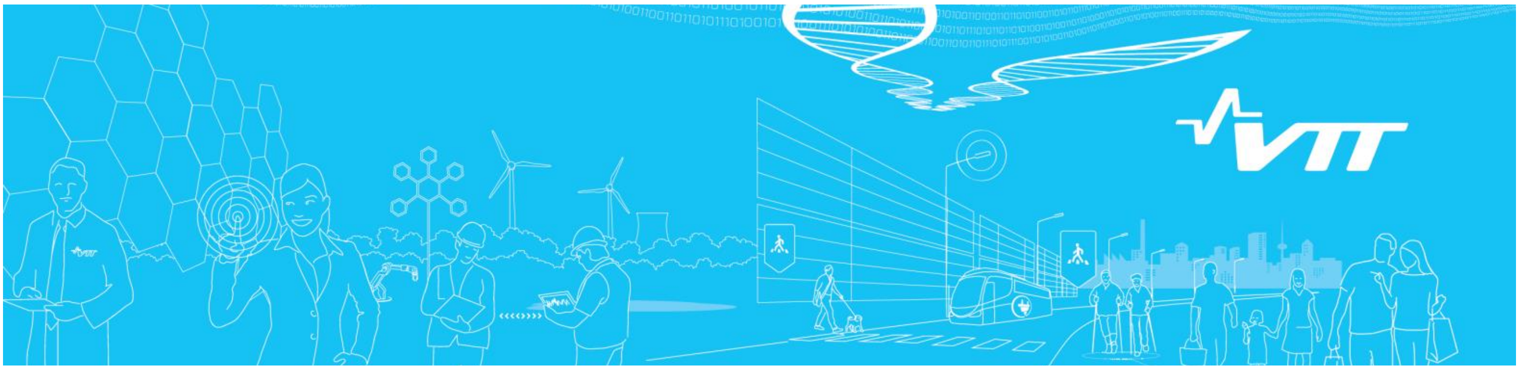

RESEARCH REPORT

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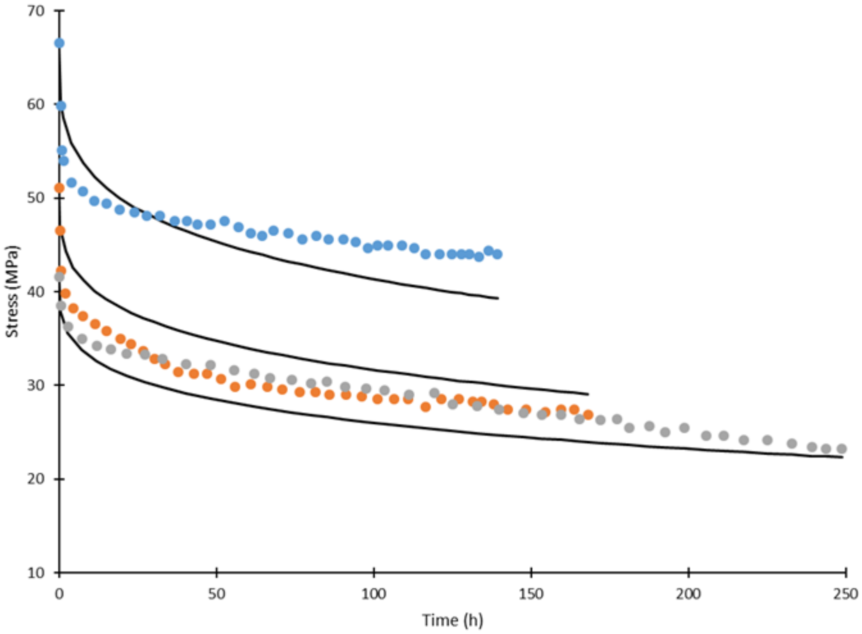

Experimentally verified model based predictions for integrity of copper overpack – Annual report 2017

Authors: Juhani Rantala, Rami Pohja, Pertti Auerkari

Confidentiality: Public

Report's title Experimentally verified model based predictions for integrity of copper overpack – Annual report 2017	
Customer, contact person, address KYT 2018	**Order reference** Dnro KYT 11/2017
Project name PRECO2017	**Project number/Short name** 114307
Author(s) Juhani Rantala, Rami Pohja, Pertti Auerkari	**Pages** 17 p.
Keywords creep, relaxation, copper, repository, life	**Report identification code** VTT-R-01499-18

Summary

In this annual report of the project "Experimentally verified model based predictions for integrity of copper overpack" (PRECO2017) the status of the experimental and modelling activities and results has been summarised up to the end of January 2018. The testing program and related activities have been continued and partly modified to support the assessment and verification of the long term integrity of the protective copper (Cu-OFP) overpack of the canister.

To consider more discontinuous uniaxial behaviour, creep tests with stepwise increasing load and stress dips were conducted, and the results were compared with those from normal constant load creep testing. In general, the transients especially from stepwise increase in loading can consume a part of the deformation capacity and shorten creep (or creep-fatigue) life.

The relaxation testing programme has continued with cyclic relaxation tests. The relaxation testing aims at developing a relaxation model for the FE calculation. It is expected that with the relaxation model the stress and strain distributions will be different when compared to the FE results with a traditional creep model only.

The results of continuing multiaxial (notched bar) creep testing program suggest notch weakening, or life reduction by tensile multiaxiality. The 10.000h testing of a CT specimen from the modified welding (FSW) process with argon protective atmosphere is complete and the specimen is going to be investigated by metallography to study the behaviour of the oxide particles.

Confidentiality	Public

Espoo, 23.3.2018

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Preface

This annual report of the project “Experimentally verified model based predictions for integrity of copper overpack” (PRECO2017) includes and summarises the experimental and modelling activities as well as the results and status of the project up to the end of January 2018. The project is a part of the Finnish national research program [1] on nuclear waste management, 2015-2018 (KYT2018). The research has been carried out by Juhani Rantala (Project manager and experimental work), Rami Pohja (relaxation testing and modelling) and Pertti Auerkari (Senior Principal Scientist).

The financial support and other guidance by the KYT2018 program are gratefully acknowledged.

Espoo, March 2018

Authors

Contents

1. Introduction

In the repository for spent fuel, the temperature of the canister surface is expected to peak at about 75-90°C before the first hundred years [2], with gradual cooling to the level of the bedrock environment (Figure 1). The top temperature will depend on the rate of wetting in individual disposal holes, which might vary a lot, depending on the flow of water in the bedrock. The development of the swelling pressure in bentonite surrounding the canisters will also depend on the rate of wetting.

For the protective copper (Cu-OFP) overpack of the canister, creep and corrosion are included as potential damage mechanisms under the repository conditions [2]. Although relatively mild in usual engineering terms, the repository conditions imply a technical challenge to life estimation for ensuring the integrity of the overpack. This is because of the discrepancy between the longest achievable laboratory tests (decades) compared to the design life that is of the order of glaciation cycles (about 10^5 years) to reduce the radioactivity of the contents close to the background level. The time difference by a factor of almost 10^4 also exceeds the usual range of extrapolation from laboratory experiments to real service conditions in most (or any) comparable engineering applications.

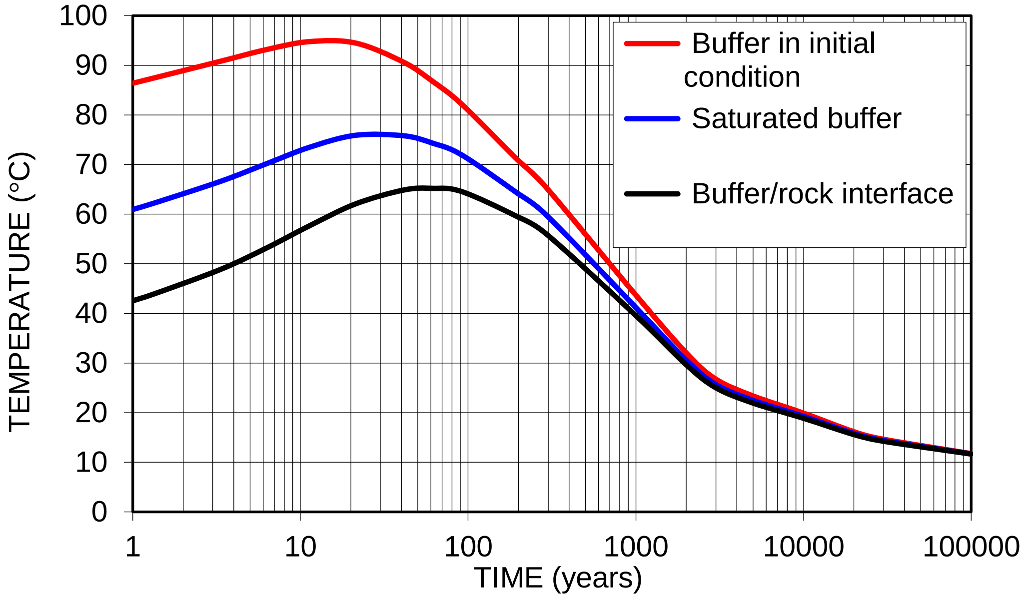

Figure 1. Predicted temperature evolution at the canister surface for EPR fuel [2]; the red curve assumes dry environment with a 10 mm gap around the canister.

2. Materials and methods

OFP copper for the experiments including friction stir welded (FSW) material from a full scale section was provided by SSM/SKI (Sweden) and the Swedish program for canister studies. The CT-specimen CS3 was removed from a cylindrical part (material code T31) and a cover lid (lock TX 82) welded together and marked KL 059 on the outer surface of the lid. Chemical analysis, short term mechanical properties and initial microstructures of the materials have been reported in [2].

For relaxation experiments, a 50 mm thick block of OFP copper plate with a reference code X579 was supplied by Posiva Oy.

For testing of the strength of the oxide particle zone, Cu-OFP blanks from FSW-welded lid 108 were supplied by Posiva Oy for manufacturing of CT specimens from an updated type of FSW material.

Metallography using light optical (LOM) and scanning electron microscopy (SEM) has been applied for the test specimens after testing. For load setting and interpretation of the results in mechanical testing, life modelling with extended parametric and other techniques has been applied.

For creep modelling, the combined Wilshire and LCSP models have been applied and further developed [3, 4] to support robust FE analyses under non-homogenous stress and strain fields.

3. Uniaxial creep behaviour with and without transients

The uniaxial creep test of Cu-OFP at 120 MPa and 152°C has been running for more than 129.200 hours (14.7 years) and has reached the minimum creep rate. This test will not be interrupted anymore for inspections before rupture, because previous tests have shown that every interruption adds a new primary creep component to the creep curve. This is expected to consume a part of the deformation capacity and shorten the creep life. The other long-running test at 70 MPa 200°C has been running for 85.300h.

According to an unpublished reference, slow loading in steps in a uniaxial test can increase the rupture strain compared to normal single step loading. This effect has been studied with a short test series by using CT specimens for Cu-OFP, already reported in [5]. In Figure 2 the initial part and in Figure 3 the full curves of the load line displacement of three CT tests are shown where the blue curve is the response in a single step test where the full load is applied in a normal manner. This can be compared to the two other curves where the load was increased to 69%, 84% and 100% of the full load in steps of 1.5 h (brown curve) and one week (green curve). Loading in multiple steps results in higher deformation than normal single-step loading, while a longer time between steps will increase the deformation. The results need to be verified by additional testing, but could mean that the gradual increase of pressure in the repository may lead to higher strain than rapid loading to the equivalent stress level.

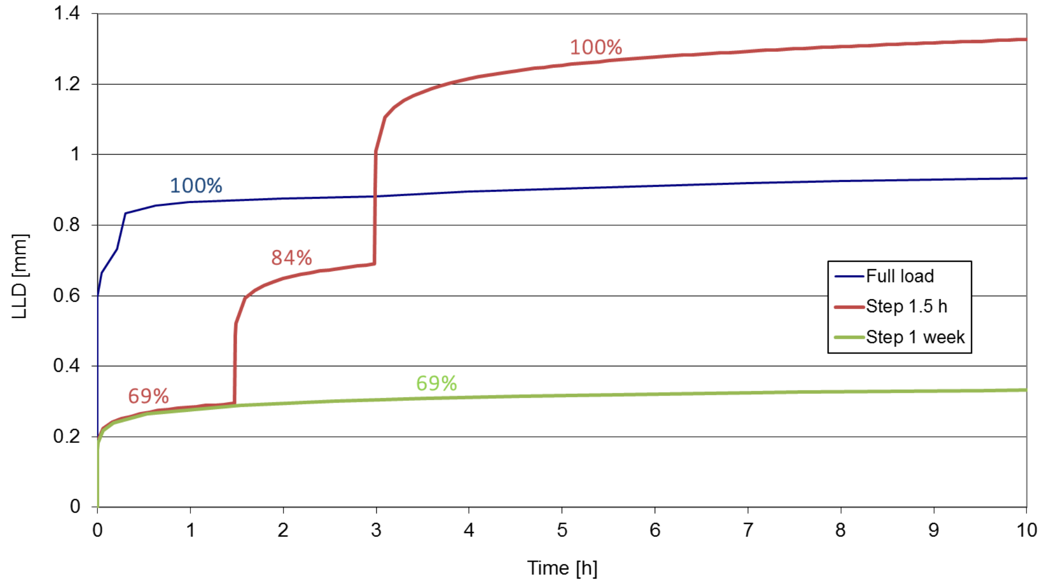

Figure 2. The initial part of the load line displacement curves of three Cu-OFP CT-specimens loaded to the same reference stress of 60 MPa at 175°C in steps.

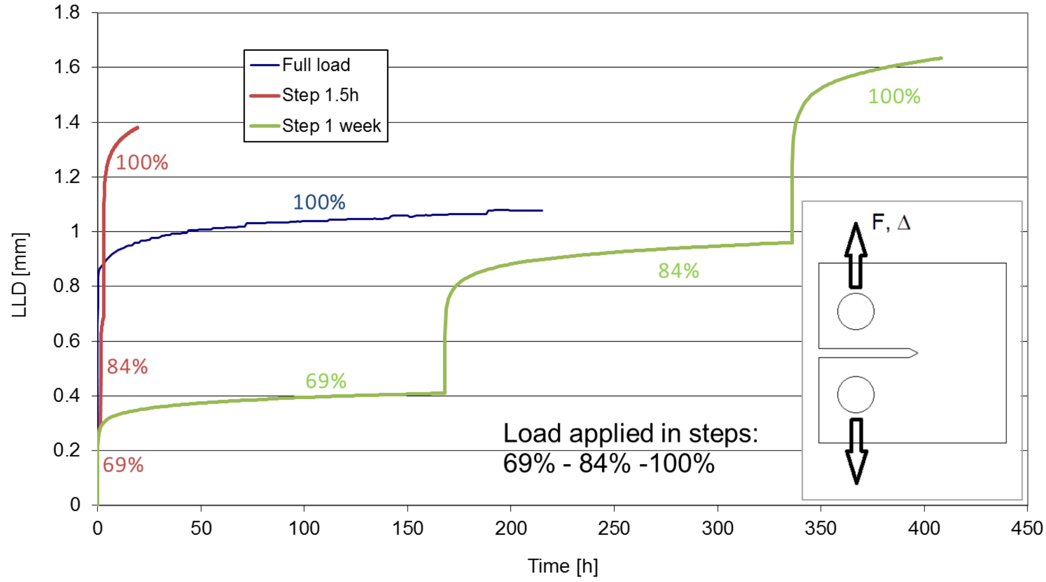

Figure 3. Load line displacement of three Cu-OFP CT-specimens loaded to the same reference stress of 60 MPa at 175°C in steps.

Repeated unloading and reloading to the same load level leads to additional strain increments as shown in Figure 4 (blue curve, test y492) for cross-weld uniaxial specimens from the EB-welded Cu-OFP lid XK10. The additional short primary phases after reloadings did not produce essentially higher cumulative strain than the corresponding continuous creep test (brown curve, test y498). Nevertheless, the repeated short reloading cycles appear to increase the cumulative strain, while in extended intermediate creep periods the strain rates decrease to values below those of the continuous creep test. More tests are needed to confirm the effects also to creep life. Note that for this comparison in Figure 4 the strain values of the test y498 had been increased by 0.519% to shift the curve to the same point as in test y492 before the first unloading. Variation of this magnitude in the initial plastic strain is common in testing of Cu-OFP.

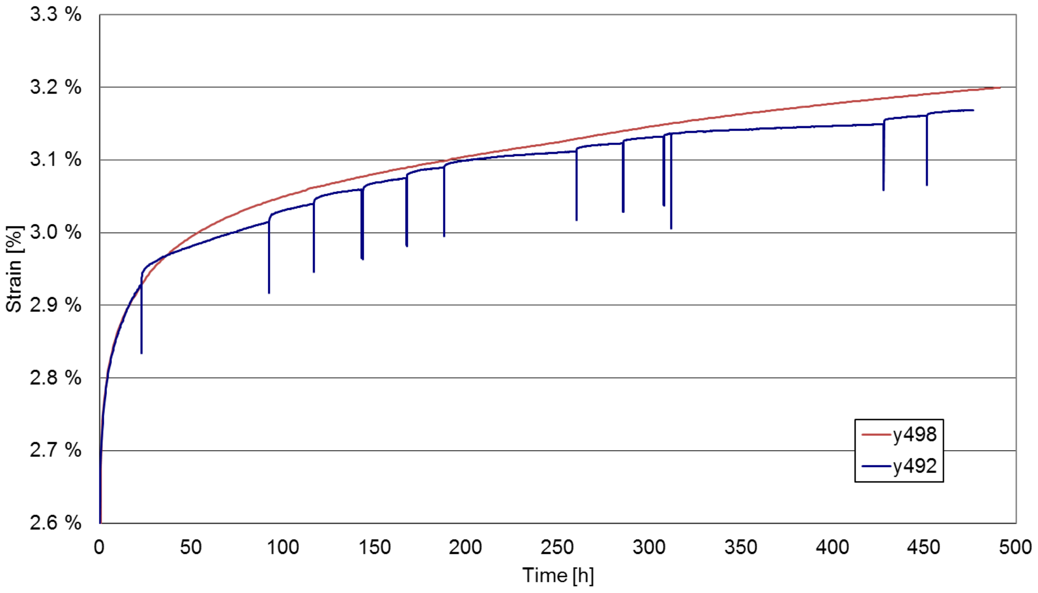

Figure 4. Strain curve with repeated unloading and loading to 75 MPa at 125°C for EB-welded Cu-OFP lid XK10, compared to a continuous creep test at the same conditions.

The effect of small stress variations (<0.2%) due to re-balancing of the lever arm of the creep machines is shown in Figure 5. In this creep test the strain grew to almost 45% and the large elongation of the specimen made several lever arm re-balancing operations necessary, resulting in acceleration of creep. This effect seems to happen only in Cu-OFP where typically large fracture strains are measured. In comparison for some reason this effect does not manifest itself in Cu-OFHC even if the load is removed completely and brought back to the original value as shown in Figure 6. The vertical lines correspond to the elastic strain. It is typical for Cu-OFHC that fracture takes place with very small strain levels with hardly any strain hardening.

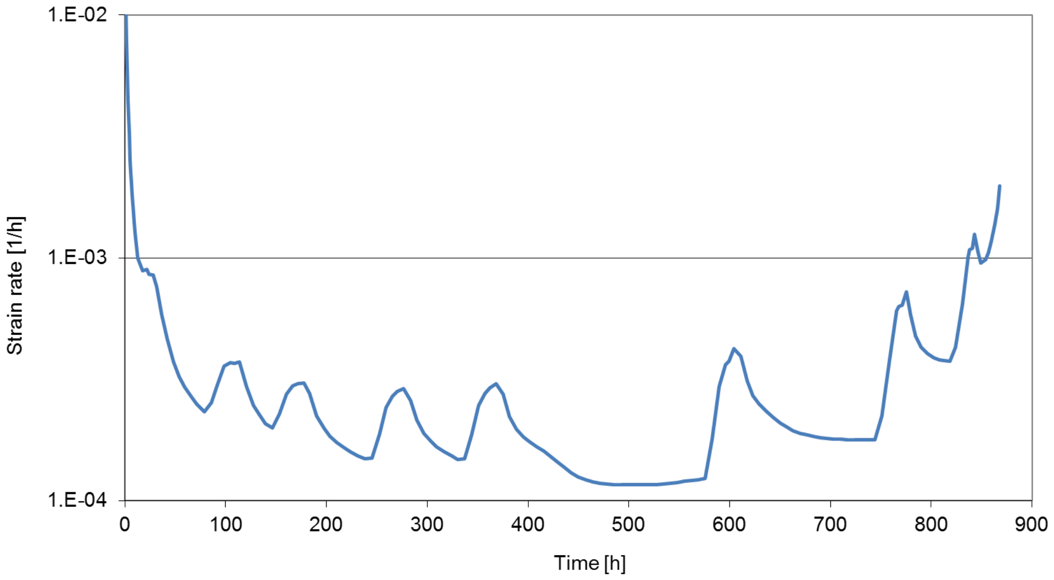

Figure 5. The effect of lever arm balancing on the strain rate in Cu-OFP at 135 MPa 175°C.

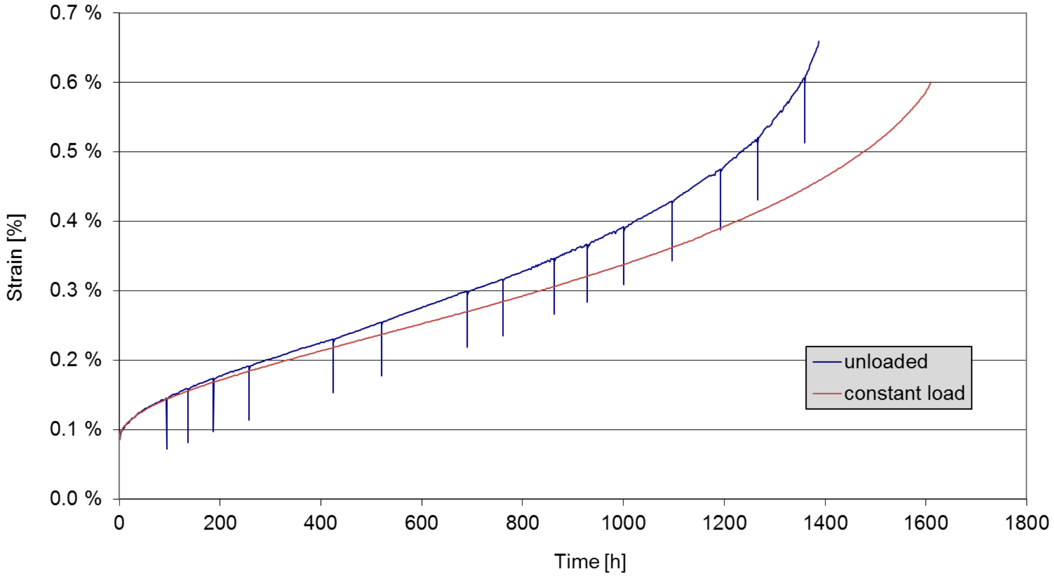

Figure 6. Strain curves from a continuous and unloaded test for Cu-OFHC.

The strange load history effect of Figure 7 reported in [6] where a tensile copper creep specimen was subjected to a constant loading rate on 0.238 MPa/h at 125°C is now believed to be a false result as the behaviour could not be repeated at VTT. It does not look plausible that after interrupting the strain would increase at a very low stress (the blue curve) as also verified experimentally in [5].

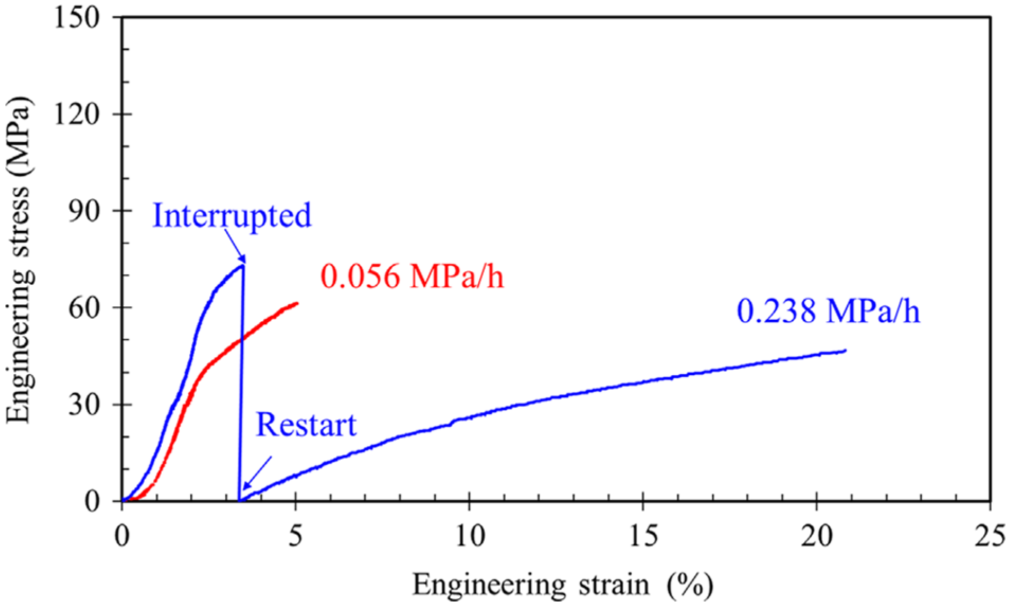

Figure 7. Stress-strain curve (in blue) of a tensile copper specimen loaded at constant loading rate, then unloaded and continued at the same loading rate [6].

4. Relaxation testing

An attempt has been made to build a stress relaxation model based on the Kohlrausch relaxation model [7] by defining the α and β terms in a more specific way:

$$\sigma = \sigma_0 \cdot \exp\left(-\alpha \cdot t^{\beta}\right) \tag{1}$$

where

$$\alpha = \left(\frac{\ln(T)}{a}\right) \cdot e^{\frac{-Q}{RT}} \tag{2}$$

and

$$\beta = \left(\frac{\log(\sigma_0)}{\sigma_{UTS}}\right) \cdot b \tag{3}$$

As defined in Equations (2) and (3), the α parameter carries an Arrhenius type temperature dependence and parameter β carries a stress dependence.

To assess the model performance, the model predictions were compared against the experimental data which was earlier produced at VTT. The data set included tests which were performed with both servohydraulic testing machine and pneumatic loading machine. Figure 8 shows the test data produced by the servohydraulic machine and Figure 9 shows the test data produced by the pneumatic machine. As can be seen in Figures Figure 8 and Figure 9, the modelled curves are in relatively good agreement with the test data.

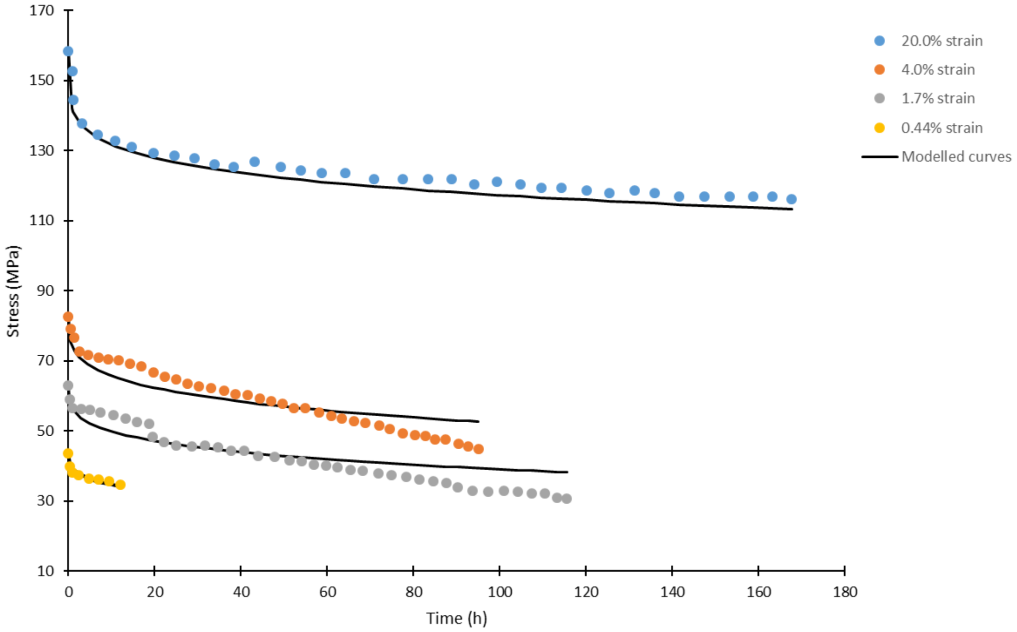

Figure 8. Stress relaxation tests (servohydraulic machine) for Cu-OFP at 80°C and the modelled stress relaxation curves.

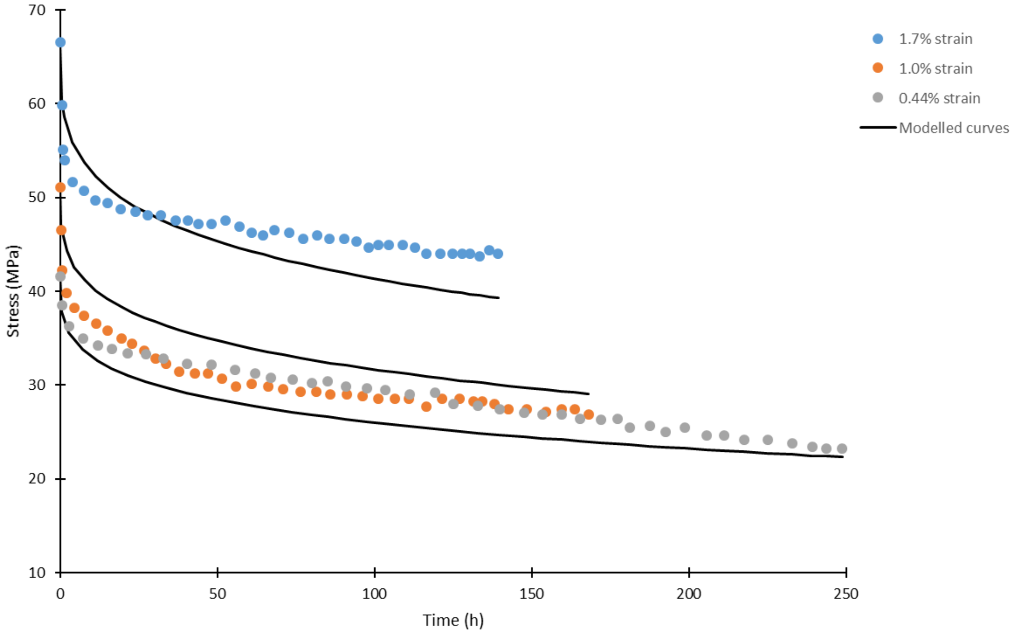

Figure 9. Stress relaxation tests (pneumatic machine) for Cu-OFP at 80°C and the modelled stress relaxation curves.

In 2017 also cyclic relaxation tests were performed for Cu-OFP. Several stress relaxation periods of 70 to 200 h under tensile stress were applied in these tests. The strain was decreased to zero and increased back to the peak strain between these relaxation periods as shown in Figure 10. First, a test with 5 stress relaxation periods was performed at 80°C with 0.6% strain in tension. After that, a test with 3 stress relaxation periods was performed at 80°C with 0.44% strain in tension. Figure 11 shows the stress ratio, i.e. the relaxed stress divided by the peak stress, as a function of time in test at 80°C with 0.6% strain in tension. It can be clearly seen that the amount of relaxed stress decreased as the amount of reloads increased in the test. It can also be seen in Figure 11 that the difference in the peak stresses at the beginning of the stress relaxation periods remained within about 2 MPa in the test.

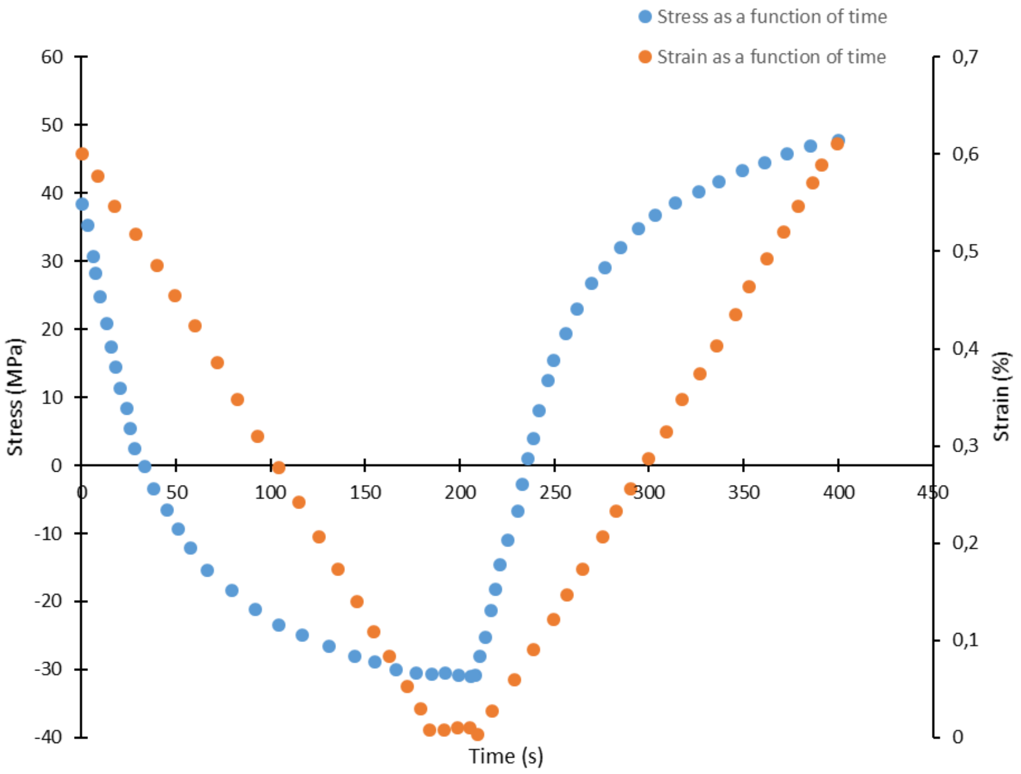

Figure 10. The reload after first (70 h) relaxation period in the cyclic stress relaxation test at 80°C with 0.6% strain in tension.

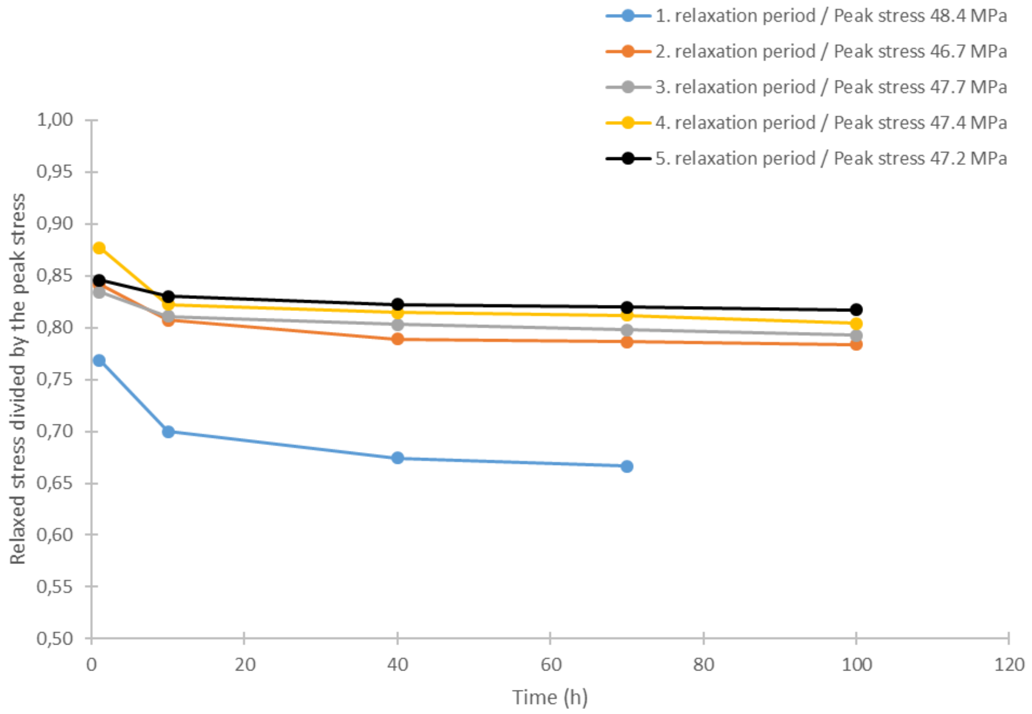

Figure 11. The stress ratio, i.e. the relaxed stress divided by the peak stress, as a function of time in test at 80°C with 0.6% strain in tension.

In the cyclic stress relaxation test at 80°C with 0.44% strain in tension, the amount of relaxed stress did not decrease in the third relaxation period in relation to the previous relaxation periods, as can be seen in Figure 12. The reason for this was the increased temperature during the test. At about 80 h of the relaxation period, an air conditioning failure occurred in the VTT creep laboratory, causing the temperature increase of about 2.5°C in the test specimen gauge section. This incident had a clear effect on the stress relaxation curve as shown in Figure 13. Thus, the test was terminated at about 170 h of the relaxation period. The stress relaxation test is a very sensitive experiment and therefore the temperature control is important for the reliable results. Other than that particular incident, the temperature remained within ±0.15°C of the set temperature (80°C), which was considered sufficient for the experiments.

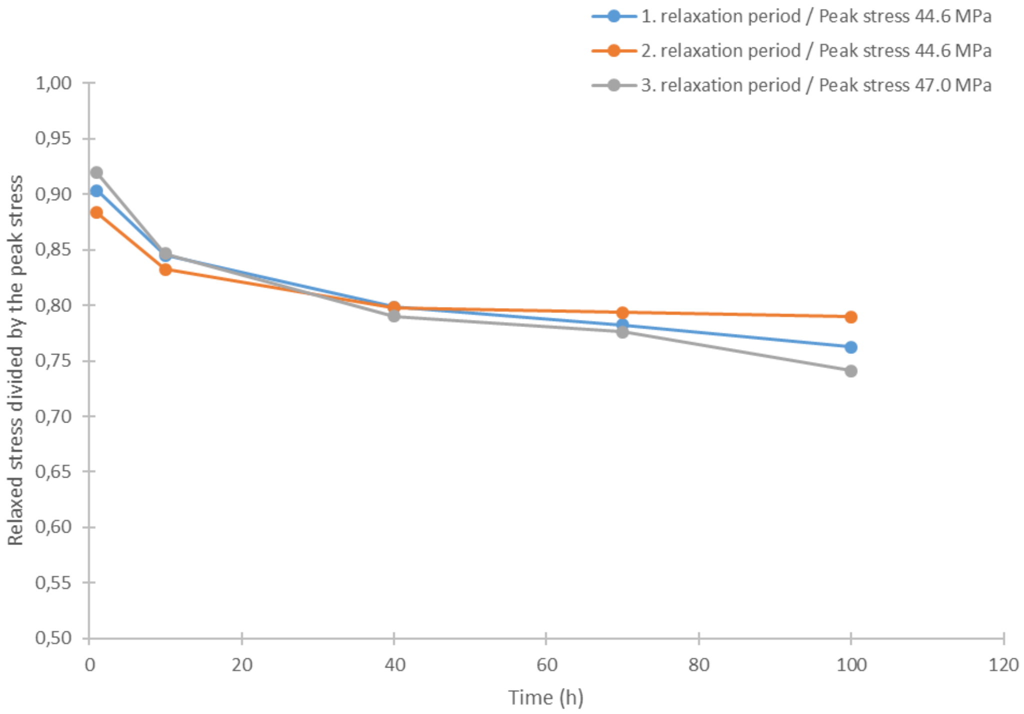

Figure 12. The stress ratio, i.e. the relaxed stress divided by the peak stress, as a function of time in test at 80°C with 0.44% strain in tension.

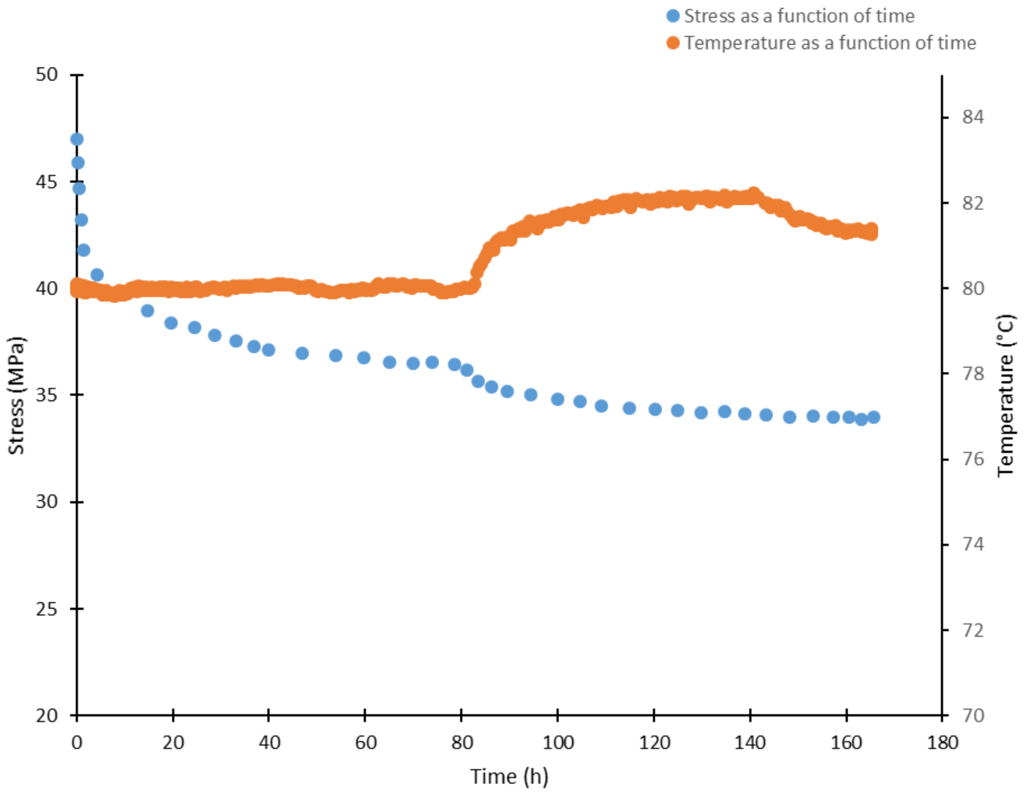

Figure 13. The stress and temperature curves in the cyclic stress relaxation test (T=80°C/ε=0.44%) for the third relaxation period.

The future objective is to expand the experiments to lower temperatures (60-40°C) to better understand the temperature dependence of the stress relaxation behaviour and to allow for calculation of stresses and strains in the case when the canister temperature is increasing very slowly while the copper material relaxes. This experimental validation is considered necessary for stress relaxation model verification and for implementing the modelled relaxation behaviour to multi-axial cases and finite element analysis (FEA) of the canister (overpack) details.

5. Notched bar tests and effects of multiaxiality

The status of the continuing test series of notched Cu-OFP bars is summarised in Figure 14, with one test running (indicated by an arrow). The continuous red curve represents the uniaxial mean data and the dashed curve is the corresponding line for the notched bar results for a strength reduction factor SRF = 0.78 to account for the effects of multiaxiality. This factor would normalise the available notched bar test data to the uniaxial level, when using von Mises stress as the equivalent stress for the notched bars according to the ESIS Code of Practice [8]. This means that (tensile) multiaxiality is shortening life and resulting in corresponding notch weakening as 22% reduction in creep strength. Omitting the actual stress state and using the nominal stress, or load divided by the net section area (Figure 15), would overly optimistically imply “notch strengthening” by a factor of 1.3 in comparison to uniaxial data.

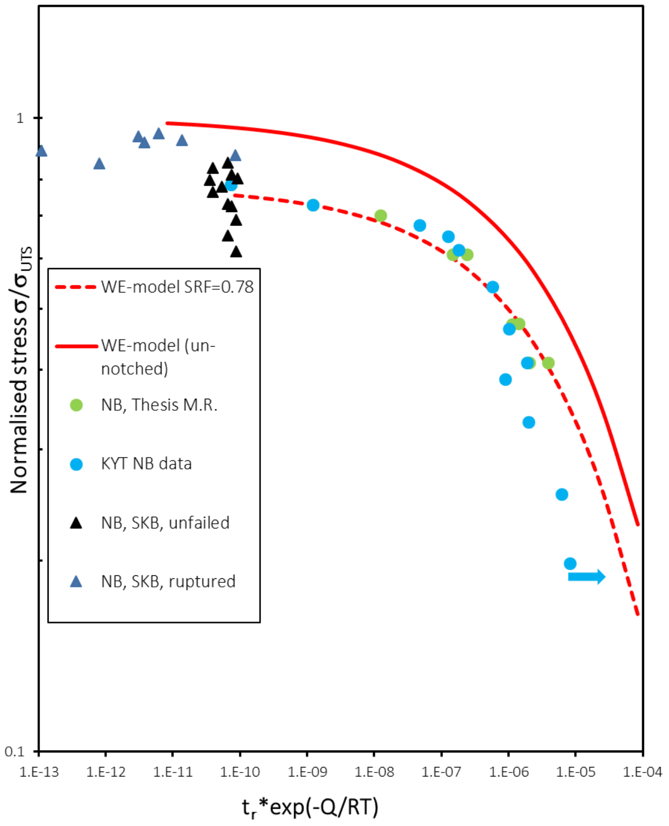

Figure 14. Notched bar (NB) test results: normalised stress vs time-temperature parameter; SRF = strength reduction factor, Q = activation energy.

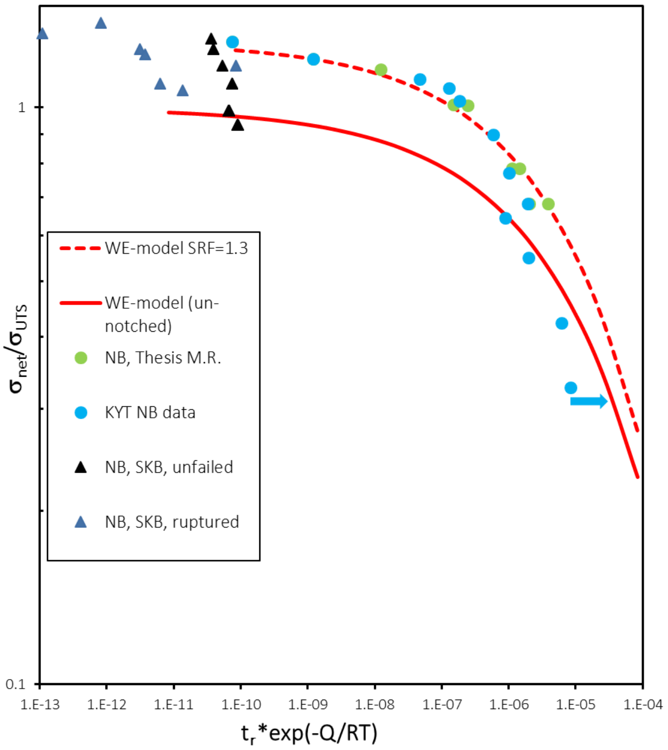

Figure 15. Notched bar test results plotted by using net section stress.

6. Oxide particle zone of the new welds

The 10.000h exposure of a friction stir weld, welded in argon, is complete and the sample is currently being studied by metallography in order to show differences with the results of the previous report [5] where the oxide particle zone after a 1000h exposure was shown. The load line displacement curve of the 10.000 hour test is shown in Figure 16 where repeated primary creep is seen at about 500h after the test had been restarted after a temperature controller failure which caused the temperature to drop. Towards the end of the test, failure of the laboratory air conditioning unit caused some pseudo strain due to increased room temperature, which had also an effect on the relaxation test programme as shown in Figure 13.

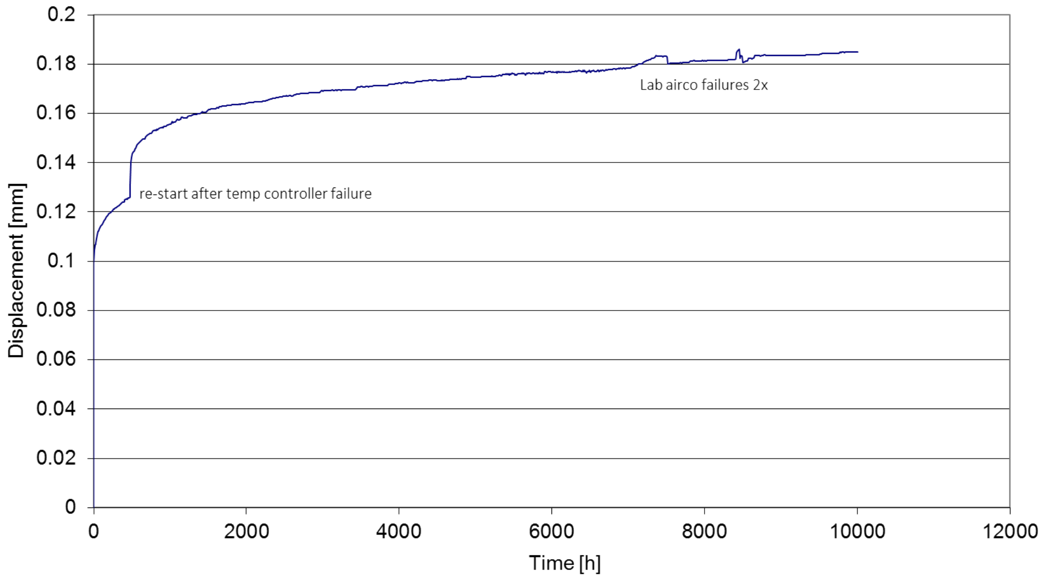

Figure 16. Load line displacement curve of the FSW CT-specimen tested at 175°C at a reference stress of 60MPa for 10.000 hours.

7. Conclusions

In this annual report of the project “Experimentally verified model based predictions for integrity of copper overpack” (PRECO2017) the status of the experimental and modelling activities and results has been summarised up to the end of January 2018. The testing program and related activities have been continued and partly modified to support the assessment and verification of the long term integrity of the protective copper (Cu-OFP) overpack of the canister.

In case of uniaxial creep testing, the longest testing time has exceeded 129.200 hours (14.7 years), and this particular specimen will be allowed to run to failure without further intermediate interruptions. To also consider more discontinuous uniaxial behaviour, creep tests with stepwise increasing load and stress dips were conducted, and the results were compared with those from normal constant load creep testing. In general, the transients especially from stepwise increase in loading can consume a part of the deformation capacity and shorten creep (or creep-fatigue) life. Such load history dependence could be relevant with slow or stepwise increase of hydrostatic pressure in the repository and thereby increasing stress experienced by the canister and its overpack.

The relaxation testing programme has continued with repeated relaxation tests where after one relaxation period the strain is forced back to zero and then brought back to the original value. This has resulted in increased stress levels after each cycle. In 2018 most of the testing effort will concentrate on relaxation testing in order to have a relaxation model available for the FE calculation. It is expected that with the relaxation model the stress and strain distributions will be different when compared to the FE results with a traditional creep model only.

The results of continuing multiaxial (notched bar) creep testing program suggest notch weakening, or life reduction by tensile multiaxiality. The 10.000h testing of a CT specimen from the modified welding (FSW) process with argon protective atmosphere is complete and the specimen is going to be investigated by metallography to study the behaviour of the oxide particles.

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