Author: Peter Segle

Technical Note

# 2015:52

Review of SKB's creep model, its implementation into ABAQUS and an evaluation of SKB's analyses of the copper canister

## SSM:s perspektiv

### Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag

### Projektets syfte

Det övergripande syftet med denna rapport är att ta fram synpunkte på SKB:s säkerhetsanalys, SR-Site. För specifikt denna trapport är syftet att granska av dels SKB:s krypmodell för syrefri forsforlegerad koppar och dels implementering av krypmodellen i den generella finita elementkoden ABAQUS. Baserat på detta underlag har dessutom några av SKB:s beräkningar av kopparkapselns deformationer i slutförvarsmiljöer genomförts.

### Författarens sammanfattning

SKB:s krypmodell för OFP-koppar och implementering av krypmodellen i ABAQUS har granskats. Vidare har vissa av SKB:s analyser av kopparkapseln granskats med avseende på kopparkapselns mekaniska integritet.

SKB:s påstående att krypmodellen för kopparmaterialet baseras på fundamentala principer och att ingen parameteranpassning är nödvändig ifrågasätts i denna granskning. "Stage IV work hardening" beaktas på ett indirekt och förenklat sätt istället för att vara en del av modellen. Den fysikaliska grunden för att använda teknologisk spänning istället för sann spänning vid tillämpningen av krypmodellen är inte självklar. Det faktum att det enligt SKB råkar bli så vid tillämpning på enaxliga krypdata tyder på att fysiken inte är fullt förstådd. I modellen styr spänningen de olika deformationsmekanismerna. Att "stage IV work hardening" skulle ha samma inverkan på de verksamma deformationsmekanismerna ifrågasätts. Vidare är det oklart om samma spänningskorrektion även gäller för fleraxligt tillstånd.

En materialmodell som ska användas för simulering av krypning i en struktur under mer än 100.000 år kommer alltid att ifrågasättas. Av denna anledning bör fokus ligga på robustheten i tillämpningen av modellen. Vad det gäller undvikande av krypbrott i kopparkapseln är det avgörande att kunna visa att laststyrda belastningsfall övergår till att bli deformationsstyrda i slutförvaret. Om de mekaniska lasterna på kopparkapseln kan betraktas som deformationsstyrda torde krypdeformationen i kopparkapseln efter 100.000 år kunna beräknas med SKB:s krypmodell.

Granskningen visar att SKB:s implementering av krypmodellen i ABAQUS gjorts på ett korrekt sätt.

SKB:s krypanalyser av laststyrda belastningsfall har två brister. Dels är analystiden för kort i vissa av analyserna och dels bör krypning beaktas i andra.

Insatsen antas vara koncentriskt placerad i kopparkapseln i SKB:s analyser. I praktiken torde dock insatsens placering vara excentrisk efter hanteringen i samband med kapselns placering i depositionshålet.

Effekten av att kopparcylindern och insatsen initialt är i kontakt längs en axiell generatris bör således studeras med avseende på ackumulerad kryptöjning i kopparkapseln. Även det axiella gapet i SKB:s analyser mellan insatsens stållock och kopparlocket behöver ses över.

SKB föreslås utföra en alternativ analys för verifiering av kopparkapseln med avseende på krypbrott och lasten yttre tryck där minsta nödvändiga nivå på krypduktilitet bestäms.

**Projektinformation**
Kontaktperson på SSM: Jan Linder
Diarienummer ramavtal: NA
Diarienummer avrop: NA
Aktivitetsnummer: 3030012-4117

## SSM perspective

### Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

### Objective

The general objective of the present project is to provide independent review comments for one area of SKB:s post closure safety analysis, SR-Site. Against this background, the purpose of this report is to review both SKB's creep model of oxygen-free phosphorus alloyed copper and the implementation of the creep model in the general finite element code ABAQUS. Based on this information some of SKB's calculations of copper canister deformations in repository environments have been conducted.

### Summary by the author

SKB's creep model for the OFP copper and its implementation into ABAQUS has been reviewed. Furthermore has some of SKB's analyses of the copper canister been reviewed with respect to the mechanical integrity of the copper canister when subjected to different types of pressure and shear loads.

SKB's statement that the copper creep model is based on fundamental principles and that no fitted parameters are needed is questioned in this review. Stage IV work hardening is taken into account in an indirect and non-fundamental way instead of being part of the model. The physical basis for using technological stress, instead of true stress, in the application of the creep model equations is not obvious. The fact that it, according to SKB, happens to be so when the model is applied on uniaxial creep data implies that the physics is not fully understood. In the model, stress controls the different deformation mechanisms. It must be questioned that the effect of stage IV work hardening has the same impact (by use of the technological stress) on both the climb and the glide deformation mechanism. It is furthermore unclear if the same correction of stress holds also for the multiaxial case.

A material model that is used to simulate creep in a structure for more than 100.000 years will always be questioned. Under such conditions main focus should be on the robustness of the application of the model. With respect to avoidance of creep rupture in the copper canister, it is necessary to show that load controlled scenarios will not be prolonged after emplacement of the canister in the repository. For the remaining deformation controlled scenarios, creep strains in the copper canister after 100.000 years should be possible to calculate by use of SKB's creep model.

The review shows that SKB's implementation of the creep model into ABAQUS is correctly done.

SKB's analyses of the load controlled scenarios have two weaknesses. Analysed time is too short in some analyses and the creep mechanism should be considered in others.

A concentric location of the insert with respect to the copper cylinder is assumed in SKB's analyses. In practice, however, it can be expected that the insert is eccentrically located as a result of the handling during the emplacement of the canister in the deposition hole. Thus, a case where the insert and the copper cylinder initially are in contact along an axial generatrix should be analysed. Also the axial gap between the steel lid and the copper lid needs to be looked over.

SKB is finally suggested to perform an alternative verification of the copper canister for the external pressure load case with respect to creep rupture where the minimum required level of creep ductility is determined.

**Project information**
Contact person at SSM: Jan Linder

Author: **Peter Segle**
Inspecta Nuclear AB, Stockholm, Sweden

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Review of SKB's creep model, its implementation into ABAQUS and an evaluation of SKB's analyses of the copper canister

# Content

# 1. Introduction

The purpose with this work is to review SKB's creep model for the OFP copper and its implementation into ABAQUS and to evaluate some of SKB's analyses of the copper canister. The outcome of this review is meant to give the Swedish Radiation Safety Authority (SSM) additional information in their review of SKB's application for final disposal of radioactive waste. Focus is on the mechanical integrity of the copper canister with respect to creep deformation.

SKB's creep model presented in [1, 2] is briefly reviewed in the perspective of giving the background for the review of the implementation of the creep model into ABAQUS. SKB's analyses presented in [3-5] are reviewed with respect to the mechanical integrity of the copper canister when subjected to different types of pressure and shear loads.

# 2. SKB's creep model

## 2.1. Creep model used in SKB's creep analyses

The creep model used in SKB's creep analyses [3-5] is given in [1, 2]. The model is here briefly summarised. For a complete description of the creep model see references [1, 2].

### 2.1.1. Uniaxial model

For $T > 400\ {}^{\circ}\mathrm{C}$, deformation in pure copper is controlled by climb of dislocations. Ignoring the dynamic recovery term $2\omega\rho$ (more important at lower temperatures) and assuming stationary conditions, i.e. the dislocation density $\rho$ is constant, plastic strain rate is given as

$$\dot{\varepsilon} = \frac{2bc_L}{m}\ \frac{D_s b}{k_{\mathrm{B}} T}\ \mathrm{e}^{\frac{\sigma b^3}{k_{\mathrm{B}} T}}\ \tau_L \rho^{3/2} \tag{2-1}$$

where $b$ is Burgers vector, $c_L$ is a constant, $m$ is the Taylor factor, $D_s$ is the self-diffusion factor, $k_{\mathrm{B}}$ is Boltzmann's constant, $T$ is the absolute temperature, $\sigma$ is the full applied stress, i.e. not considering the internal back stress, $\tau_L$ is the dislocation line tension and $\rho$ is the dislocation density, respectively. The dislocation density can be related to the stress as

$$\sigma = \alpha G b \sqrt{\rho} \tag{2-2}$$

where $G$ is the shear modulus and $\alpha$ is a constant. If instead pipe diffusion is assumed to be dominating, equation (2-1) still gives a creep rate of the right order of magnitude from 400 down to 200 °C.

For $T < 200$ °C, deformation in pure copper is suggested to be glide controlled. The strain rate due to glide of dislocations can be expressed as

$$\dot{\varepsilon} = f\sigma^2 e^{-\frac{Q}{RT}\left[1-\left(\frac{\sigma}{\sigma_{imax}}\right)^{q_1}\right]^{q_2}} \tag{2-3}$$

where $Q$ is an activation energy, $R$ is the gas constant, $\sigma_{imax}$ is the maximum back stress, and $f$, $q_1$ and $q_2$ are constants, respectively. $q_1 = 2$ and $q_2 = 1$ have been chosen previously in the literature for copper.

The two equations (2-1) and (2-3) are now combined in a unified model for stationary conditions as

$$\dot{\varepsilon}_{OF,stat} = \frac{2bc_L}{m}\frac{D_{s0}b\tau_L}{k_B T}\left(\frac{\sigma}{\alpha mGb}\right)^3 e^{\frac{\sigma b^3}{k_B T}} e^{-\frac{Q_{eff}}{RT}\left[1-\left(\frac{\sigma}{\sigma_{imax}}\right)^2\right]} \tag{2-4}$$

where the index OF is the designation for oxygen free pure copper (Cu-OF).

Addition of 50 ppm phosphorus to Cu-OF reduces the creep rate and increases the creep ductility. The ratio in creep rate between Cu-OF and Cu-OFP (phosphorus doped Cu-OF) is expressed as

$$f_P = \frac{\dot{\varepsilon}_{OF}}{\dot{\varepsilon}_{OFP}} = \begin{array}{ll} K_1 \exp(K_2 e^{-k_3 T}) & T > 75 \text{ °C} \\ 3000 & T \leq 75 \text{ °C} \end{array} \tag{2-5}$$

where $K_1 = 0.1695$, $K_2 = 55.73$ and $k_3 = 0.005$ 1/°C.

Combining equations (2-4) and (2-5) gives the creep rate for Cu-OFP at stationary condition as

$$\dot{\varepsilon}_{OFP,stat} = \frac{2bc_L}{m}\frac{D_{s0}b\tau_L}{k_B T}\left(\frac{\sigma}{\alpha mGb}\right)^3 e^{\frac{\sigma b^3}{k_B T}} e^{-\frac{Q_{eff}}{RT}\left[1-\left(\frac{\sigma}{\sigma_{imax}}\right)^2\right]} / f_P \tag{2-6}$$

In order to capture the primary creep stage, a non-stationary model is used. This model considers an effective stress given as

$$\sigma_{eff} = \sigma - \sigma_i \tag{2-7}$$

where $\sigma_i$ is an internal back stress. The back stress is related to the plastic strain $\varepsilon$ (work hardening) according to

$$\sigma_i = C(1 - e^{-\omega\varepsilon}) \tag{2-8}$$

where $C$ is a constant and $\omega$ is given as

$$\omega = \frac{B\dot{\varepsilon}^{n_b}}{(T-273)^{p_b}} \tag{2-9}$$

where $B = 4.02$, $n_b = 0.0481$ and $p_b = 0.277$ are given from fitting to experimental Cu-OFP data.

The non-stationary model also considers the ratio between initial creep rate at one hour and the creep rate at one third of the creep rupture time (corresponds approximately to the minimum creep rate). The ratio is given as

$$g_{\text{rate}} = \frac{\dot{\varepsilon}_{\text{init}}}{\dot{\varepsilon}_{\text{min}}} = \left(\frac{t_{\text{min}}}{t_{\text{init}}}\right)^{\phi_2/(1+\phi_2)} \tag{2-10}$$

where $t_{\text{init}} = 1$ hour and $t_{\text{min}} = t_{\text{R}}/3$ and

$$\phi_2 = 13.3 - 0.022T \tag{2-11}$$

where the temperature $T$ is given in Kelvin.

Considering $\sigma_{\text{eff}}$ and $g_{\text{rate}}$, the non-stationary model can be expressed as

$$\dot{\varepsilon}_{\text{OFP,non−stat}} = \frac{2bc_L}{m} \frac{D_{s0}b\tau_L}{k_B T} \left(\frac{\sigma_{\text{eff}}}{\alpha mGb}\right)^3 e^{\frac{\sigma_{\text{eff}}b^3}{k_B T}} e^{-\frac{Q_{\text{eff}}}{RT}\left[1-\left(\frac{\sigma_{\text{eff}}}{\sigma_{i\max}}\right)^2\right]} g_{\text{rate}}/f_P \tag{2-12}$$

The total creep rate for Cu-OFP and uniaxial conditions is now given as

$$\dot{\varepsilon}_{\text{OFP,tot}} = \dot{\varepsilon}_{\text{OFP,stat}} + \dot{\varepsilon}_{\text{OFP,non−stat}} \tag{2-13}$$

## 2.1.2. Multiaxial model

In [2], two approaches are suggested for the consideration of the multiaxial state. One important difference between approach A and B is the way the back stress is expressed.

In approach A (section 10.2.1 in [2]), the back stress is given as a tensor $\boldsymbol{\sigma}_i$. The stress invariant $J(\boldsymbol{\sigma} - \boldsymbol{\sigma}_i)$ and the effective strain are applied in equation (2-13). The stress invariant is given as

$$J(\boldsymbol{\sigma} - \boldsymbol{\sigma}_i) = \sqrt{\frac{3}{2}(\boldsymbol{\sigma}' - \boldsymbol{\sigma}_i'):(\boldsymbol{\sigma}' - \boldsymbol{\sigma}_i')} \tag{2-14}$$

where $\boldsymbol{\sigma}'$ and $\boldsymbol{\sigma}_i'$ are the deviatoric part of the stress tensor $\boldsymbol{\sigma}$ and the back stress tensor $\boldsymbol{\sigma}_i$, respectively. See section 10.2.1 in [2] for further details.

In approach B (section 10.2.2 in [2]), the back stress is given as a scalar as

$$\sigma_i = C\left(1 - e^{-\omega\varepsilon_{\text{eff}}^{\text{cr}}}\right) \tag{2-15}$$

where $\varepsilon_{\text{eff}}^{\text{cr}}$ is the effective creep strain and $\omega$ is given by equation (2-9). According to Odqvist's equation, the creep rate tensor is given as

$$\dot{\boldsymbol{\varepsilon}}^{\text{cr}} = \frac{3}{2}\dot{\varepsilon}_{\text{eff}}^{\text{cr}} \frac{\boldsymbol{\sigma}'}{\sigma_e} \tag{2-16}$$

where $\sigma_e = \sqrt{\frac{3}{2}\boldsymbol{\sigma}'\boldsymbol{\sigma}'}$ (Mises stress). By use of equation (2-13), the effective creep rate $\dot{\varepsilon}_{\text{eff}}^{\text{cr}}$ can be calculated. This is done by replacing $\sigma$ in equation (2-6) with $\sigma_e$ and replacing $\sigma_{\text{eff}}$ in equation (2-12) with $\sigma_e - \sigma_i$.

SKB has chosen approach B for their implementation of the creep model into ABAQUS.

### 2.1.3. Effect of stage IV work hardening

Stage IV work hardening in copper has a very large effect both on stress-strain curves and on creep curves. It gives a linear stress (true stress) dependence as a function of strain [6]. Due to stage IV work hardening, the true stress measure in equations (2-6) and (2-12) has to be corrected [2, 7]. In the uniaxial case this correction, according to [6], happens to be

$$\sigma = \sigma_{\text{true}} e^{-\varepsilon_{\text{eff}}^{\text{cr}}} \tag{2-17}$$

where $\varepsilon_{\text{eff}}^{\text{cr}}$ is the effective creep strain. Thus, $\sigma$ equals the technological stress.

Considering the multiaxial case according to approach B and stage IV work hardening, $\sigma$ in equation (2-6) is replaced by $\sigma_{\text{e,true}} e^{-\varepsilon_{\text{eff}}^{\text{cr}}}$, and $\sigma_{\text{eff}}$ in (2-12) is replaced by $\left(\sigma_{\text{e,true}} - \sigma_i\right) e^{-\varepsilon_{\text{eff}}^{\text{cr}}}$. Here, $\sigma_{\text{e,true}}$ is the true Mises stress.

## 2.2. Review comments on SKB's creep model

SKB has developed a constitutive model considering creep and other plastic deformation mechanisms for Cu-OFP in the temperature range from 20 to 400 $^{\circ}$C. Basic dislocation mechanisms form basis for their model which takes work hardening, dynamic recovery and static recovery into account. SKB claims that the model is based on fundamental principles and that no fitted parameters are needed.

A number of comments and questions are raised with respect to the robustness of SKB's creep model for Cu-OFP and the possibility to use it for extrapolations to repository conditions with a time scale beyond 100.000 years.

1. The values of the constants $q_1$ and $q_2$ in equation (2-3) are chosen as 2 and 1, respectively. According to SKB, these values have been chosen previously in the literature for copper.
   It is not obvious that the same $q_1$ and $q_2$ should be chosen as addition of phosphorous influences the creep deformation properties of copper.

2. The constants $B$, $n_b$ and $p_b$ in equation (2-9) are determined by fitting to stress-strain curves.

3. $g_{rate}$ in equation (2-12) is the ratio of the initial creep rate and the minimum creep rate in a creep test [2]. SKB has chosen to determine these creep rates at one hour and at one third of the creep rupture time, respectively. By use of the $\phi$-model, $g_{\text{rate}}$ is reformulated according to equation (2-10). The influence of temperature on $g_{\text{rate}}$ is considered according to equation (2-11).
   The stress level used in the creep test (for determination of $g_{\text{rate}}$) influences $t_{\text{min}}$ in equation (2-10). Thereby $g_{\text{rate}}$ is also influenced. Furthermore are constants in equation (2-11) determined by fitting to creep data. As a consequence of these facts, the robustness of $g_{\text{rate}}$ is questioned.

4.   In the application of the creep model in SKB's creep analyses, a scalar back stress is used according to approach B in [2]. SKB also suggests a tensor formulated back stress (approach A) in [2]. Approach A is however rejected by SKB as the Armstrong-Frederick equation causes problems in the multiaxial implementation.
The reasons why SKB chooses a scalar instead of a tensor formulated back stress are, according to the present author, probably two. Firstly, with a scalar back stress, implementation of the creep model into ABAQUS is substantially simplified. Secondly, in order to validate the tensor formulated back stress, multiaxial creep data would be needed. The effect of choosing a scalar instead of a tensor formulated back stress is difficult to judge without creep data from multiaxial creep testing. With the present scalar formulation of the back stress, the Bauschinger effect cannot be captured. However, and as SKB states, the present load scenarios are essentially monotonic.

5.   The stress used in equations (2-6) and (2-12) is corrected due to stage IV work hardening. In the uniaxial case this stress happens to equal the technological stress according to SKB [6].
The physical basis for using technological stress in equations (2-6) and (2-12) is not obvious. The fact that it, according to [6], happens to be so when the model is applied on uniaxial creep data implies that the physics is not fully understood. A development of the creep model would be to include the modelling of stage IV work hardening in the model. Thereby, true stress given by the finite element analysis could be used directly in the creep model without correction. In equations (2-6) and (2-12), the stress controls different deformation mechanisms. It must be questioned that the effect of stage IV work hardening has the same impact (by use of the technological stress) on both the climb and the glide deformation mechanism. It is furthermore unclear if the same correction of stress holds also for the multiaxial case.

6.   SKB's creep model is of importance in the assessment of stress corrosion cracking in the copper canister. The creep model influences relaxation of stresses under deformation controlled conditions. The faster the stresses relax, the shorter the time is when conditions for stress corrosion cracking to happen are fulfilled.

SKB claims that their creep model is based on fundamental principles and that no fitted parameters are needed. According to SKB, this fact facilitates the possibility to use the model for extrapolations to repository conditions with a time scale beyond 100.000 years. This possibility is questioned in this review. Even if fundamental principles are considered in the model, parameter fitting is still needed. Furthermore, stage IV work hardening is taken into account in an indirect and non-fundamental way instead of being part of the model.

A material model that is used to simulate creep in a structure for more than 100.000 years will always be questioned. Therefore, under such conditions main focus should be on the robustness of the application of the model. With respect to avoidance of creep rupture in the copper canister, it is necessary to show that load controlled scenarios will not be prolonged after emplacement of the canister in the repository. For the remaining deformation controlled scenarios, creep strains in the copper canister after 100.000 years should be possible to calculate by use of SKB's creep model.

# 3. Implementation of SKB's creep model into ABAQUS

## 3.1. General

Implementation of user-defined mechanical material models into ABAQUS [8] can be done in a number of ways. Use of the user subroutine UMAT (implicit integration) or VUMAT (explicit integration) is the most general form of implementation. This approach requires considerable effort and expertise. The feature is very general and powerful, but its use is not a routine exercise. In order to somewhat simplify implementation of material models into ABAQUS, a number of partly pre-programmed user subroutines are available for the user. One of these is the user subroutine CREEP. This subroutine is intended to provide the "uniaxial" creep laws that are to be included in a general time-dependent, viscoplastic material formulation.

## 3.2. User subroutine CREEP

In ABAQUS, the user subroutine CREEP is called at all integration points of elements for which the material definition contains the user subroutine defined material. For the present application of the subroutine, only metal creep has to be considered.

If implicit integration is used in ABAQUS, the following variables need to be determined by the user subroutine:

$\Delta \bar{\varepsilon}^{cr}$      equivalent (uniaxial) deviatoric creep strain increment, DECRA(1).

$\frac{\partial \Delta \bar{\varepsilon}^{cr}}{\partial \bar{\varepsilon}^{cr}}$      partial derivative of equivalent deviatoric creep strain increment with respect to equivalent deviatoric creep strain, DECRA(2).

$\frac{\partial \Delta \bar{\varepsilon}^{cr}}{\partial p}$      partial derivative of equivalent deviatoric creep strain increment with respect to equivalent pressure stress $p = -\frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33})$, DECRA(4).

$\frac{\partial \Delta \bar{\varepsilon}^{cr}}{\partial \tilde{q}}$      partial derivative of equivalent deviatoric creep strain increment with respect to equivalent deviatoric stress $\tilde{q}$, here the von Mises stress, DECRA(5).

The derivatives can be determined analytically or numerically depending on the complexity of the constitutive model. State variables (STATEV) can be defined by the user in order to follow the evolution of specific measures of interest.

If explicit integration is used in ABAQUS, only $\Delta \bar{\varepsilon}^{cr}$ needs to be determined.

## 3.3. Implementation of SKB's creep model

The creep model described in [2] has been implemented by SKB into ABAQUS by the use of the user subroutine CREEP. In brief, the user subroutine is based on the following expressions.

The creep rate is divided in two parts, one stationary and one non-stationary. In the uniaxial case the stationary part is given as

$$\dot{\varepsilon}_{\text{OFP,stat}} = \frac{2bc_L}{m} \frac{D_{s0} b \tau_L}{k_B T} \left(\frac{\sigma}{\alpha m G b}\right)^3 e^{\frac{\sigma b^3}{k_B T}} e^{-\frac{Q_{\text{eff}}}{RT}\left[1 - \left(\frac{\sigma}{\sigma_{i\text{max}}}\right)^2\right]} / f_P \tag{3-1}$$

where $\sigma$ is the full applied stress (not considering the back stress) and $f_P$ is a factor taking account for the effect of adding phosphorous to the copper.

The non-stationary part, which captures the effect of varying stress, is given as

$$\dot{\varepsilon}_{\text{OFP,non-stat}} = \frac{2bc_L}{m} \frac{D_{s0} b \tau_L}{k_B T} \left(\frac{\sigma - \sigma_i}{\alpha m G b}\right)^3 e^{\frac{(\sigma - \sigma_i) b^3}{k_B T}} e^{-\frac{Q_{\text{eff}}}{RT}\left[1 - \left(\frac{\sigma - \sigma_i}{\sigma_{i\text{max}}}\right)^2\right]} g_{\text{rate}} / f_P \tag{3-2}$$

where $\sigma_i$ is the back stress and $g_{\text{rate}}$ is a factor considering the ratio between the creep rate at one hour and the creep rate at one third of the creep rupture time in a creep test.

The total creep rate is given as

$$\dot{\varepsilon}_{\text{OFP,tot}} = \dot{\varepsilon}_{\text{OFP,stat}} + \dot{\varepsilon}_{\text{OFP,non-stat}} \tag{3-3}$$

In the creep analyses performed in ABAQUS with the user subroutine, true stress is used. In order to consider the effect of stage IV work hardening, the stress used in the subroutine is reduced. For the uniaxial case, the reduction happens to be such that technological stress is used instead of true stress in the subroutine. Thus, $\sigma$ in equation (3-1) and $\sigma - \sigma_i$ in equation (3-2) are multiplied by $e^{-\varepsilon_{\text{eff}}^{\text{cr}}}$ where $\varepsilon_{\text{eff}}^{\text{cr}}$ is the effective creep strain.

SKB's creep analyses performed in ABAQUS are multiaxial. Approach B in section 10.2.2 in [2] describes the procedure used in the subroutine.

In SKB's user subroutine, $\Delta\bar{\varepsilon}^{cr}$, $\frac{\partial\Delta\bar{\varepsilon}^{cr}}{\partial\bar{\varepsilon}^{cr}}$ and $\frac{\partial\Delta\bar{\varepsilon}^{cr}}{\partial\bar{q}}$ are defined. The two latter are determined by use of numerical derivation.

SKB's implementation of the creep model into ABAQUS is further described in [9].

## 3.4. Review comments on implementation of SKB's creep model

The creep model described in [2], using approach B in section 10.2.2 in [2], is correctly implemented into ABAQUS by use of the user subroutine CREEP. In equation (2-16), the creep rate tensor $\dot{\boldsymbol{\varepsilon}}^{\text{cr}}$ is given as $\frac{3}{2}\dot{\varepsilon}_{\text{eff}}^{\text{cr}}$ times $\frac{\sigma'}{\sigma_e}$. In SKB's finite element application, the former factor is based on a corrected stress according to equation (2-17) while the latter factor is based on a non-corrected stress. The

mixture of stress measures used for the two factors in equation (2-16) could be questioned. However, as $\frac{\sigma'}{\sigma_e}$ only gives the direction of the creep strain increment, it is judged that present approach can be applied.

Tests with SKB's user subroutine show that:

1. Simulation of a creep test of OFP copper at temperature 175 $^o$C and stress150 MPa shows that the subroutine rather well predicts test results. For example, the model result shown in figure 5 in [1] can be reproduced.

2. The subroutine predicts zero creep strain for a hydrostatic stress state which is expected.

3. Using true stress in the creep model equations (instead of $\sigma_{\text{true}}e^{-\varepsilon_{\text{eff}}^{\text{cr}}}$) results in overestimated creep strains compared to creep test results. Figure 3-1 shows a comparison between the use of $\sigma_{\text{true}}$ or $\sigma_{\text{true}}e^{-\varepsilon_{\text{eff}}^{\text{cr}}}$ in SKB's subroutine.
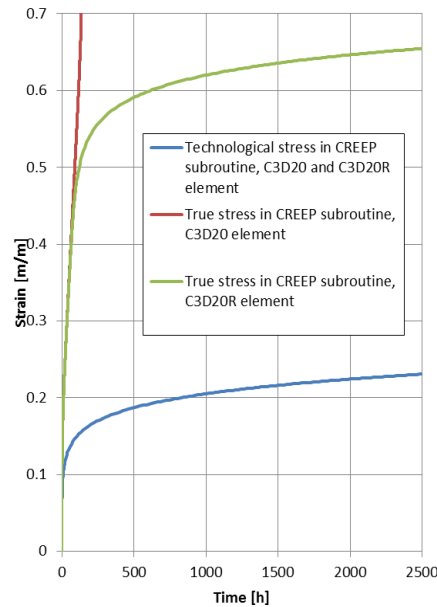


**Figure 3-1:** Numerical simulation of the creep test shown in figure 5 in [1] using technological or true stress in SKB's subroutine. Simulations are done with the ABAQUS elements C3D20 and C3D20R (reduced integration).

In SKB's consecutive creep analyses, explicit integration is utilized why the two variables $\frac{\partial \Delta\bar{\varepsilon}^{cr}}{\partial \bar{\varepsilon}^{cr}}$ and $\frac{\partial \Delta\bar{\varepsilon}^{cr}}{\partial \bar{q}}$ are not needed to be determined. The reason why they still remain in the subroutine is probably that the initial intention was to use implicit integration. It is expected that implicit integration resulted in too time-consuming calculations.

An implementation of the multiaxial formulation according to approach A (the back stress is defined as a tensor) in section 10.2.2 in [2] would require UMAT or VUMAT programming in ABAQUS.

# 4. SKB's analyses of the copper canister

## 4.1. SKB's creep analyses presented in 1399768 rev 2.0

### 4.1.1. General

The creep analyses performed in 1399768 rev 2.0 [4] is a development of that performed in 1399768 rev 1.0 [3]. All results in [3] are covered by [4]. Hence, focus in this report will be on the later revision.

### 4.1.2. FE model and analysis

The axisymmetric model consists of the copper shell, the steel lid and the insert. Figure 4-1 shows the FE mesh of the junction between the steel lid/insert, the copper lid and the copper cylinder. Figure 4-2 shows the FE mesh of the bottom corner of the canister.
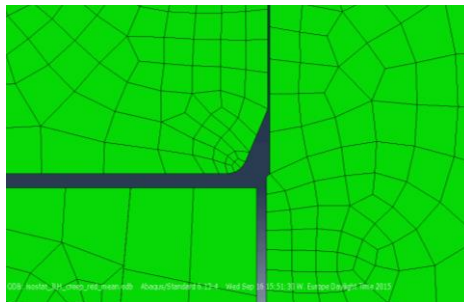


**Figure 4-1:** FE mesh of the junction between the steel lid/insert (bottom left), the copper lid (top left) and the copper cylinder (to the right). Axisymmetric model.
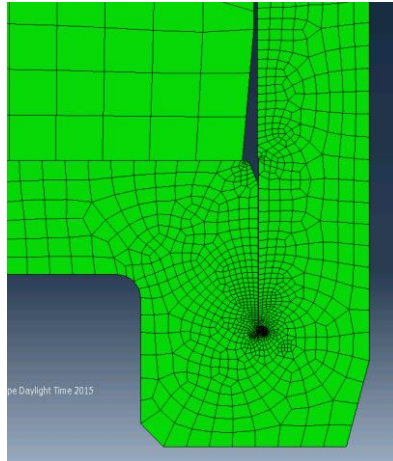
**Figure 4-2:** FE mesh of the bottom corner of the canister. Defect is modelled as in the friction stir weld region. Axisymmetric model.

The geometry of the friction stir weld and the bottom weld is modelled by an axial slit and a 3 mm root defect in radial direction. Figure 4-3 shows the slit and the defect in the friction stir weld region. All boundaries of the insert and the steel lid interact through contact surfaces with the inside of the copper shell. Friction coefficient is 0.1. Initial gap is 1.57 mm between the insert and the copper cylinder in the radial direction and 2.15 mm between the steel lid and the copper lid in the axial direction. An internal pressure caused by thermal evolution and gas production is applied on the insert and the inside of the copper shell. External pressure caused by a swelling buffer and hydrostatic water pressure is applied directly on the outside of the copper shell. In order to be conservative regarding the development of creep strain in the top and bottom weld region, two types of boundary conditions are chosen, see figure 8-2 in [4].
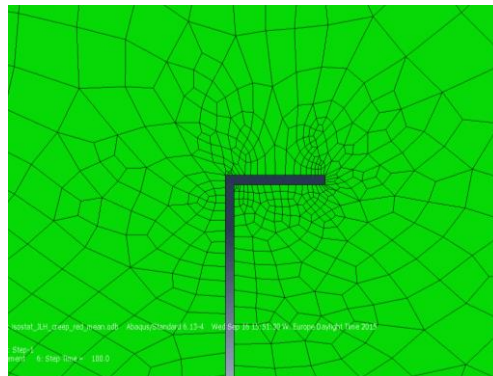


**Figure 4-3:** FE mesh of the slit and the 3 mm radial defect in the friction stir weld region. Axisymmetric model.

Four axisymmetric analyses are performed. The impact of how dry the deposition hole is (wet or dry) and the temperature evolution in the repository (mean or dimensioning) are investigated. For the wet hole analyses, the external pressure is ramped up to 15 MPa over the first ten years and is then held constant. For the dry hole analyses, the external pressure is ramped up to 15 MPa between year 10 and 100 and is then held constant. For more details about this up-ramping se figure 2-3 in [4]. For all four analyses, the glacial period starts at year 20.000 and the external

pressure is then increase to 60 MPa. An internal pressure is furthermore ramped up to 0.5 MPa over the first ten years and then held constant throughout the simulation. All creep analyses in [4] use SKB's implemented copper creep model [2]. Temperature varies during the simulation according to figure 2-1 in [4]. For comparison reasons, also a 3D model is analysed where half of a BWR canister is modelled. In this simulation, a dry deposition hole and a dimensioning temperature evolution are assumed. Further details about the models and the analyses are given in [4].

### 4.1.3. Results

Results in [4] show that thermal expansion and internal pressure in the canister give negligible strain effects. The dominant factor that causes strains in the copper shell is the applied external pressure.

The analysis with the dry deposition hole and dimensioning temperature evolution shows the highest level of equivalent creep strain (CEEQ). Maximum CEEQ equals 61.4 % and is found in the top weld, see figure A1-10 and A1-13 in [4]. The hydrostatic pressure is positive (compressive stresses) for the element with the highest level of CEEQ. According to [4], this is beneficial from a structural integrity perspective. Furthermore is the highest creep strain very localized and concentrated to elements in the vicinity of geometric discontinuities.

Creep caused by internal pressure, before the external pressure is applied, is very small and of minor importance.

According to [4], the chosen boundary conditions at the copper shell base probably imply stresses and strains higher than would be the case with the buffer included in the analyses.

A comparison of results from an axisymmetric analysis and a 3D analysis shows that the axisymmetric approximation is sufficiently accurate.

## 4.2. SKB's analyses of unfavourable pressure load presented in 1419643 rev 1.0

### 4.2.1. General

Analyses of the canister with unfavourable pressure loads are presented in [5]. Two different load cases are studied:

1. A horizontal crack in the bentonite close to the copper lid flange implies a radial swelling pressure at the outer surface of the flange at the same time it is assumed that no radial counter swelling pressure will be build up during the water saturation phase as the recess in the copper lid cannot be fully filled with bentonite along the periphery. Furthermore, an axial swelling pressure also develops acting on the lid and interacts with the radial pressure.

2. Several evenly distributed horizontal cracks in the bentonite imply a radial swelling pressure at the outer surface of the copper shell and at the same

time generates an axial expansion of the bentonite which implies axial shear stresses at the outer surface of the copper shell. Same assumptions regarding counter pressure and vertical pressure at the lid as in case 1.

## 4.2.2. FE model and analysis

The axisymmetric model consists of the copper shell, the steel lid and the insert. The geometry of the friction stir weld and the bottom weld is modelled by an axial slit and a 3 mm root defect in radial direction. All boundaries of the insert and the steel lid interact through contact surfaces with the inside of the copper shell. Friction coefficient is 0.1. Initial radial gap between insert and copper shell is 1.56 mm [10]. As the buffer is not included in the model, pressure and shear loads caused by the swelling buffer are applied directly on the copper shell. The canister is constrained to move in the vertical direction at the bottom flange, see figure 6-3 in [5].

The shear stress that can be transferred from the buffer to the copper shell is limited to 1.75 MPa which corresponds to the shearing capacity of the buffer [10]. This shear stress is applied in load case 2. Half of the copper shell surface has shear stresses pointing upwards and the other half has shear stresses pointing downwards, see figure 6-4 in [5]. Gravity forces are also applied in load case 2.

All analyses are elasto-plastic considering the rate-dependence of the materials. Creep in the copper shell is not taken into account. The pressure load is linearly ramped up from 0 to 12.3 MPa [10]. Temperature is constant in the analyses.

## 4.2.3. Results

For load case 1, no contact between the insert and the copper shell is established [10]. For load case 2, contact is established partly, see figure 4-4.
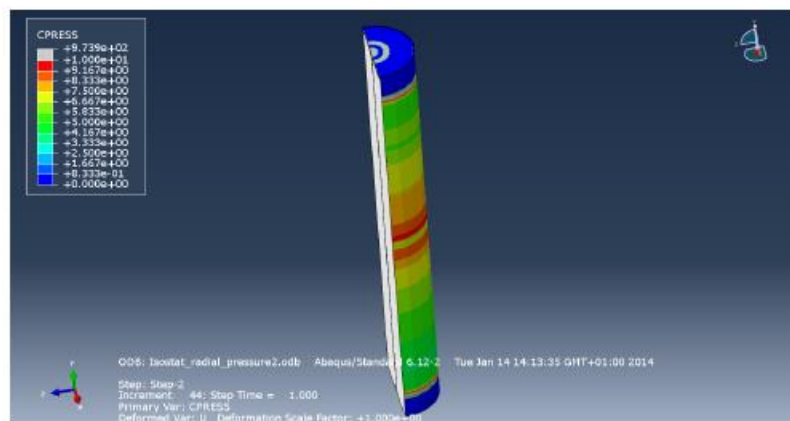


**Figure 4-4:** Established contact for load case 2 [10].

Developed equivalent plastic strain (PEEQ) is higher for load case 2 than for load case 1. Figure 4-5 shows PEEQ in the top region of the copper canister. Highest level of plastic strain is found in the lid and in the copper shell below the friction stir weld region. Maximum plastic strain is 6.2 % (in a point). In the grey region in figure 4-5, PEEQ is between 1 and 6.2 %. Also in the bottom weld region of the

copper canister, PEEQ is locally relatively high for load case 2, see figure 8-5 in [5]. Corresponding hydrostatic pressure for load case 2 is shown in figure 4-6.
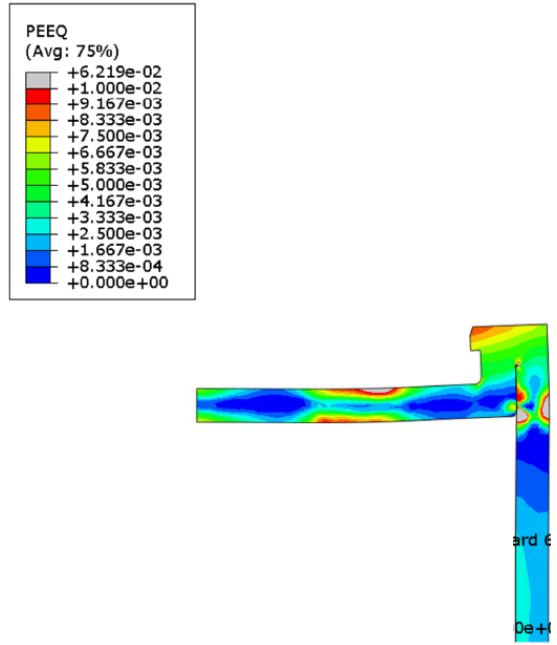According to [5], maximum PEEQ is located in a region with compressive stresses.



**Figure 4-5:** Equivalent plastic strain (PEEQ) in top region of the copper shell for load case 2 [5].
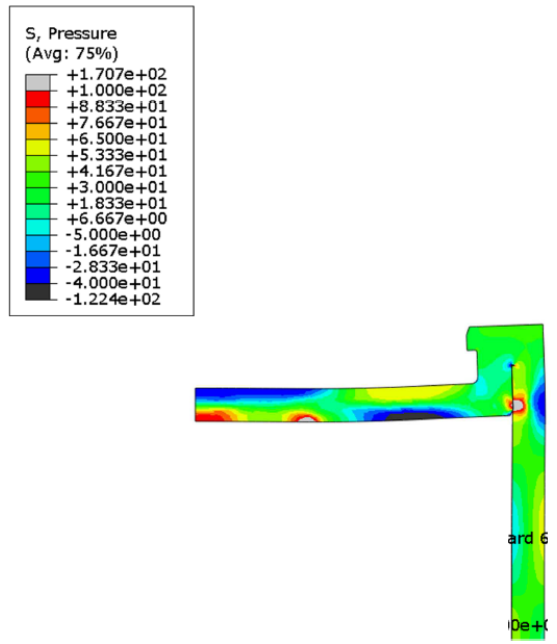


**Figure 4-6:** Hydrostatic pressure $p = -\frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33})$ in top region of the copper shell for load case 2 [5].

Uncertainties are discussed in [5]. Regarding the element mesh the following is written:

*A more refined mesh will probably increase the maximum stress and strain levels. Fortunately, the use of non-linear material properties (such as plasticity and creep) will decrease the sensitivity to the used mesh. The used mesh has been judged to be accurate enough. Since several models have been executed with different mesh densities it has been possible to compare and the conclusion is that the mesh in a global sense is accurate.*

SKB summarises the results of the analyses in [5] as follows:

*Despite the various pessimistic assumptions, the simulations show that the plastic strain in the copper shell is not exceeding 6.2% which is considerably lower than the strains the copper shell can withstand.*

SKB also emphasizes the fact that maximum equivalent plastic strain is located in a region with compressive stresses.


## 4.3. Review comments on SKB's analyses of the copper canister


### 4.3.1. General

External pressure caused by a swelling buffer is an important load scenario for the canisters in the repository as it may result in a common cause failure. SKB's creep analyses reported in [4] are thus important in verifying the mechanical integrity of the copper canister.

With respect to avoidance of creep rupture in the copper canister, it is necessary to show that load controlled scenarios will not be prolonged after emplacement of the canister in the repository. If this can be shown, there is a possibility not being fully dependent on SKB's creep model. If the mechanical loads on the copper canister can be regarded as deformation controlled, calculated creep strain should be more or less independent of the creep model.

Creep analyses of the copper canister should focus on creep development in the copper material from a global perspective. Local results at geometric discontinuities are mesh dependent and should be used with care in the verification the mechanical integrity of the copper canister.

The element mesh used in the analyses is discussed in both [4] and [5]. In chapter 12 in [4] it is written that: *Element mesh is rather fine but nevertheless it is too coarse in some regions, especially at the welds and regions with geometric discontinuities. A more refined mesh will probably increase the maximum stress and strain levels. Fortunately, the use of non-linear material properties (such as plasticity and creep) will decrease the sensitivity to the used mesh"*. It is judged that this conclusion is correct and that the present element meshes used in the analyses are sufficiently

refined to capture the global response of the structure. Results shown for the most loaded elements in [4] have to be handled with care as they are mesh dependent.

According to [4] and [5], it is beneficial that the highest equivalent creep strain and the highest equivalent plastic strain occur where the hydrostatic pressure is positive (compressive conditions). This conclusion should be correct as long as the loading is monotonic. However, even in a compressive state positive creep or plastic strain can develop and the material might be subjected to damage, see figure 4-7. Now, if for example the external pressure case is followed by an earthquake shear, the loading will not be monotonic and the material might locally be damaged and thereby not being able to carry changed stresses.
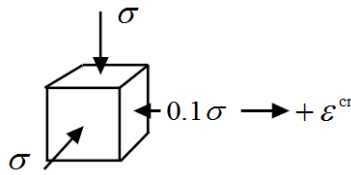


**Figure 4-7:** Example of a compressive multiaxial stress state where positive creep (or plastic) strain develops.

SKB's strategy in verifying avoidance of creep rupture in the copper canister relies on the possibility to extrapolate properties of the copper material to repository conditions based on creep test results and their creep model. As it is impossible to prove that a creep model is fully reliable for times beyond 100.000 years, a complementary structural verification would be valuable. A suggestion of an alternative verification strategy is given in section 4.3.4.

It is unclear how the tolerances of the axial gap between the copper lid and the steel lid have been calculated in TR-10-14 [11]. As most creep strain is accumulated in the copper lid region, it is important that relevant axial gap is assumed in the analyses of the copper canister.
As potential load controlled scenarios are most vulnerable for the mechanical integrity of the copper canister, it is important to have a continuous awareness for such load scenarios.

## 4.3.2. Review of 1399768 rev 2.0

The content in 1399768 rev 2.0 [4] comprises the content in 1399768 rev 1.0 [3]. Thus, the following review comments on [4] also cover the review of [3].

Given the conditions in [4] regarding geometry of canister components, axial and radial gap between insert and copper canister as well as temperature and loading evolution, the review finds calculated creep strains at 100.000 hours reliable from a global perspective. As the external pressure load case is judged to be deformation controlled, calculated creep strains at 100.000 hours should be more or less independent of creep model.

According to section 2.2.1 in [4], the axial gap between the steel lid and the copper lid is 3.1 mm. However, in the model this gap equals 2.15 mm. It is furthermore unclear how the tolerances of the axial gap between the copper lid and the steel lid are calculated in TR-10-14 [11]. The use of correct axial gap in the analysis is important as it influences the load controlled phase of the external pressure scenario for the top region of the copper canister.

In the analyses in [4], an initial radial gap of 1.57 mm between the insert and the copper cylinder is assumed. This corresponds to a concentric location of the insert with respect to the copper cylinder. In practice, however, it can be expected that the insert is eccentrically located as a result of the handling during the emplacement of the canister in the deposition hole. Thus, a case where the insert and the copper cylinder initially are in contact along an axial generatrix should be analysed. Furthermore, the maximum initial radial gap of 1.75 mm reported in TR-10-14 [11] should be assessed.

Based on a comparison of the results from the axisymmetric and the 3D analysis, [4] states that the use of the axisymmetric model is pessimistic. The reason according to [4] is that the axisymmetric model shows larger creep damage than the 3D model does. However, as long as it has not been shown that the 3D analysis gives the "true" answer, the use of the word pessimistic is not correct.

An internal pressure is applied in all analyses. From year 10, this pressure is kept constant at 0.5 MPa throughout the simulations, see figure 2-5 in [4]. External pressure in a dry deposition hole is applied from year 10 according to figure 2-3 in [4]. In the present analyses, the impact of the internal pressure can be neglected from year 10 as the external pressure will dominate. In recent years, it has been shown that saturation of the buffer can be delayed several thousands of years and thereby postponing the onset of external pressure. It is important to simulate such a scenario since the internal pressure load case is load controlled.

The effect of the difference in coefficient of thermal expansion between the copper canister and the insert is rather small according to [4]. It is judged that this conclusion is correct.

Results in chapter 10 in [4] show the response of the canister located in a dry deposition hole (slow resaturation of the buffer) with the dimensioning temperature evolution. Results from this simulation are also given in appendix 1. A comparison of the contour plots in chapter 10 and appendix 1 reveals that they differ. In chapter 10, the increment number at 100.000 years is 1587 while in appendix it is 1723. Furthermore is the file name *creep2_red_dim* used in chapter 10 while *isostat_JLH_creep_red_dim* is used in appendix 1. It is expected that correct results are shown in appendix 1 as the file name *isostat_JLH_creep_red_dim* corresponds with that given in section 9.1.1.

Among the four cases investigated in [4], largest amount of equivalent creep strain (CEEQ) at 100.000 years is developed in the canister placed in a dry deposition hole with long buffer resaturation time and a dimensioning temperature evolution. The higher temperature in this deposition hole (see figure 2-1 in [4]) results in a lower yield stress and a higher creep rate for the copper material. Figure 4-8 shows CEEQ in the friction stir weld region just before glacial period at 20.000 years and at 100.000 years [10]. As seen in the figure, the increase of the external pressure from 15 to 60 MPa has an impact on the CEEQ field. However, figure A1-13 in [4], which shows the evolution of CEEQ in the most loaded element in the copper shell, indicates that the CEEQ fields in figure 4-8 have stabilized. This indicates that, for the respective pressure level, the external pressure load scenario is deformation controlled, i.e. creep deformation of the copper canister is limited by the contact with the insert.
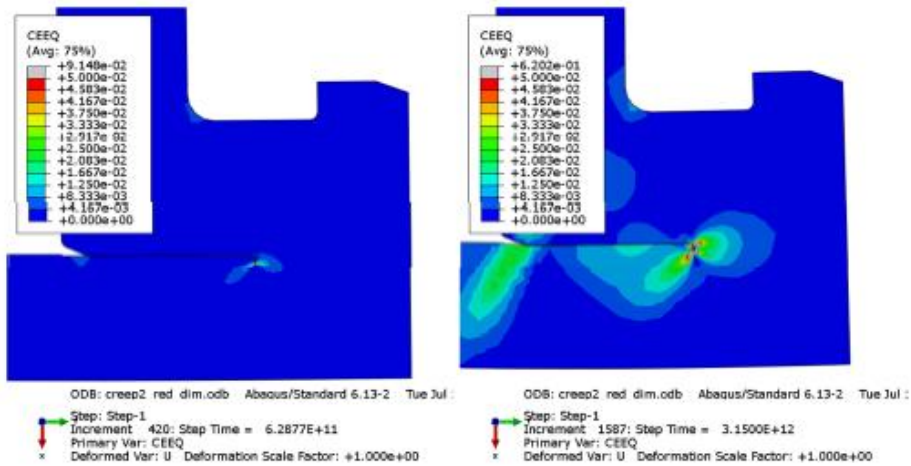
**Figure 4-8:** Equivalent creep strain (CEEQ) in the canister placed in a dry hole with a dimensioning temperature evolution just before 20.000 years (left figure) and at 100.000 years (right figure) [10]. The figure shows the copper lid / copper cylinder junction.

An alternative way of assessing SKB's creep analysis results could be as described in the following example. Assuming that the copper material is fully creep damaged when a certain level of equivalent creep strain (CEEQ) is exceeded, the contour plots in [4] can be used for a simplified verification of the mechanical integrity of the copper cylinder when subjected to external pressure. For a CEEQ limit of about 1.7 %, half of the thickness of the copper cylinder (opposed to bottom of copper lid) would be fully damaged at 100.000 years, see figure 4-9. According to figure 10-15 in [4], micro-cracks are oriented essentially perpendicular to the radial direction. With a limited equivalent creep strain of say 2 %, the copper cylinder will stay leakage tight, with some margin, for the external pressure load case after 100.000 years. Suggested assessment approach could give an idea of needed copper creep ductility for the respective load scenarios.
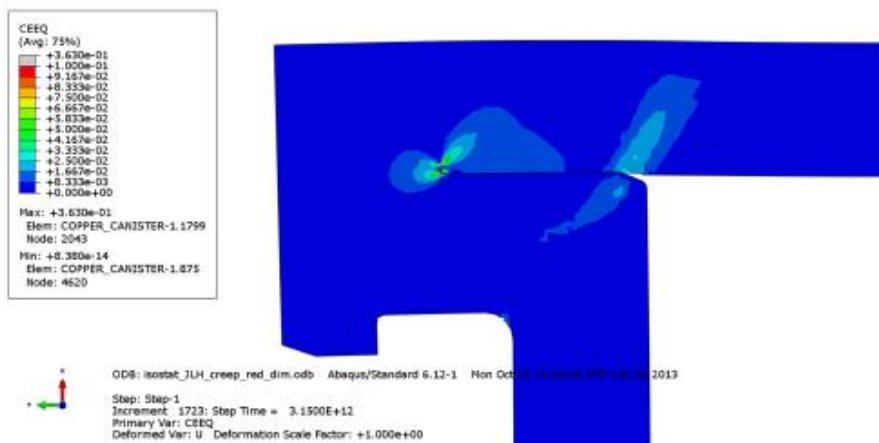


**Figure 4-9:** Equivalent creep strain (CEEQ) in the canister placed in a dry hole with a dimensioning temperature evolution at 100.000 years [4]. The figure shows the copper lid / copper cylinder junction.

It is expected that SKB's creep model has a minor influence on the amount of creep strain accumulated in the copper canister for deformation controlled scenarios. Regarding stress corrosion cracking, however, the creep model is of importance as it

controls the stress evolution. Figure 10-2 in [4] shows maximum principal stress in the friction stir weld region after 100.000 years for one of the cases. The stress level is still sufficiently high to make stress corrosion cracking possible. This stress level depends on the creep model.

Contour plots of equivalent creep strain are shown in [4]. Contour plots of creep strain at a component level (radial, hoop, axial) in the copper lid region and the copper bottom region would add value to the report.

### 4.3.3. Review of 1419643 rev 1.0

Two load cases with unfavourable pressure load are investigated in [5]. The analysis is elasto-plastic with rate dependent material properties. Creep is not considered. For load case 1, no contact is established between the insert and the copper shell. This fact points out a load controlled scenario. For load case 2, the gap is partly closed which reveals a mixture of load and deformation controlled scenario. SKB motivates their analyses by saying that the material model for the short duration analysis is based on a simplified elastic-plastic model using data from the creep model assuming a strain rate of $5 \cdot 10^{-3}$ 1/s. However, SKB's approach is not capable to capture the physics in the present load controlled scenarios as time and strain rate are fictive in their analysis. As load controlled scenarios cannot be excluded, creep should be considered in the analysis of the unfavourable pressure loads. In such an analysis, SKB's creep model described in [1, 2] could be utilized. Considering creep would give a better and an enhanced understanding of the physics of the copper shell deformation.

According to [10], the initial radial gap between the insert and the copper shell is 1.56 mm in the analyses. The axial gap between the steel lid and the copper lid is however not reported in [5]. It is important that the latter gap corresponds with the design premises as it has a substantial impact of local strain development in the copper shell top region.

The water pressure $p_{H_2O} = \rho g h$ contributes to the external pressure on the canister. In the analyses reported in [5], this 5 MPa pressure contribution is not considered.

The correctness of the shear stress 1.75 MPa that is transferred from the buffer to the copper shell has not been reviewed.

### 4.3.4. Alternative structural verification of the copper canister

In order to verify avoidance of creep rupture in the copper canister, it is necessary to show that load controlled scenarios will not be prolonged after emplacement of the canister in the repository. For the remaining deformation controlled scenarios, this review suggests that SKB in addition performs a complementary verification of the mechanical integrity of the copper canister with respect to creep rupture.

An alternative verification approach would be to determine the minimum creep ductility needed to maintain sufficient safety margins for the copper canister. This could be done by use of a continuum damage mechanics concept. In such an approach, total strain can be divided in one elastic and one plastic part where the latter represents both plastic and creep strain. This approximation/simplification should be possible to make for deformation controlled scenarios. By use of the

continuum damage mechanics concept, the impact of localized straining at geometric discontinuities can be taken into account in a more realistic way. For example, if plastic strain is limited to 1% in the analysis, regions in the finite element model reaching this level will stop carrying tension load. As the copper material gets fully damaged in regions with localized straining, damage continues to spread into adjacent regions until the damage development stops or the copper canister ruptures in the simulation. With this approach, needed level of copper ductility can be determined for the different deformation controlled scenarios which would be valuable in verifying avoidance of creep rupture in the copper canister.

# 5. Main review findings and recommendations to SSM

## 5.1. Main review findings

Main review findings are summarised as follows:

1. SKB claims that their creep model for Cu-OFP presented in [1, 2] is based on fundamental principles and that no fitted parameters are needed. According to SKB, this fact facilitates extrapolations to repository conditions with a time scale beyond 100.000 years. These statements must be questioned according to the following:
   - Some of the constants in the constitutive equations are fitted to test data.
   - $g_{rate}$ depends on creep rupture time used in the creep test.
   - Stage IV work hardening is taken into account in an indirect and non-fundamental way instead of being part of the model. The physical basis for using technological stress (instead of true stress) in the application of the creep model equations is not obvious. The fact that it, according to SKB, happens to be so when the model is applied on uniaxial creep data implies that the physics is not fully understood. The stress controls different deformation mechanisms. It must be questioned that the effect of stage IV work hardening has the same impact (by use of the technological stress) on both the climb and the glide deformation mechanism. Furthermore, it is unclear if the same correction of stress holds also for the multiaxial case.

2. A material model that is used to simulate creep in a structure for more than 100.000 years will always be questioned. Therefore, under such conditions main focus should be on the robustness of the application of the model. With respect to avoidance of creep rupture in the copper canister, it is necessary to show that load controlled scenarios will not be prolonged after emplacement of the canister in the repository. For the remaining deformation controlled scenarios, creep strains in the copper canister after 100.000 years should be possible to calculate by use of SKB's creep model.

3. SKB's creep model presented in [1, 2] is correctly implemented into ABAQUS by use of the user subroutine CREEP. The multiaxial stress state is taken into account according to approach B in [2]. Explicit integration is used in SKB's creep analyses [3, 4].

4. Given the conditions in [4] regarding geometry of canister components, axial and radial gap between insert and copper canister as well as temperature and loading evolutions, the review finds calculated creep strains at 100.000 hours reliable from a global perspective. As the external pressure load case is judged to be deformation controlled, calculated creep strains at 100.000 hours should be more or less independent of creep model used.

5. As load controlled scenarios cannot be excluded in [5], creep should be considered in the analysis of the unfavourable pressure loads. In such an analysis, SKB's creep model described in [1, 2] could be utilized. Considering creep would give a better and an enhanced understanding of the physics of the copper shell deformation when the canister is subjected to unfavourable pressure loads.

6. An internal pressure is applied in all analyses in [4]. From year 10, this pressure is kept constant at 0.5 MPa throughout the simulations, see figure 2-5 in [4]. External pressure in a dry deposition hole is applied from year 10 according to figure 2-3 in [4]. In the present analyses, the impact of the internal pressure can be neglected from year 10 as the external pressure will dominate. In recent years, it has been shown that saturation of the buffer can be delayed several thousands of years and thereby postponing the onset of external pressure. It is important to simulate such a scenario as the internal pressure load case is load controlled.

7. Use of correct axial gap between the steel lid and the copper lid in the analysis of the copper shell is important as it influences the load controlled phase of the external pressure scenario for the top region of the copper canister. According to section 2.2.1 in [4], the axial gap is 3.1 mm. However, in the model this gap equals 2.15 mm. In [5] the axial gap is not given. It is furthermore unclear how the tolerances of the axial gap between the copper lid and the steel lid are calculated in TR-10-14 [11]. It is important that relevant axial gap is assumed in the creep analyses of the copper canister.

8. In the analyses in [4], a concentric location of the insert with respect to the copper cylinder is assumed. In practice, however, it can be expected that the insert is eccentrically located as a result of the handling during the emplacement of the canister in the deposition hole. Thus, a case where the insert and the copper cylinder initially are in contact along an axial generatrix should be analysed. Furthermore, the maximum initial radial gap of 1.75 mm reported in TR-10-14 [11] should be assessed.

9. An alternative way of assessing SKB's creep analysis results could be as described in the following example. Assuming that the copper material is fully creep damaged when a certain level of equivalent creep strain is exceeded, the contour plots in [4] can be used for a simplified verification of the mechanical integrity of the copper cylinder when subjected to external pressure. With a limitation of the equivalent creep strain to say 2 %, the copper cylinder will stay leakage tight, with some margin, for the external pressure load case after 100.000 years. Suggested assessment approach could give an idea of needed copper creep ductility for the respective load scenarios.

10. An alternative approach, in verifying avoidance of creep rupture in the copper canister for deformation controlled scenarios, would be to determine the minimum creep ductility needed to maintain sufficient safety margins. This could be done by use of a continuum damage mechanics concept.

11. SKB's creep model is of importance in the assessment of stress corrosion cracking in the copper canister. The creep model influences relaxation of stresses under deformation controlled conditions. The faster the stresses relax, the shorter the time is when conditions for stress corrosion cracking to happen are fulfilled.

12. As potential load controlled scenarios are most vulnerable to the mechanical integrity of the copper canister, it is important to have a continuous awareness for such loading scenarios.

## 5.2. Recommendations to SSM

Recommendations to SSM are summarised as follows:

1. It is necessary for SKB to show that load controlled scenarios will not be prolonged after emplacement of the canister in the repository.

2. SKB's copper creep model can be used for analysis of deformation controlled scenarios. The creep model implemented into ABAQUS can be used in such analyses.

3. SKB has to consider relevant radial and axial gap between the insert and the copper canister in their analyses of the copper canister.

4. SKB should determine minimum required copper creep ductility for the different load scenarios. This information could give confidence to the structural verification of the copper canister.

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

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