes copper neglecting consumption by pyrite in bentonite, rock minerals and microbial activity.  Potentially intruding O2 during glaciation: Integrated handling of rock, backfill and buffer conditions.  Localised O2 corrosion: Assessed with probabilistic pitting model.  Localised sulfide corrosion: described as micro-galvanic corrosion, only possible for very high sulfide fluxes.  Corrosion due to radiation: Negligible corrosion depths and minor localised corrosion, based on experimental studies and modelling.  Chloride assisted corrosion neglected as long as the combinations of pH and chloride concentration is below (the right-hand side of) the limiting curve (i.e a total copper concentration in solution of less than 10−6 mol/kg).  Effects of different corrosion behavior of cold worked or welded material neglected due to small (if any) effects on fundamental corrosion properties.  Corrosion by water disregarded based on thermodynamic considerations. | Not relevant for failed canister. |
| C12 Stress corrosion cracking, copper canister | For aerobic conditions the possible concentrations of SCC promoting agents close to the canister surface are compared to the threshold concentrations where SCC has been noticed in laboratory experiments.  For radiolytic conditions, neglected due to low dose rate and thus insignificant effect on corrosion potential, material defect structure and mechanical properties.  For reducing sulfidic conditions, the sulfide flux is compared with experimental threshold values for observed interfacial cracking. | Neglected |
| C13 Earth currents – stray current corrosion | Negligable increase in corrosion from external electrical field from natural earth currents or present HVDC installations. Future installations mentioned as a stylised case of future human action, with negligible consequences. | Neglected |
| C14 Deposition of salts on canister surface | Neglected due to small consequences (and only relevant during bentonite saturation phase). | Neglected |
| C15 Radionuclide transport | Not relevant | COMP23 |
| C16  Hydrogen embrittlement of copper canister | Embrittlement due to reduction of oxides neglected since the concentration of oxygen in Cu-OFP is sufficiently low, and since welding under inert gas has been shown as efficient to avoid enhanced oxide concentrations in the weld.  The levels of hydrogen potentially absorbed by copper under the H2 flux generated at the canister surface by radiolysis and sulfide corrosion, are compared with the initial concentration of H in Cu-OFP and/or the concentrations of H known to experimentally affect the material properties and tendency to crack under tensile stress. | Neglected |

# Fuel processes

## Radiation related processes

### Radioactive decay

#text with structure in chapter 1

#### Description

Transformation of radionuclides in the fuel assembly due to radioactive decay.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | No | Intact canister |  | Yes The radiation intensity is a result of radioactive decay. | Intact canister | The radiation intensity as a function of time is calculated from the radioactive decay of the inventory of radionuclides (see the Spent fuel report, SKB TR-10-13). |
| Failed canister | Failed canister |  |
| Temperature | No | Intact canister |  | Yes Most of the decay energy is transformed into heat. | Intact canister | The heat generation (and the temperature in the fuel) is calculated as a function of time from the radioactive decay of the inventory of radionuclides. |
| Failed canister | Failed canister |  |
| Hydrovariables (pressure and flow) | No | Intact canister |  | No But indirectly through radiolysis. | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory | Yes This is the source of the process. | Intact canister | Obvious. | Yes The process both consumes and produces radionuclides. | Intact canister | The radionuclide inventory is calculated as a function of time. |
| Failed canister |  | Failed canister |  |
| Material composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Water composition | No | Intact canister |  | Yes Negligible compared to other processes influencing the water composition. | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition | No | Intact canister |  | Yes Negligible compared to other processes influencing the gas composition. | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Radiation attenuation/heat generation

#text with structure in chapter 1

#### Description

Transfer of energy by radiation to the materials in the fuel and the canister cavity.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | Yes The decay energy deposited in the fuel generates heat. | Intact canister | The heat generation is calculated from the radioactive decay of radionuclides (see Spent fuel report, SKB TR-10-13). | Yes Attenuation lowers the radiation intensity. | Intact canister | Implicit in the model. |
| Failed canister |  | Failed canister |  |
| Temperature | No | Intact canister |  | Yes Obvious. Heat generation increases the temperature. | Intact canister | Implicit in the model. |
| Failed canister | Failed canister |  |
| Hydrovariables (pressure and flow) | Yes In a failed canister, the presence of water will influence the radiation attenuation. | Intact canister | At the time of water intrusion, the g-radiation will have decayed. The fuel and the cladding will attenuate a- and b-radiation. | No But indirectly through temperature. | Intact canister |  |
| Failed canister |  | Failed canister |
| Fuel geometry | Yes Most of the decay energy is deposited in the fuel and the geometry of the fuel has a small effect. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses | No | Intact canister |  | Yes Increased temperature may create increased stresses in the fuel. | Intact canister | This is of no importance for the stability of the fuel. |
| Failed canister | Failed canister |  |
| Radionuclide inventory | Yes The radionuclides are the source of heat. | Intact canister | Implicit in the model. | No The decay itself influences the radionuclide inventory. The generated heat does not. | Intact canister |  |
| Failed canister |  | Failed canister |
| Material composition | Yes Different materials have different attenuation properties. | Intact canister | All fuel elements have essentially the same material composition. | No | Intact canister |  |
| Failed canister |  | Failed canister |
| Water composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Thermal processes

### Heat transport

#text with structure in chapter 1

#### Description

Heat transport through the fuel and canister cavity by conduction and radiation to the canister insert.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | No No, but indirectly through the temperature. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Temperature | Yes The temperature and the temperature gradient control heat flow. | Intact canister | The thermal evolution of the fuel and the canister is included in the temperature modelling. | Yes Heat transport will increase the temperature at distances away from the heat source . | Intact canister | The thermal evolution of the fuel and the canister is included in the temperature modelling. |
| Failed canister |  | Failed canister |  |
| Hydrovariables (pressure and flow) | Yes The gas pressure and the possible presence of water in the canister influence the heat transport in the canister cavity. | Intact canister | Included in the temperature modelling. | No But indirectly through increased temperature which will increase the gas pressure. | Intact canister |  |
| Failed canister |  | Failed canister |
| Fuel geometry | Yes | Intact canister | Included in the temperature modelling. | No | Intact canister |  |
| Failed canister |  | Failed canister |
| Mechanical stresses | No | Intact canister |  | No But indirectly through increased temperature which may lead to heat induced stresses. | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory | No The decay influences the temperature. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Material composition | Yes Different materials have different thermal properties. | Intact canister | The thermal properties of the canister materials are included in the temperature modelling. | No | Intact canister |  |
| Failed canister |  | Failed canister |
| Water composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition | Yes The heat conduction depends on the type of gas in the cavity. | Intact canister | The thermal properties of gas inside the canister are included in the temperature modelling. | No | Intact canister |  |
| Failed canister |  | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Hydraulic processes

### Water and gas transport in the canister, boiling/condensation

#text with structure in chapter 1

#### Description

Transport of water, water vapour and other gases in a penetrated canister including boiling and condensation.

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Mechanical processes

### Mechanical cladding failure

#text with structure in chapter 1

#### Description

Temperature changes in the fuel and mechanical impacts associated with handling and transport will affect the fuel cladding.

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Structural evolution of the fuel matrix

#text with structure in chapter 1

#### Description

The effects of radioactive decay, mainly alpha decay and build-up of helium in the fuel, on the physical and chemical behaviour of the fuel over long time periods.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Temperature | Yes Influences the distribution between water and vapour. | Intact canister | Neglected for an intact canister. | No | Intact canister |  |
| Failed canister | For a failed canister the temperature is assumed to be constant at 11oC. | Failed canister |
| Hydrovariables (pressure and flow) | Yes Obvious | Intact canister | Neglected for an intact canister. | Yes Obvious. | Intact canister | Neglected for an intact canister. |
| Failed canister | For a failed canister the development inside the canister is based on the modelling by Bond et al. 1997, SKB TR 97-19. | Failed canister | For a failed canister the development inside the canister is based on the modelling by Bond et al. 1997, SKB TR 97-19. |
| Fuel geometry | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses | No | Intact canister |  | Yes Pressure build-up inside the canister. | Intact canister | Neglected for an intact canister. |
| Failed canister | Failed canister | For a failed canister, see C07. |
| Radionuclide inventory | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Material composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Water composition | Yes Water composition influences the corrosion rate and the corrosion products formed. | Intact canister | Neglected for an intact canister. | Yes Release of soluble corrosion products. | Intact canister | Neglected for an intact canister. |
| Failed canister | For a failed canister see C07. | Failed canister | See C07. |
| Gas composition | Yes Presence of water vapour. | Intact canister | Neglected for an intact canister. | Yes Hydrogen build-up. | Intact canister | Neglected for an intact canister. |
| Failed canister | For a failed canister see C07. | Failed canister | See C07. |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Chemical processes

### Advection and diffusion

#text with structure in chapter 1

#### Description

Transport of solutes dissolved in the water to and from the interior of the canister via advection and diffusion.

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Residual gas radiolysis/acid formation

#text with structure in chapter 1

#### Description

Air and water in an intact canister can be decomposed by means of radiolysis. The products can then be converted to corrosive gases such as nitric and nitrous acids.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | Yes The intensity determines the extent of radiolysis. | Intact canister | The amount of radiolysis products (nitric acid) is estimated based on the availability of nitrogen in the canister. | No | Intact canister |  |
| Failed canister | Not relevant | Failed canister |
| Temperature | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) | Yes The amount of radiolysis products depends on the availability of water and residual gases in the canister. | Intact canister | The amount of radiolysis products (nitric acid) is estimated based on the availability of nitrogen in the canister. | Yes But any effect is negligible. | Intact canister | The amount of radiolysis products (nitric acid) is estimated based on the availability of nitrogen in the canister. |
| Failed canister | Not relevant | Failed canister | Not relevant |
| Fuel geometry | No Indirectly through the radiation intensity. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory | No Indirectly through the radiation intensity. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Material composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Water composition | Yes Dissolved solids and gases will influence the radiolysis products formed. | Intact canister | The water trapped inside the canister will be either reactor water or water from the storage pools at Clab. It can, therefore, be assumed to be clean water with very low ionic strength. | Yes Radiolysis products will be formed in the water. | Intact canister | The amount of radiolysis products (nitric acid) is estimated based on the availability of nitrogen in the canister. |
| Failed canister | Not relevant | Failed canister | Not relevant |
| Gas composition | Yes Gases will influence the radiolysis products formed. | Intact canister | The gas inside the canister is assumed to be at least 90% Ar and the balance being air. | Yes Gaseous radiolysis products will be formed. | Intact canister | The amount of radiolysis products (nitric acid) is estimated based on the availability of nitrogen in the canister. |
| Failed canister | Not relevant | Failed canister | Not relevant |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Water radiolysis

#text with structure in chapter 1

#### Description

Water that enters a damaged canister and reaches the cavities between the fuel assemblies and the canister insert is affected by the ionizing radiation emitted by the spent fuel. This causes the excitation, or ionisation of water molecules followed by breaking of their chemical bonds (radiolysis) producing primarily free electrons, OH-radicals and hydrogen atoms.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | Yes The radiolysis is proportional to the dose rate. | Intact canister | In a failed canister the contribution to hydrogen gas production is considerably smaller than the contribution from iron corrosion. For radiolysis effects on fuel dissolution, see F12. | No | Intact canister |  |
| Failed canister |  | Failed canister |
| Temperature | Yes | Intact canister | See first row above and Section 2.5.3 in SKB TR-10-46. | No | Intact canister |  |
| Failed canister |  | Failed canister |
| Hydrovariables (pressure and flow) | Yes Presence of water in the canister is required. | Intact canister | See first row above and Section 2.5.3 in SKB TR-10-46. | Yes Radiolytic gas production. | Intact canister | See first row above and Section 2.5.3 in SKB TR-10-46. |
| Failed canister |  | Failed canister |  |
| Fuel geometry | No Indirectly through radiation intensity. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory | No Indirectly through radiation intensity. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Material composition | No | Intact canister |  | No Radiolysis may form corrosive species. | Intact canister |  |
| Failed canister | Failed canister |
| Water composition | Yes Water solutes participate in radiolytic reactions | Intact canister | See first row above and Section 2.5.3 in SKB TR-10-46. | Yes Radiolytic production of water solutes. | Intact canister | See first row above and Section 2.5.3 in SKB TR-10-46. |
| Failed canister |  | Failed canister |  |
| Gas composition | Yes Gases participate in radiolytic reactions. | Intact canister |  | Yes Radiolytic gas production. | Intact canister | See first row above and Section 2.5.3 in SKB TR-10-46. |
| Failed canister | Failed canister |  |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Metal corrosion

#text with structure in chapter 1

#### Description

Corrosion of the cladding tubes for the fuel and other structural elements in the fuel leading to the liberation of activation products from these metal parts.

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Fuel dissolution

#text with structure in chapter 1

#### Description

If water enters the canister cavity, the fuel will start to dissolve, resulting in the release of uranium and other radionuclides contained in the fuel matrix.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Temperature |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Material composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Water composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Dissolution of the gap inventory

#text with structure in chapter 1

#### Description

Radionuclides that have been segregated to the gap between fuel and cladding, as well as crack and grains boundaries, are dissolved rapidly when water enters the canister.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity | No Indirectly through radiolysis that may form corrosive species and water composition. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Temperature | Yes Corrosion rates tend to increase with temperature. | Intact canister | This effect is limited under anoxic conditions. | No | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) | Yes Presence of water is required. | Intact canister | Water is assumed to be present after canister failure. | No | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry | No | Intact canister |  | Yes Metal corrosion changes the geometry of corroding fuel elements. | Intact canister | Changes in fuel geometry does not affect corrosion rates |
| Failed canister | Failed canister |  |
| Mechanical stresses | Yes May cause stress corrosion cracking of the fuel metal parts. | Intact canister | No credit is given to cladding integrity | No | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory | No Indirectly through radiation intensity. | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |
| Material composition | Yes Different alloys may have different corrosion rates. The effect will most likely be negligible. | Intact canister | Corrosion rate estimates based on stainless steel. | No | Intact canister |  |
| Failed canister | Failed canister |
| Water composition | Yes Metals have different corrosion rates in different waters. The effect will most likely be negligible. | Intact canister | Limited influence under anoxic conditions. | Yes The influence is small due to the low Zr solubility. | Intact canister | See Section 2.5.4 in SKB TR-10-46. |
| Failed canister | Failed canister |  |
| Gas composition | No | Intact canister |  | No | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Speciation of radionuclides, colloid formation

#text with structure in chapter 1

#### Description

Radionuclide solubility and speciation within a water-filled, failed canister and the formation of colloidal or pseudocolloidal particles caused by the nucleation of new solid phases inside the canister. Chemical speciation refers to the distribution of an element amongst defined chemical species in a given system. Thermodynamic modelling is required to ascertain the chemical distribution of radionuclides in a failed canister.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Temperature |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Material composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Water composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Helium production

#text with structure in chapter 1

#### Description

Helium build-up in spent fuel due to the alpha decay of actinides.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Temperature |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Material composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Water composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Chemical alteration of the fuel matrix

#text with structure in chapter 1

#### Description

The process of altering the fuel matrix to other stable minerals depending on the chemical conditions. For reducing conditions the main relevant mineral is coffinite, a uranium silicate. The identification of stable, potentially solubility controlling minerals require thermodynamic modelling

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Temperature |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Material composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Water composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Radionuclide transport

#text with structure in chapter 1

#### Description

Transport of dissolved radionuclides inside the canister by advection and diffusion and transport in the gas phase of nuclides that may occur in gaseous form (C-14, Rn-222, Kr-85) in the canister.

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable** | **Variable influence on process** | | | **Process influence on variables** | | |
| **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** | **Influence present? (Yes/No Description)** | **Time period/Climate domain** | **Handling of influence (How/If not - Why)** |
| Radiation intensity |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Temperature |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Hydrovariables (pressure and flow) |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Fuel geometry |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Mechanical stresses |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Radionuclide inventory |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Material composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Water composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |
| Gas composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

Text

# Canister processes

## Radiation related processes

### Radiation attenuation/heat generation

#text with structure in chapter 1

Description

Text

Dependencies between processes and variables

Text

Natural and anthropogenic analogues

Text

Boundary conditions

Text

Model and experimental studies

Text

Time perspective

Text

Impact on safety functions

Text

Handling of the process in the assessments of post-closure safety

Text

Handling in the FSAR

Text

Changes since the PSAR

Text

Handling of uncertainties in the FSAR

## Thermal processes

### Heat transport

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Hydraulic processes

### Water and gas transport in the canister, boiling/condensation

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Mechanical processes

### Introduction

#Kolla om den behövs?

### Deformation of cast iron insert

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Variable | Variable influence on process | | | Process influence on variables | | |
| Influence present? (Yes/No Description) | Time period/Climate domain | Handling of influence (How/If not - Why) | Influence present? (Yes/No Description) | Time period/Climate domain | Handling of influence (How/If not - Why) |
| Radiation intensity | Influence present? | Intact canister |  | SR-Site db, checked against TR-21-02, differences highlighted in yellow | Intact canister |  |
| Failed canister | Failed canister |  |
| Temperature |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |  |
| Canister geometry |  | Intact canister |  |  | Intact canister |  |
| Failed canister | Failed canister |  |
| Material composition |  | Intact canister |  |  | Intact canister |  |
| Failed canister |  | Failed canister |  |
| Mechanical stresses |  | Intact canister |  |  | Intact canister |  |
| Failed canister |  | Failed canister |  |

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Deformation of copper shell from external pressure

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Thermal expansion

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Deformation from internal corrosion products

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Radiation effects

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Hydrogen embrittlement of copper

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

## Chemical processes

### Corrosion of cast iron insert

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Galvanic corrosion

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Stress corrosion cracking of insert

#text with structure in chapter 1

#### Description

Stress corrosion cracking (SCC) of metals requires a combination of tensile stresses, a specific chemical environment and a susceptible material. Unfavourable combinations of these conditions can lead to the initiation and propagation of local cracks through the matrix over a period of time. Radiolysis on residual quantities of air and moisture within a canister can produce nitric acid (nitrate) as well as ammonia, which both are stress corrosion cracking agents for carbon steel. Also oxidising conditions (or more precisely an oxide film), as well as (at least) a water film on the metal surface are required.

The material for the outer tube, P355N, is a ferritic carbon steel, and could, in general, be susceptible to stress corrosion cracking. The other parts in the insert also consist of carbon steel (see ###), but any differences between various carbon steels have not been evaluated. There are several environments known to cause SCC in carbon steel, including solutions with chloride, nitrate, ammonia, phosphate, carbonate, sulfide and high pH (Ciaraldi 1992, King 2010). Of these, nitrate and ammonia are conceivable inside an intact canister. Nitric acid can form from the radiolysis of residual quantities of nitrogen in moist air (Jones 1959), and as described in updated analyses of the gas phase within the insert ammonia can also be formed (Henshaw and Spahiu 2021, Henshaw and Evins 2023).

#As stress corrosion cracking will influence the mechanical integrity of the insert, it is of importance for #isostat/skjuv/asymmetriska laster#.#

#### Dependencies between processes and variables

Table 1‑1 shows how the process influences, and is influenced by, all canister variables.

Table 1‑1. Direct dependencies between the process “Stress corrosion cracking of the insert” and the defined canister variables and a short note on the handling in the FSAR.

| Variable | Variable influence on process | | Process influence on variable | |
| --- | --- | --- | --- | --- |
|  | Influence present? (Yes/No) Description | Handling of influence  (How/If not – why) | Influence present? (Yes/No) Description | Handling of influence  (How/If not – why) |
| Radiation intensity | Yes. The agents that may cause SCC are produced through radiolysis. | Neglected. Tensile stresses only occur locally in small areas. Also, if water is present inside the insert it is only expected to be present in small amounts and during a relatively short period. | No. | – |
| Temperature | Yes. | Neglected, due to small effects. | No. | – |
| Canister geometry | Yes. The geometry gives different areas and volumes, that affect the corrosion #times#. | Actual insert geometries are considered. | No. | – |
| Material composition | Yes.  Different materials have different sensitivities to SCC. | Actual insert materials are considered. | No. | – |
| Mechanical stresses | Yes. Tensile stresses are required. Compressive stresses prevent SCC. | Neglected. Tensile stresses only occur locally in small areas. | Yes. SCC relaxes tensile mechanical stresses. | Pessimistically neglected. |

#### Natural and anthropogenic analogues

Not applicable.

#### Boundary conditions

Nitric acid (HNO3) and ammonia (NH3) from radiolysis of nitrogen in residual quantities of moist air in the void inside the canister could conceivably cause SCC in the insert, in areas with tensile stresses. The geometric boundaries are the dimensions of the insert.

#### Model and experimental studies

***The environment***

Usually, the occurrence of the “aggressive anions” that are needed is the starting point for the discussion of SCC, but equally important is the presence of oxidising species as well as water. Liquid water could condense if the RH exceeds the dew point, but also below this RH a thin surface film could be formed on the corroding surface, and thus be sufficient for corrosion reactions to occur (see e.g. Hedin (2025)). The oxidising environment is required for driving a cathode reaction, which together with the anodic reaction (metal oxidation), forms the corrosion reaction.

In the many reviews available, a number of environments are described as possible causes of SCC, but most of them can readily be shown not to be applicable for the sealed insert of the canister for spent nuclear fuel in a repository. The only compounds present initially in non-negligible amounts within the deposited canister are argon, air (nitrogen and oxygen gas) and water, and only the elements Ar, H, O and N need to be considered. The possible environments that can be formed from these elements and where SCC has been noted to occur in carbon steel, are listed in Table 1‑2. Thus all SCC caused by chlorides, phosphates, sulfur (hydrogen sulfide, sulfates) or carbon components (carbon dioxide, carbon oxide, cyanides) can be ruled out. It can be concluded from the table that the only environments that need to be considered for the insert are nitrate and ammonia solutions.

Table 1‑2. Environments that have been noted to cause stress corrosion cracking in carbon steel, for the elements H, O and N, together with the main arguments on whether further assessment is needed.

|  |  |
| --- | --- |
| Environment |  |
| nitrate | Nitrate solutions are known to induce stress corrosion cracking in carbon steel (Ciaraldi 1992), generally at high concentrations, but also at lower concentrations in boiling solutions. Welded steel and high-strength steel seem to be more susceptible. Several factors can enhance or mitigate the SCC (temperature, potential, other ions etc), but are not easily evaluated in sufficient detail to be used as argument for exclusion of nitrate as an SCC agent. For this study nitrate is therefore considered in the assessment. |
| ammonia | Anhydrous ammonia has been reported to cause stress corrosion cracking in transportation containers (Dawson 1956), but generally connected to cold-formed material, and not in stress-relieved material. Dawson (1956) also noted “anhydrous ammonia” used in the agricultural services (where the containers were used) could contain both air and water. As at least some studies show SCC in ammonia, this is considered in the assessment. |
| caustic (hydroxide) | Cracking in concentrated sodium hydroxide solutions has been noted, but iron corrosion will not cause the pH to increase to levels as in concentrated hydroxide solutions. Further no sodium is present in the insert, and the only possible cation could be NH4+. Such caustic environments are not considered possible in the insert. |
| high-temperature water | Cracking in water at temperatures of 200-320 °C has been observed (Ciaraldi 1992) and even down to 150 °C in laboratory experiments (Seifert and Ritter, 2005). The maximum temperature in the outer tube of the insert is around 100 °C (see Section **Fel! Hittar inte referenskälla.**), making SCC of the tube part of the insert due to exposure to high-temperature water considered unlikely. |
| hydrogen gas | Cracking (by an SCC mechanism) of steel vessels by high-pressure hydrogen gas has been observed, but mostly in higher-strength steel (Ciaraldi 1992). As the partial pressure of hydrogen within the insert would not exceed of the order of 1 bar, this SCC mechanism is disregarded. (The maximum amount of water, 600 g, would give a maximum amount of hydrogen of 33 mol, which at 100 °C would give a pressure of around 1 bar, see Section **Fel! Hittar inte referenskälla.**.) |

The environment in the insert is evaluated in Hedin (2025), with regards to the evolution of the composition of gases, caused by corrosion reactions. The influence of the radiation is analysed in Henshaw and Evins (2023), where several parameters are varied in a number of calculations cases, especially the amount of water (30 or 600 g), and the residual air (1, 2, 5 or 10 %, corresponding to 99, 98, 95 or 90 % argon). As described in Section **Fel! Hittar inte referenskälla.** of #TR-25-05, few, if any, canisters are expected to contain even close to 600 g water. Further, the design requirement of the atmosphere in the insert is given as > 97 % argon. Many of the calculation cases are thus pessimistic in relation to the expected conditions in a canister.

The consumption time for water for all the calculation cases are originally compiled in Table 4-1 in Henshaw and Evins (2023). In Table 1‑3 the consumption time for the oxidising species oxygen, hydrogen peroxide, nitric acid and nitrous acid has been added for the calculation cases where the water consumption time is longer than 2.5 years. These cases all have an iron corrosion rate that is low (all the time or for RH < 60%), or set to zero for RH < 60%. Note that these cases all have an air content exceeding the maximum allowed 3 % (corresponding to the required Ar content of 97%) and that all cases but one have the maximum allowed amount of water, 600 g.

Table 1‑3. Consumption times for water, oxygen, hydrogen peroxide, nitric acid and nitrous acid for the calculation cases in Henshaw and Evins (2023) that have a water consumption time longer than 2.5 years. The consumption times are determined with a cut-off of 0.001 mol (approximately, as interpolations are sometimes needed within the time steps in the calculation), from the supporting material[[1]](#footnote-1) to Henshaw and Evins (2023). SA/V = surface area/volume ratio.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Case | Fuel type | Water (g) | Air (%) | Other parameters changed | Time to consume H2O | Time to consume O2 | Time to consume H2O2 | Time to consume HNO3 | Time to consume HNO2 |
| 2c | BWR | 600 | 10 | low SA/V; low corr. rate for RH<60% | 8.8 y | 8 h | < 15 h | -  (<8×10−6 mol) | -  (<5×10−6 mol) |
| 10a | BWR | 600, re-leased at 1.8 g/d | 5 | no corrosion for RH<60% | > 500 y | 0.9 y | 1.1 y | 1.0 y | 1.6 y |
| 11a | BWR | 30, re-leased at 1.8 g/d | 5 | no corrosion for RH<60% | > 500 y | 6.3 y | 3.5 y | 23 y | 2.5 y |
| 13c | PWR | 600 | 10 | low SA/V, low corr. rate all the time | 21.1 y | < 10 d | < 15 h | -  (<2×10−4 mol) | -  (<2×10−5 mol) |
| 13f | PWR | 600 | 10 | no corrosion for RH<60% | > 500 y | 23.9 y | 24.9 y | 25 y | 33 y |

The species and environments that are necessary for SCC to occur may be initially present or formed by the radiation, but are also “consumed”, either by radiation or corrosion reactions. A crucial question is whether there is any possibility that all the environmental conditions are fulfilled at the same time. The time periods could be summarised as follows:

* An amount of 600 g water is generally consumed in one or a few years (already 10-20 days for 30 g water), but with low corrosion rates (at RH < 60 %) it remains for about 20 years. Only the cases assuming no corrosion at RH < 60 %, gives water persisting for longer times, more than 500 years.
* Most calculation cases in Henshaw and Evins (2023) show that oxygen and hydrogen peroxide is consumed very fast, in a few days. The consumption time increases to 25 years if no corrosion is assumed for RH < 60 % and the water is available from the start (case 13f).
* The nitrogen oxides are decomposed by radiation once the oxygen is consumed, giving approximately the same time periods for the occurrence of nitric acid (HNO3) and nitrous acid (HNO2) as for oxygen and hydrogen peroxide. It is not evaluated in detail how nitric and nitrous acid would influence the redox potential, but the persistence of these species does not exceed 35 years. The time period for nitrate and nitrite to exist in solution (a water film) and available to act as SCC agents, is thus also in the range of a few tens of years.
* Ammonia, NH3, starts to be produced by radiation when the conditions change from oxidising to reducing and H2 is formed. This, in itself, indicates that the prerequisites for SCC are not fulfilled, even if ammonia and water exist at the same time for some cases.
* The assumptions on iron corrosion and its possible dependence on relative humidity have the largest impact on the calculated time periods for the persistence of water, and of nitric and nitrous acid. However, only the assumption of strictly no corrosion for RH < 60 % gives consumption times for nitric and nitrous acid in the range of the shortest possible buffer saturation times (around 20 years).
* In the text above, the various time periods during which the different environments may persist in the insert are discussed, and it is concluded that only cases with no corrosion below RH < 60 % gives water persisting longer than 2.5 years. Such an assumption would influence also the evaluation of SCC, as it is hard to envisage that a more complex corrosion process like SCC could take place if not even corrosion by water is feasible. To make the assumptions consistent within a certain evaluated case in the analysis, the possible cases with water persisting more than 500 years due to low corrosion need not be analysed for SCC.

It could in principle be possible to calculate the concentrations of SCC agents in a liquid water phase in equilibrium with the gas phase in the interior of the insert. Nitric acid (HNO3) is highly soluble (2100 mol/(m3 Pa)), and nitrous acid (HNO2) much less (0.48 mol/(m3 Pa)) (Henry’ law constants, Sander (2023)), and as the gas phase amounts of HNO3 is larger than for HNO2 (at least for the more critical cases 10a, 11a and 13f), this would cause the solution to be dominated by HNO3 and the pH to be very low. There are though several reactions between the nitrogen- and oxygen-containing species, and radiolysis would also affect the solution composition, and together with the uncertainty of the volume of a water phase, this makes estimations of the solution composition difficult. The difficulties in estimating the concentrations in the water phase were also discussed in the Canadian programme, referring primarily to the many combinations of the water droplet and headspace geometries (Morco et al. 2017).

***The stress state***

A prerequisite for SCC is the presence of tensile stresses. Residual stresses in a manufactured component can be tensile as well as compressive, depending on e.g. the cooling process (temperature, phase transformations) and later machining. Residual stresses have been measured for samples from three trial manufactured steel tubes (Lundin and Holmberg 2024, 2025). The measurements were performed with X-ray diffraction, on both the inner and outer surfaces of the tubes. For the tube ST7, the surface measurements show medium to high compressive stresses (250 to 500 MPa), while the measurements for the tubes ST13 and ST17 show tensile, and higher, stresses (up to slightly over 700 MPa). The stresses vary over the surfaces, but not in any consistent way between the tubes. The authors suggest these residual stresses (both tensile and compressive) originate from the machining (turning) process. Depth profiles were also measured, and showed that the residual stress state below the surface relatively rapidly approaches zero, at depths of around 50 µm, which means that any crack propagation further into the material would be counteracted. Residual stresses in the framework plates have not been measured, but stresses from machining can in general be considered superficial, and in analogy to the case for the outer tube, assumed not to cause SCC.

Regarding stresses from external loads, asymmetric loads from the swelling buffer need to be considered, see Section **Fel! Hittar inte referenskälla.**. In the design analysis for the reference canister (Jonsson et al. 2018) the possible load cases are described, and for the period up to 100 years, the only external load is from the swelling of the buffer (the internal load from gas pressure is negligible in comparison). The saturation time differs depending on the inflow of groundwater to the deposition hole and, for deposition holes with no intersecting water-bearing fractures, on the permeability of the rock. The resulting time scales are discussed in Section 10.3.8 of SKB (2022 #TR-21-01). Only a few percent of the deposition holes will be saturated faster than 100 years for the comparatively dry conditions at the Forsmark site intended for the final repository, while it will take considerably longer for the majority of the deposition holes; saturation times are generally on the order of 1000 years. The modelling in (Jonsson et al. 2018) used saturation periods of 0-10 years for “wet holes” and 10-100 years for “dry holes”. The sum of the swelling pressure and the hydrostatic pressure at 500 m depth will be a maximum of 15 MPa, but could be asymmetric due to uneven swelling or imperfections in the deposition hole geometry.

For the insert, calculations of asymmetric loads are reported in Section **Fel! Hittar inte referenskälla.** and show tensile stresses at 225° in the steel tube and copper shell for both load case 1a and 2a. The stresses are up to 200 MPa, and going all through the steel tube thickness at 225°. The stresses in the framework have not been evaluated in detail.

For the further analysis, it is concluded that tensile stresses may develop as the buffer becomes water saturated. The swelling pressure will take time to develop, at the earliest in the range of 20 years, and with only a few percent of the deposition holes having developed significant swelling pressures in 100 years at the intended Forsmark site (SKB 2022 #TR-21-01). The extent of asymmetry of the loads on the canister during and after swelling of the buffer is determined by deviations from the ideal geometry of the deposition hole and initial buffer inhomogeneities. It is also determined by the way in which water is supplied to the hole. This supply is generally a combination of inflow from water bearing fractures intersecting the deposition hole and water supplied from the deposition tunnel backfill above the hole and the rock mass surrounding it. At a dry site like Forsmark, the relatively few holes intersected by fractures with a significant water flow may generally be expected to exhibit more asymmetric loads than the majority of holes that are expected to require hundreds to thousands of years to fully saturate.

#### Time perspective

The effect of radiolysis decreases with time, and is negligable after 300 years due to the decay of Cs-137.

#### Impact on safety functions

#As stress corrosion cracking will influence the mechanical integrity of the insert, it is of importance for #isostat/skjuv/asymmetriska laster#.#

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

#Nedan bara kopierat slutsatserna i ur Rebusrapporten (ver 2.34)

The likelihood of stress corrosion cracking (SCC) in the Rebus insert has been assessed, by considering the possibilities of simultaneous occurrence of the necessary conditions. SCC is dependent on three factors (the material, the environment and tensile stresses), none of which can be used solely to disregard the process for the Rebus insert. The carbon steels are materials that could be sensitive to SCC.

Tensile stresses in the surfaces facing the insert void could occur as residual stresses or stresses induced by asymmetric saturation of the buffer. Tests on trial manufactured Rebus tubes showed the possibility of tensile stresses in the surface of the steel, however, the stress state approached zero already at a depth of around 50 µm. This means any crack propagation further into the material would be counteracted. The saturation period, and hence the period where asymmetric swelling may occur, varies depending on the rock hydraulic conditions, and full saturation is reached in 20 years for a few canisters, but is expected to take much longer time for the majority of the deposition holes.

The development of the environment in the insert is mainly dependent on the radiation, temperature, and the residual amounts of water and oxygen (from air) enclosed at closure. The SCC active agents ammonium (NH4+) and nitrate (NO3−) could form through radiolysis. The necessary oxidising conditions do not prevail longer than 35 years (at the most), during which HNO3 and HNO2 could persist. This would though build on inconsistent assumptions of no corrosion but still SCC. Ammonia is not formed until the oxidising species have been depleted.

Taking into account the timing of the prerequisites for stress corrosion cracking, i.e. that the environment will neither contain water nor experience oxidising conditions longer than hours or days, while tensile stresses, as an effect of saturation of the buffer will not occur until later (full saturation in 20 years for a few canisters), it is concluded that the likelihood of SCC in the Rebus insert is negligible.

##### Changes since the PSAR

The conclusion that stress corrosion cracking of the insert does not need to be taken further in the analysis of post-closure safety assessment remains the same. However, the conclusion in FSAR is that the likelihood is negligible, compared to “deemed to be of no importance for the integrity of the canister” in the PSAR. The main changes are that the insert design has been changed quite radically (carbon steel tube and framework, instead of a cast iron matrix with carbon steel tubes embedded). New calculations of the mechanical integrity, and a new analysis of radiolysis on the gas phase of the interior of the canister, have been performed.

#### Handling of uncertainties in the FSAR

##### Uncertainties in mechanistic understanding

There are uncertainties in the understanding of stress corrosion cracking, but they will be of no importance for the safety assessment, since the extent of the process will be limited.

##### Model simplification uncertainties

Stress corrosion cracking of the insert will not be modelled.

##### Input data and data uncertainties

The probability of SCC jeopardising the canister integrity is deemed to be small, since only local areas in the insert have tensile stresses. The uncertainty of the quantity of nitrogen that may have been left in the canister is bounded by the design premises of exchanging the atmosphere from air to > 90 % argon. Also, the amount of remaining water is limited to a maximum of 600 g.

-----------------------------

***References to section 3.5.3***

TR-25-05 Post-closure safety evaluations of alternative KBS-3 canister insert designs  
#f.n. klippt ur SKBdoc 1963442, gr ver 2.34

**Ciaraldi S W, 1992.** Stress-corrosion cracking of carbon and low-alloy steels (yield strengths less than 1241 MPa), in Stress-Corrosion Cracking Materials Performance and Evaluation, R.H. Jones (ed.). ASM International (Metals Park, OH), chap. 2.

**Dawson T J, 1956.** Behavior of welded pressure vessels in agricultural ammonia service. Weld J 35 p. 568.

**Hedin A, 2025.** Thermal and hydrological conditions in a sealed KBS-3 canister, SKBdoc 1999391 ver 2.0, Svensk Kärnbränslehantering AB.

**Henshaw J, Evins L Z, 2023.** Radiolysis calculations of gases in a KBS-3 canister. SKB TR-22-15, Svensk Kärnbränslehantering AB.

**Henshaw J, Spahiu K, 2021.** Radiolysis calculations of air, argon and water mixtures in a KBS-3 canister. SKB TR-21-11, Svensk Kärnbränslehantering AB.

**Jones A R, 1959.** Radiation–induced reactions in the N2–O2–H2O system. Radiation Research 10, 655–663.

**King F, 2010.** Stress corrosion cracking of carbon steel used fuel containers in a Canadian deep geological repository in sedimentary rock. NWMO TR-2010-21, Nuclear Waste Management Organization, Canada.

**Jonsson M, Emilsson G, Emilsson L, 2018.** Mechanical design analysis for the canister. Posiva SKB Report 04, Posiva Oy, Svensk Kärnbränslehantering AB.

**Morco R P, Joseph J M, Hall D S, Medri C, Shoesmith D W, Wren J C, 2017.** Modelling of radiolytic production of HNO3 relevant to corrosion of a used fuel container in deep geologic repository environments. Corrosion Engineering, Science and Technology, 52:sup1, 141-147.  
<https://doi.org/10.1080/1478422X.2017.1340227>

**Lundin P, Holmberg J, 2024.** Residual stress measurements of steel tubes, Ø 950 mm, ST7. Lundin Stress Service AB. SKBdoc 2035847, ver 1.0.

**Lundin P, Holmberg J, 2025.** Residual stress measurements of steel tubes, Ø 950 mm, ST13 and ST17. Lundin Stress Service AB. SKBdoc 2080379, ver 1.0.

**Sander R, 2023.** Compilation of Henry’s law constants (version 5.0.0) for water as solvent. Atmospheric Chemistry and Physics 23, 10901–12440.   
<https://doi.org/10.5194/acp-23-10901-2023>

**Seifert H P, Ritter S, 2005.** Research and service experience with environmentally-assisted cracking in carbon and low-alloy steels in high-temperature water”. SKI Report 2005:60, Swedish Nuclear Power Inspectorate.

**SKB 2022.** Post-closure safety for the final repository for spent nuclear fuel at Forsmark. Main report, PSAR version. SKB TR-21-01, Svensk Kärnbränslehantering AB.

### Corrosion of copper canister

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Stress corrosion cracking of the copper canister

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Earth currents – stray current corrosion

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

### Deposition of salts on the canister surface

#text with structure in chapter 1

#### Description

*In the current design, the fuel generates up to 1,700 W of heat, raising the canister surface temperature. This temperature increase depends on heat transfer to the surrounding bentonite. The SR-Site safety assessment calculated a maximum canister surface temperature of 90 °C, which is below the 100 °C threshold that could affect the chemical stability of the bentonite. Elevated temperatures may cause salt redistribution and enrichment in the bentonite and potential deposition on the canister surface. This process depends on the salt content in the groundwater and bentonite porewater, and thus concerns both chlorides and sulfates from the groundwaster, and sulfates and carbonates from the accessory minerals in the bentonite.*

The process of deposited salts on the canister surface relates to two safety functions, one for the canister and one for the buffer material. Deposition of salt on the canister surface could influence localised corrosion and therefore relates to Can1. Provide corrosion barrier. Deposition of salt on the canister surface could furthermore influence the heat dissipation from the canister and thus relates to Buff4. Resist transformation, which requires a temperature below 100 °C.

In the present design, the heat generation in the fuel is 1 700 W (at a maximum), resulting in an increased canister surface temperature. The temperature development will, among other things, depend on heat transfer to the surrounding bentonite. In the safety assessment SR-Site, the maximum canister surface temperature was calculated to be 90 °C, which is lower than the 100 °C required to compromise the chemical stability of the bentonite, see further Section 3.5.8 in the PSAR Buffer, backfill and closure process report (SKB 2022b). At elevated temperatures, the corrosion reactions may proceed with enhanced rates, but this will be of negligible importance since the corrosion processes involved are either under mass transport or mass balance control. A more important consequence of the higher canister surface temperature is the possible redistribution and enrichment of salts in the bentonite and their deposition onto the canister surface. The extent to which this may occur will depend on the salt content of the groundwater and of the bentonite porewater. The salts that may be of concern are chlorides and sulfates from the groundwater, and sulfates and carbonates from the accessory minerals in the bentonite. The redistribution and enrichment of salts in the buffer material is further discussed in Section 3.3.1 of the Buffer, backfill and closure process report (SKB 2022b).

#### Dependencies between processes and variables

Table X-XX shows how the process influences, and is influenced by, all canister variables.

Table X-XX. Direct dependencies between the process “Deposition of salts on the canister surface” and the defined canister variables and a short note on the handling in the PSAR.

| Variable | Variable influence on process | | Process influence on variable | |
| --- | --- | --- | --- | --- |
|  | Influence present? (Yes/No) Description | Handling of influence  (How/If not – why) | Influence present? (Yes/No) Description | Handling of influence  (How/If not – why) |
| Radiation intensity | No. | – | No. | – |
| Temperature | Yes. The temperature affects the precipitation of salts. | Neglected, due to small effects. | Yes, the precipitation of salts affects the temperature. | #handling of influence |
| Canister geometry | Yes. The canister surface roughness affects the precipitation of salts. | #handling of influence | No. | – |
| Material composition | No. | – | Yes. Surface deposits may occur. | Neglected. The process has no implications for safety. |
| Mechanical stresses | No. | – | No. | – |

#### Natural and anthropogenic analogues

Not applicable.

#### Boundary conditions

The heat flux at the canister-buffer interface and the abundance of salts dissolved in water at the surface constitute the boundary conditions for this process. The flux of salts to the

surface and what limit this flux is discussed in Section X.X.X in the Buffer, backfill and closure

process report (SKB 202Xy).

#### Model and experimental studies

Salt enrichment has been studied in a number of repository-like field tests. In the Long Term Test of Buffer Materials (LOT), copper heaters are embedded in compacted bentonite and exposed to groundwater in the Äspö HRL. The two pilot packages S1 and A0, heated to copper surface temperatures of 90 °C and 130 °C, respectively, were retrieved after one year (Karnland et al. 2000). Examination of the heaters showed that in both packages the copper surfaces were covered with a thin layer of calcium sulfate and/or calcium carbonate. No chloride enrichments were apparent even though the groundwater had a chloride content of over 8 000 mg/L.

Precipitates of calcium sulfate and calcium carbonate were found also in the LOT/A2 package, retrieved after 6 years exposure at 130 °C. The longer exposure did not, however, seem to cause precipitation of larger amounts of these phases on the heater surface (Karnland et al. 2009). The bentonite pore water concentration of chloride was measured as a function of the distance from the central heater for both colder and warmer parts of the LOT/A2 package. The chloride concentration was nearly constant in both the axial and radial directions in the blocks examined, and the total content was very close to that of a mixture of salt content of the original bentonite and the salt content of the amount of Äspö groundwater needed for saturation. The total amount of chloride was actually a little lower than that of a mixture, which could be explained by ion equilibrium, as described by Birgersson and Karnland (2009).

The LOT/S2 and A3 test parcels were heated to 90 °C and 120 °C, respectively, and were exposed to the Äspö environment for 20 years. As for the earlier test parcels in the LOT series, precipitates of calcium sulfate were present at the copper clay interfaces, which was verified with XRD (Johansson et al. 2020). The copper surfaces were examined extensively using SEM-EDS at different magnifications. It was generally found that the levels of chlorine on the copper surfaces was less than one at.%, however, at high magnification, local spots could be found where the levels of chlorine were up to a few at.%. The corrosion product Cu2(OH)3Clwas identified on the bottom plates of the test parcels, however, this is not regarded as the result of salt deposition but rather a different corrosion environment, since the bottom plate was in contact with sand (Johansson et al. 2020).

The LOT/XX test parcel…

Examination of the bentonite from two of the deposition holes in the Prototype Repository, in which full-scale copper canisters were heated and and exposed to the Äspö groundwater for 7 years, showed results very similar to LOT/A2 (Olsson S et al. 2009). No systematic variation of the chloride concentration was found in the pore water from bentonite at different distances from the heated canisters in the test, and the measured chloride concentrations were found to result from proportional mixing of the initial pore water and the Äspö groundwater.

Analysis of salt deposition from the inner section of the Prototype repository showed….

An enrichment of chloride at the bentonite–heater interface has been reported in the large scale experiment Febex, performed by Nagra at the Grimsel test site (Fernández et al. 2018). However, near the interface, the bulk of the bentonite was depleted in chloride compared to the initial concentration. The observed enrichment could have been caused by the condensation and evaporation that is expected during the saturation process and which would lead to a redistribution of the initial chloride content. The enrichment close to the heater could also have been augmented due to leakage through the cabling system (Giroud 2014). The data show no overall accumulation of chloride in the buffer surrounding the heater, rather a loss to the groundwater in the rock.

It is at this time not established whether or not the precipitation of the sulfates and the carbonates were caused by evaporation of water or by the lower solubility of the calcium salts at elevated temperatures. In the latter case, they are likely to redissolve as the temperature decreases again. Alternatively, the deposits can be redissolved when contacted with water undersaturated with respect to calcium carbonate and calcium sulfate. Deposits of calcium sulfate and calcium carbonate have been observed in all packages retrieved from the LOT series and in the Prototype Repository. Until the expected redissolution of deposited calcium sulfate and calcium carbonate, these deposits could influence the heat dissipation from the used fuel over the canister–bentonite interface. Similar salt deposits were also observed in a heater experiment performed in Stripa (Pusch et al. 1992). Furthermore, higher chloride concentrations have been found to promote active dissolution of oxic corrosion products in the repository environment and would thus lower the susceptibility of copper to localised corrosion during the oxic phase (King et al. 2001, Briggs et al. 2020, 2021).

#### Time perspective

Elevated temperatures will remain for several hundred years. The effects discussed above will only persist during the bentonite saturation phase.

#### Impact on safety functions

Temperatures up to 100 °C and even 130 °C are not expected to lead to deposition of salts on the canister surface to an extent that would affect the corrosion behaviour of the copper canister. The process is thus not expected to have any impact on the safety function Can1. Provide corrosion barrier.

The canister geometry, and more specifically, the surface roughness of the canister #beskriv påverkan på saltanrikning#. A deposited salt layer on the outside of the canister is considered to impact the heat dissipation from the canister. From the evaluation of model and experimental studies above, the process is #not?# expected to have an impact on the safety function Buff4. Resist transformation.

#### Handling of the process in the assessments of post-closure safety

##### Handling in the FSAR

The influence of deposited salts on the corrosion behaviour of the copper canister, is neglected due to small influence and will not be further evaluated in the FSAR.

#här behövs en beskrivning av hur saltanrikning kan tänkas påverka FSAR utifrån perspektivet ökad temperatur. Det här har inte analyserats till provskrivningen 2025-05-13#

Text above has been updated, but the handling of the process is the same in the FSAR as in the PSAR

##### Changes since the PSAR

A dependency has been added to consider the process influence on the temperature variable. A dependency has been added to consider the influence of the variable Canister geometry on the process.

#### Handling of uncertainties in the FSAR

There are uncertainties concerning the mechanisms and quantity for possible salt deposition. There are no major uncertainties in understanding the consequences of such a deposit on the lifetime of the canister.

## Radionuclide transport

#text with structure in chapter 1

#### Description

Text

#### Dependencies between processes and variables

Text

#### Natural and anthropogenic analogues

Text

#### Boundary conditions

Text

#### Model and experimental studies

Text

#### Time perspective

Text

#### Impact on safety functions

Text

#### Handling of the process in the assessments of post-closure safety

Text

##### Handling in the FSAR

Text

##### Changes since the PSAR

Text

#### Handling of uncertainties in the FSAR

Text

# References

#references according to the formatted examples below

SKB’s (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications. SKBdoc documents will be submitted upon request to document@skb.se.

**Aaltonen J, Gustafsson C, Nilsson P, 2003.** Oskarshamn site investigation. RAMAC and BIPS logging and deviation measurements in boreholes KSH01A, KSH01B and the upper part of KSH02. SKB P-03-73, Svensk Kärnbränslehantering AB.

**Leskinen N, Ronneteg U, 2011.** Tillverkning av kapselkomponenter. SKBdoc 1175208 ver 5.0, Svensk Kärnbränslehantering AB. (In Swedish.)

**Sena C, Grandia F, Arcos D, Molinero J, Duro L, 2008.** Complementary modelling of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data. SKB R-08-107, Svensk Kärnbränslehantering AB.

**SKB, 2003.** Planning report for the safety assessment SR-Can. SKB TR-03-08, Svensk Kärnbränslehantering AB.

# Appendix A or 1 – Heading 1 in appendix is included in table of content

Title of appendix, included in table of content

Let appendices have consecutive chapter numbers, do not change to letters or renumber from 1. The reason is that figures and tables cannot follow chapter numbering with letters, and that renumbering from 1 sometimes fails.

When layout of a public report, during proofreading production, the numbering is redone.

## Heading 2 in appendix is not included in table of content

In this template, however, heading 2 is included in the table of content. When layout of a public report, this level is removed from the table of content.

### Heading 3 in appendix is not included in content

In this template, however, heading 3 is included in the table of content. When layout of a public report, this level is removed from the table of content.

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |
|  |  |  |

Table - Direct dependencies between the process “Radioactive decay” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Radiation attenuation/heat generation” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Heat transport” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Structural evolution of the fuel matrix” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Residual gas radiolysis/acid formation” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Water radiolysis” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Fuel dissolution” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Dissolution of the gap inventory” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Speciation of radionuclides, colloid formation” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Helium production” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Chemical alteration of the fuel matrix” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Radionuclide transport” and the defined Fuel/cavity in canister variables and a short note on the handling in the [TODO].

Table - Direct dependencies between the process “Deformation of cast iron insert” and the defined Cast iron insert and copper canister variables and a short note on the handling in the [TODO].

1. BWR Cases, SKBdoc 2002171, PWR Cases SKBdoc 2002172. (Internal documents.) [↑](#footnote-ref-1)