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## Creep of OFHC and silver copper at simulated final repository canister-service conditions

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September 1991

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# CREEP OF OFHC AND SILVER COPPER AT SIMULATED FINAL REPOSITORY CANISTER-SERVICE CONDITIONS

## ABSTRACT

Results of high-resolution creep rate measurements are described for estimating very long term creep life of copper and silver alloyed copper at room temperature and at stresses approaching the expected service conditions of final repository canisters. The aim was to assess the limiting service stress levels for potential canister wall materials.

The 0.1 % silver alloyed copper showed minimum creep rates of $10^{-9}$ to $10^{-10}$ 1/h, corresponding to 1 % strain in about 1000 to 10 000 years, at room temperature and uniaxial stress level of 50 to 75 MPa. The predicted time to 1 % strain, when extrapolated from literature data, was at least one order of magnitude shorter. From the results of the present work, the 1 % creep life for OFHC copper was at most a few hundreds of years at 50 MPa stress level.

The technique developed and used in this work for measuring very low strain rates appears useful for assessing low temperature creep life of practical structures essentially without accelerating the test from the service conditions.

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# FOREWORD

This report summarizes the results of creep rate measurements for estimating the very long term creep life of copper and silver alloyed copper, aimed to assess the limiting service stress levels for final repository canister wall materials. The work has been performed at the Metals Laboratory of the Technical Research Centre of Finland (VTT) and it has been financed by Teollisuuden Voima Oy (TVO), Finland and Svenska Kärnbränslehantering AB (SKB), Sweden. The test materials were supplied by Outokumpu Copper, Finland.

The contact persons have been Mr. Jukka-Pekka Salo (TVO), Mr. Lars Werme (SKB) and Mr. Pertti Auerkari (VTT).

# 1 INTRODUCTION

Pure or low alloyed coppers are considered as candidate materials for final repository canisters. However, these materials may be prone to creep deformation at relatively low stress (at or below 50 MPa) and temperature (20 - 100 °C) levels, when the design life is very long (10 000 years or more). This conclusion is based on a previous analysis of data from short-term accelerated tests, where stresses or temperatures have been considerably higher than in actual service (Auerkari and Sandlin, 1988).

When extrapolations from short term creep tests (typically up to one year) to very long term service (usually up to 30 years, but in this case far beyond) are attempted, there is a danger of accumulating errors that are difficult to estimate and correct. Since in the present case the extrapolation would extend at least over 4 to 5 orders of magnitude in time, the errors from the test acceleration and extrapolation could be unacceptably large. The purpose of this work is to obtain creep life estimates for silver alloyed and oxygen-free high conductivity (OFHC) coppers from direct strain and strain rate measurements, essentially without the traditional test acceleration. The goal was set to strain rates down to $10^{-10}$ 1/h, corresponding approximately 1 % linear strain in 10 000 years. The approach inherently assumes that no cracking intervenes before attaining higher creep strains than 1 %.

The appropriate stress levels leading to such low creep rates at room temperature were to be set for OFHC (oxygen free high conductivity) copper and silver alloyed copper materials of this programme. At these stress levels uninterrupted tests for about 8 000 hours of maximum testing time were to be performed, to establish the actual strain rates at realistic service stress levels (about 50 MPa).

This report discusses the results of the test programme and also in short the likely acceptable design stress levels of the candidate canister materials.

## 2 MATERIALS AND TESTING PROCEDURES

The test materials were delivered as round bars by Outokumpu Copper, and included two types of OFHC copper (approx. 5 % and 15 % cold work) and two types of silver alloyed copper (also approx. 5 % and 15 % cold work).

The chemical compositions of the test materials according to the supplier's certificates are shown in Table 1. The mechanical properties of the materials according to same certificates are shown in Table 2. In both tables, as well as later, CuAg or CuAg0.1 means the silver alloyed copper of this work. From Table 2 it is seen that the strength and hardness of the 15 % cold worked OFHC copper are clearly higher than those of the 5 % cold worked OFHC copper, but comparable to those of the Ag alloyed coppers. Table 2 also shows the measured hardness from the specimen heads after completing the experimental programme.

All tests were performed in lever type constant load test machines, but due to very small strains the tests can also be regarded constant stress tests with an inaccuracy of less than 0.01%. One single specimen constant load creep testing (Mayes) machine for the 5 % cold worked silver alloyed copper and one constant load (Distington) machine for four specimens, one of each material type of this programme, were used for creep testing of the materials. Two types of 8 mm specimens, depending on the testing machine, were machined to dimensions shown in Fig. 1 of Appendix 1. The longer specimen was used in the single specimen machine. Care was taken in machining to avoid additional cold working of the material, and to keep the diameter as constant as possible over the specimen shaft region; after machining the specimens were inspected and the actual diameter to within ± 0.005 mm was used in later analysis.

The masses used for loading were weighed to an inaccuracy of 0.1 g, so that the inaccuracy of the initial stress was determined essentially by the errors in testing machine lever ratio and specimen geometry. The estimated error in the initial stress was estimated to remain below 0.1 % of the nominal stress in the whole stress range of the tests. Loading was applied manually by lowering the weights to full load in a time period of approximately 30 s to one minute, using a screw driven weight support.

The initial stress levels were selected to provide roughly the expected target strain rates. A starting point was 51.5 MPa stress level, which however was too high for the OFHC copper with 5 % cold work, and therefore a stress level of 43.6 MPa was used for this material. Duplicate tests were possible for the silver alloyed copper with 5 % cold work, and the specimen in the single specimen Mayes testing machine was loaded stepwise to a final test stress of 73.6 MPa. All the other specimens were kept at a stress level of about 51.5 MPa.

All testing was performed in an underground laboratory (40 m below surface), in a testing room with a controlled temperature of 21 $\pm$ 0.2 °C. The testing furnaces of the creep testing machines were only used for insulating the specimens from the short-term temperature variation. This was assumed to be sufficient due to the temperature compensation in the strain measurements.

High sensitivity strain gauges with a high resolution (about 1 nV/V) digital instrument (DMP) were used to measure strain from the specimens during testing. To compensate for the effects of thermal strains, compensating strain gauges on a similar but unstressed specimen were used in full bridge (Fig. 2 in Appendix 1) in the testing chamber. The strain gauge measurements are in principle comparable to those used for cryogenic creep testing (Yen et al, 1984; McDonald and Hartwig, 1991), but the target sensitivity in strain measurements of the present work is about one order of magnitude lower (about $10^{-7}$).

To check for the possible variations in creep strength along the specimen as well as in the performance of strain gauges, three pairs of strain gauges were used in the silver copper specimen with 5 % cold work, tested in the single specimen testing machine. All strain gauges were XY-gauges, yielding also the transverse strains of the specimens. A total of six

XY-gauges on both the loaded and compensating specimens were hence used in the single specimen machine. In the other four specimens and four compensating specimens, tested in the Distington machine, two pairs of similar XY-gauges were used at the centre section of the shaft region. In all cases both the X- and Y-strain gauges were connected to yield the average strain from the opposite sides of the specimens.

The strain gauges as well as the adhesive and the curing procedure were selected to minimize the errors due to creep in the gauge installation. To control the possible effects of short- and long-term drift in the measuring equipment, a reference voltage source with a tested drift of less than $10^{-6}$ over a period of three years was used for periodic checks. The recording sensitivity of the reference voltage was selected to correspond approximately $10^{-8}$ in terms of strain.

Computer controlled periodic calibration and measurement was developed for testing several specimens simultaneously and for recording the strain, temperature and reference voltages over the testing period. The calibration and measurement procedure needed about 10 s for one channel, and therefore the initial fast creep was not well covered in the results. However, only the slow creep at or near the minimum creep rate was considered to be of interest in this work. To obtain appropriate stable zero load signal level, reference zero was recorded over extended periods after load removal and before subsequent loading until the initial transient strains had faded. Resistance type temperature sensors were used for recording the temperature in each testing chamber and in the testing room.

Table 1. Chemical composition (ppm) of the test materials according to the supplier. CW stands for cold worked material.

| Material | OFHC-Cu/5% & 15%CW | CuAg/5%CW | CuAg/15%CW |
|---|---|---|---|
| Ag | 12 | 1100 | 1020 |
| Al | <1 | 1 | 3 |
| As | 3 | <5 | <5 |
| Bi | <1 | 1 | 1 |
| Fe | 4 | 20 | 13 |
| H | 0.82 | 0.63 | 0.35 |
| Mn | 1 | 1 | 1 |
| Ni | 4 | <3 | 3 |
| O | 1.6 | 1.5 | 2.2 |
| P | 2 | 3 | 11 |
| Pb | 1 | 3 | <2 |
| S | 9 | 12 | 9 |
| Sb | 3 | 6 | 5 |
| Se | 1 | <3 | <3 |
| Si | 1 | <1 | <1 |
| Sn | <3 | <3 | <3 |
| Te | <3 | <3 | <3 |
| Zn | <1 | 20 | 9 |
| Zr | <3 | <3 | <3 |
| Cd | <1 | - | - |
| Co | <1 | - | - |
| Cr | <3 | - | - |
| Hg | <1 | - | - |

Table 2. Mechanical properties of the test materials according to the supplier. CW stands for cold worked material, BT hardness before and AT after creep testing, the latter determined also by VTT.

| Material | OFHC-Cu/5%CW | OFHC-Cu/15%CW | CuAg/5%CW | CuAg/15%CW |
|---|---|---|---|---|
| $Rp_{0,2}$ (MPa) | 105 | 219 | 211 | 225 |
| $R_m$ (MPa) | 224 | 250 | 248 | 254 |
| A5 (%) | 39 | 27 | 34 | 35 |
| HV 5 (BT) | 60 | 86 | 74 | 88 |
| (AT) | 60 | 82 | 74-77 | 84 |

The testing was performed in two phases, first up to about 7 500 hours with strain recording for all samples, and only at one (central) level of strain gauges in the single specimen machine. In the second phase the testing conditions regarding stress and temperature were set to be same, but only the specimen in the single specimen machine was tested under load for about 3000 additional hours, now using all three levels of strain gauges (six gauge pairs) on the specimen.

After testing, all specimens were first unloaded and the strain indications as well as temperature further recorded for at least 300 hours, to inspect the condition of the strain gauges. The maximum time for this type of relaxation tests was about 3 000 hours, for the specimen of OFHC copper with 5 % cold work and for the silver alloyed copper with 15 % cold work. The recording frequency was kept at 1/hour as in the previous testing phases.

After removing the specimens from the testing chambers, they were tested for Vickers hardness at the unstressed threaded heads after appropriate surface preparation. This was done to compare hardness in as-delivered material and in the machined specimens, and to exclude the possibilities of accidental material changes during the process of delivery, machining and testing setup of the specimens.

One specimen head from each active specimen of the silver alloyed copper specimens were additionally sent to the supplier for chemical analysis, to ensure that no accidental switch of the specimens had occurred. The supplier also performed Vickers hardness tests from these specimen heads. Both hardness (Table 2) and chemical composition matched the expected values given initially by the supplier.

## 3 TESTING RESULTS AND PRELIMINARY ANALYSIS OF TEST DATA

Results from the tests with all materials up to 7 500 h of testing, corresponding to the first phase of testing, are shown in Figs. 3 - 9 of Appendix 1, describing the strain [$\ln(l/l_0)$, where $l$ is current gauge length and $l_0$ initial gauge length, in microstrains or $10^{-6}$] as a function of testing time in both longitudinal (x-direction) and transverse (hoop, y-) direction of each specimen.

These strain rate-time curves were obtained from raw strain-time data by first smoothing out random or relatively high-frequency noise by the technique of running medians. The original data points (Fig. 4), obtained once every hour, appeared in this way to include some short-term noise, possibly from electrical and small-scale temperature fluctuations, within a time scale of about one day. In addition there was a significant longer term strain variation with the systematic temperature fluctuations within the testing chamber (correlation coefficient for normalized data about 0.4 to 0.7). Since this correlation was not very good and the absolute changes in strain indications apparently not too much affected by the small temperature fluctuations, the strain was not corrected with regard to temperature. The temperature in the testing chambers and in the testing room are shown in Fig. 10 of Appendix 1.

The apparent noise or short (and temperature-independent longer term) fluctuations do not necessarily imply external electrical disturbances, since stochastically fluctuating creep rate has been recorded from bcc metals in a fully mechanical strain measurement system (LeMay and Da Silveira, 1989). Also, it is conceivable that at the very small strain increments of this work the lever and joint mechanisms of the testing machine are no more functioning smoothly.

The resulting net creep rate is obtained by using the simple technique of the running medians very well at least down to a strain rate of $10^{-8}$ 1/h. Although below this strain rate the longer term systematic fluctuations become more pronounced, reasonably reliable strain rate measurements with a factor of two seem possible down to an average creep rate of $10^{-10}$ 1/h, provided that no excessive temperature fluctuations (> 0.1 °C) intervene. No measurable electrical zero drift has been found in the reference voltage within the test periods of up to 5 000 h (Fig. 11 of Appendix 1). In spite of occasional transients in the reference voltage, the disturbances were apparently not reflected in the strain recordings.

In the case of the first phase of testing (initial 7 500 hours), the minimum strain rate was taken to correspond to the rate at the end of this testing phase. This rate was obtained by direct linear fitting of the measured strains and time for the last 1500 hours of this testing phase. In case of the second testing phase (3 000 additional hours) for silver alloyed copper with 5 % cold work, a period of 1 570 hours of testing with a reasonably stable recorded temperature (within about $\pm$ 0.1 °C, from 1 090 to 2 660 hours after starting the second phase) was used for the same purpose in a similar way (Fig. 12 of Appendix 1).

A summary of the testing results is given in Table 3, which shows the measured average longitudinal creep rates from the 1 500 last hours of the first phase of testing, and for the silver alloyed copper (5 % cold work and 76.3 MPa) the corresponding average rate for the 1 570 hours of stable temperature. For this specimen the error ranges indicated in Table 3 are estimated from the results of the three independent strain gauge pairs on the same specimen. In case of other specimens, the corresponding range only refers to the scatter in the results when the size of the strain data sets is varied between 500 and 2 000 last hours (data points) of the initial 7 500 h testing period.

The indicated creep rates are believed to represent the minimum creep rate of each material within a factor of two to three, with a possible exception of the silver alloyed copper with 5 % cold work in the first testing phase, where the temperature fluctuations were relatively large in comparison with the required sensitivity for the strain measurement. In general, the equipment and its measuring sensitivity appears to limit the accuracy in the creep rate assessment (Fig. 13 of Appendix 1).

Table 3. Summary of the testing results after 7 500 h of initial and 3 000 hours of additional testing time. CW stands for cold worked material; strain rate is indicated for the last 1 500 h in the longitudinal direction of the specimen, and for CuAg0.1 (5 % CW) at 76.3 MPa also for 1 570 hours of the additional testing period.

| Material | Initial stress, MPa | Estimated min. strain rate, 1/h | Projected time to 1% strain, years[1)] |
|---|---|---|---|
| OFHC-Cu 5%CW | 43.6 | $3.6(+/-0.5)*10^{-9}$ | 320-/+40 |
| OFHC-Cu 15%CW | 51.4 | $3.1(+/-0.2)*10^{-9}$ | 370-/+20 |
| CuAg0.1 5%CW | 51.5 | $3.3(+/-1.0)*10^{-10}$ | 3460-/+1050 |
| CuAg0.1 5%CW | 76.3 | $[1.3(+/-1.0)*10^{-10}]$ | [8780][2)] |
| ", additional period | | $1.3(+/-0.4)*10^{-10}$ | 8780-/+2060 |
| CuAg0.1 15%CW | 51.5 | $1.6(+/-0.5)*10^{-9}$ | 710-/+220 |

1) assuming constant rate equal to minimum rate
2) last 1 500 h of the initial 7 500 h of testing; result uncertain due to 1.5 times higher strain rate indications in the transverse direction

The results from CuAg0.1 material at 51.5 MPa appeared to contradict the expected order, since the material with 15 % cold work was creeping faster than that with 5 % cold work. To clarify possible accidental switch of materials, the specimen with 15 % cold work, loaded at 51 MPa stress level, was switched after about 2500 h of testing during the first testing phase with the nominally identical specimen used for gauge compensation, so that the active specimen became the new compensation specimen. However, no change was seen in creep rates measured after this change. The switch of active and compensating specimens did influence the level of strain readings for other specimens as well; this is likely to be a purely electrical transient of the measuring system and no change was found in the rates of strain indications.

The CuAg0.1 specimen loaded to a stress of 76.3 MPa showed slower longitudinal creep than similar material at 51.5 MPa after the first 7 500 h of testing. The result appeared uncertain due to the fact that the transverse strain rate indication for this specimen at 76.3 MPa was about 1.5 times (but as expected of opposite sign) the longitudinal strain rate indication, while it should be - if reflecting fully plastic strain - only half of the longitudinal indication. If in fact the transverse strain rates were correct and the ratio of transverse and longitudinal strain rates were the expected -0.5, then the longitudinal strain rate were about three times the estimated strain rate given in Table 3. The projected time to 1 % strain were then comparable with that of the same material at a stress of 51.5 MPa.

In an extended test in the second phase of testing, the longitudinal strain rate indication for the silver alloyed copper with 5 % cold work (76.3 MPa) remained at $(1.3 \pm 0.4)*10^{-10}$ 1/h, as shown in Table 3 and Fig. 13 as an average of six longitudinal strain gauge indications from the same specimen. The scatter between the indications from the three gauge sets remained small, suggesting that the results are reasonably reliable. In the transverse direction the average strain rate was pratically zero, but this results from unexpected increasing strain indication in one of the three levels of strain gauges; this level was the one used alone for the measurements during the initial 7500 h of testing. Since the transverse strain from this level also showed anomalously large effects of temperature fluctuations, these results may have resulted from an improperly functioning strain gauge. Discarding these results gives an average transverse strain rate (from four gauges) of $(4.5 \pm 1.0)*10^{-11}$ 1/h for the second (additional) testing period. The result is reasonably consistent with the expected contraction ratio of -0.5 for fully plastic creep strain.

The results from the second testing phase (1 570 h data of the total 3 000 h of additional testing time) suggest that the directly projected time to 1 % creep strain could reach values up to 7 000 - 11 000 years in case of the silver alloyed copper at 76.3 MPa stress level. However, the two other specimens of the nominally same material type indicated strain rates corresponding to much shorter times to 1 % strain (500 to 4 000 years) even at lower stresses of 51.5 MPa. This is clearly short of the target life of at least 10 000 years in these conditions. In spite of the precautions to retain high resolution and reliability in the measurements, there appears to remain a relatively large discrepancy between the results from different specimens. As a result it is difficult to confirm whether the long term target strain rates are in fact achieved for the silver alloyed copper. In case of OFHC copper, not much hope seems to be justified for a longer time to 1 % creep strain than few hundred years at the 50 MPa stress level and at room temperature.

Possible error sources in the results are:
- simultaneous creep of the strain gauge attachment;
- thermal and frictional inaccuracies in the loading train; and
- untested differences between materials (e.g. grain size).

One the most important systematic error sources in the strain measurements can arise from simultaneous creep of the strain gauge attachment. The adhesive and the plastic around the strain gauge will creep during the test. Then the strain reading is systematically somewhat lower than without strain gauge creep, and the actual substrate creeps faster. Since the strain gauges, adhesive and the procedure to attach gauges on specimens were specifically selected to minimize such effects, they should remain within about 1 % of the full strain reading in 1 000 h of testing (Hoffmann, 1987). This suggests that the estimated minimum strain rates should not be systematically too low by a higher factor than two to three. However, the present tests can be considered as unusually long in comparison with the strain rates in the literature data on gauge drift, and this casts some doubt especially on the reliability of measurements with only few gauges per specimen.

Another conceivable error source arises from the thermal movements of the loading train. Very small thermal expansion is magnified by the lever mechanism, and slight displacements can occur throughout the loading train. This includes several joints, which are by no means frictionless. In ordinary creep testing this is of no importance, but for the present high resolution measurements the loading is no more constant. Discontinuous movements due to friction do not follow the temperature fluctuations in a unique way, unless the change in temperature is sufficiently large. As a result the effect of temperature fluctuations cannot be subtracted from the strain readings by using correlation between strain and temperature. It was found that in spite of more consistent changes with larger temperature changes, correction for such changes in strain was still impossible, possibly due to accumulating friction effects. Best results were obtained by keeping temperature as constant as possible (preferably within better than $\pm$ 0.1 °C). It were also better to use direct loading, or a single lever machine (like the single specimen machine of the present testing programme) rather than the double lever machine to minimize the number of joints causing the friction effects. However, the large discrepancy between the expected strain rates of silver alloyed copper specimens at different stress levels and degrees of cold work are difficult to accommodate by thermal or friction effects alone.

Also other differences may exist between the various material types of the present testing programme than those considered above. Of the quantities known to affect creep rate of copper, e.g. grain size is significant, but often less so at low temperatures and relatively high stresses (Frost and Ashby, 1982). The grain size of the materials was not measured in the present programme. Other microstructural features like configuration and strength of grain boundaries, dislocation substructures, impurities or secondary phases may also be relevant but were not addressed in this programme. Nevertheless, it is not expected that the magnitude of the observed differences are easily explained by such differences.

The results of silver alloyed copper (CuAg0.1) in Table 3 can be compared with the prediction according to the previous work (Auerkari and Sandlin, 1988): the predicted minimum creep rate at 51.5 MPa would be about $1.66 \cdot 10^{-8}$ 1/h, which corresponds a time of 69 years to 1 % creep strain. Therefore the earlier predictions from the extrapolated literature creep data appear overly conservative by at least one and possibly by two orders of magnitude.

The nominal strain rate of the order of $10^{-10}$ 1/h seems technically measurable, but is likely to represent the practical lower limit for the present technique. To improve the technique for consistent long term life prediction, the following recommendations are made:

- microscopy and microanalysis should be used to clarify the role of grain boundaries and impurities in creep;

- uninterrupted testing time for target predictions beyond 10 000 years should extend to 4 - 5 years;

- temperature stability should be improved to be better than $\pm$ 0.1 °C during the testing period; this could probably be achieved by using a water blanket for the specimen chamber;

- a minimum of six pairs of strain gauges should be used for the strain measurements from a single specimen at room temperature (or higher); and

- an identical specimen of a stronger material but with the same strain gauge arrangement should be simultaneously tested so that the creep of strain gauges can be properly evaluated and subtracted from the data.

For pure copper the total testing time of this work appears sufficient to demonstrate the minimum creep rates within a factor of about two or less. The test results beyond some 4 000 h did not show apparent exhaustive ("primary") creep, often considered typical for creep at relatively low temperatures.

However, when recording strain from the pure copper specimen, the relaxation curve (Fig. 14 of Appendix 1) does not show clear exhaustion either even months after the load removal. Again, it were probably useful to compare the results from a similar test with the same strain gauges and a comparable initial strain, but using a stronger substrate material to exclude the secondary effects from creep of the strain gauges.

At a constant initial stress level the strain rate $d\epsilon_p/dt$ as a function of time was at first very accurately a straight line on a fully logarithmic scale, or

$$d\epsilon_p/dt = K(\sigma,T)\cdot[1+C(\sigma,T)\cdot t]^{-p} \quad , \tag{1}$$

where $K(\sigma,T)$, $C(\sigma,T)$ and p ($\approx$ 1) are positive constants at constant initial stress and temperature. Integrating (1) from zero to a specified time, with p = 1, yields creep strain $\epsilon_p$ as a function of time before reaching the minimum creep rate

$$\epsilon_p = K(\sigma,T)\cdot \ln[1+C(\sigma,T)\cdot t] \quad , \tag{2}$$

which is the classical expression for logarithmic creep, often thought to occur at low homologous temperatures ($T < 0.3\cdot Tm$). This expression could be used to describe the initial (primary) creep in the creep curve modelling. To limit the number of free parameters in data fitting, at low temperatures and limited strains a quite satisfactory expression for later stages of creep $\epsilon_t$ would be simply

$$\epsilon_t = Q(\sigma,T)\cdot t \quad , \tag{3}$$

where $Q\ (\sigma,T)$ is constant at constant stress and temperature. When clear accelerating tertiary creep occurs, similar functions as in the previous analysis (Auerkari and Sandlin, 1988) can be adopted. However, when analysis is limited to low strains like in this study, this appears unnecessary.

## 4 SUMMARY

It appears possible that for copper-based canister materials creep strain rates can be measured to yield realistic creep life predictions, essentially without accelerating the strain rates from those expected in actual service. The results for the silver alloyed copper, which included considerable unresolved scatter, suggest that these materials could be used at stress level of about 50 MPa for up to some thousands of years, when the service temperature is not well above the room temperature.

For silver alloyed copper (0.1 % Ag and 5 % cold work) lowest measured minimum strain rate of about $(1.3 \pm 0.4) \cdot 10^{-10}$ 1/h was demonstrated from one specimen, corresponding 1 % strain in about 7 000 - 11 000 years at 21 °C and 76.3 MPa. Another specimen with the same material gave somewhat more than twice this strain rate at 51.5 MPa. At this stress level the specimen of similar material but with 15 % cold work showed further about five times higher strain rate, corresponding to only about 500 - 900 years to 1 % strain. The order of the measured strain rates in the silver alloyed copper specimens is unexpected. However, consistent results from independent strain gauges in the same specimen (CuAg0.1, 5 % CW) and from the case where active and compensating specimens of the same material (Cuag0.1, 15 % CW) provide considerable confidence on the reliability of the measurements.

Due to some simultaneous creep of the strain gauges during testing, as well as actual service temperature exceeding initially the room temperature, the above estimates are likely to correspond lower limits of the creep rate, the actual life being possibly about two to three times shorter. Nevertheless, the predicted creep life for the silver alloyed copper is at least about an order of magnitude longer than that from extrapolated literature data. The reasons for the unexpected order in the results is not related to any accidental material change, but as a result it is difficult to confirm whether the long term target strain rates are in fact achieved for the silver alloyed copper. In case of OFHC copper, longer times to 1 % creep strain than few hundred years seem unlikely at the 50 MPa stress level and at room temperature.

The technique developed and used in this work for measuring very low strain rates appears useful for determining low-temperature creep rates of practical structures essentially without accelerating the test from the service conditions. With the present technique the lower limit is about $10^{-10}$ 1/h in strain rate.

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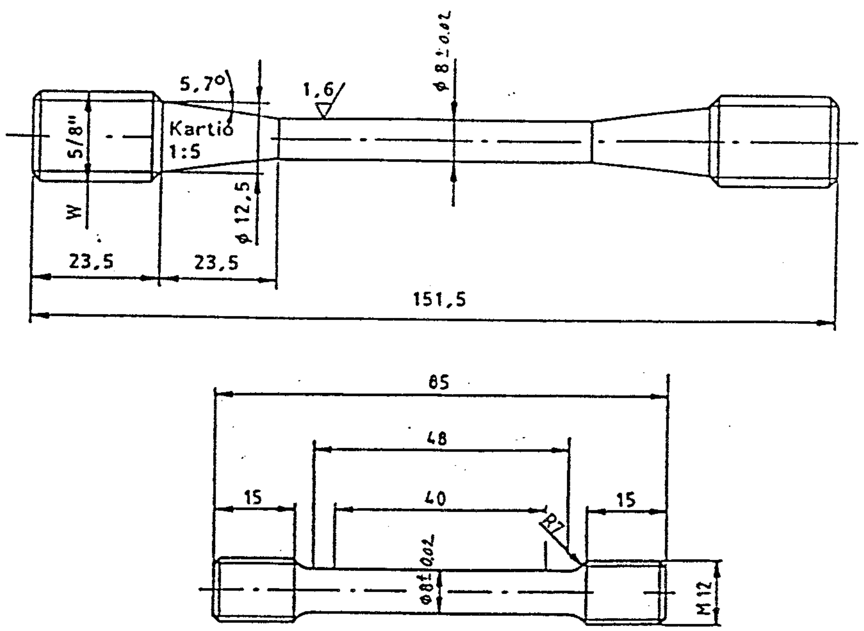


Fig 1. Dimensions of creep testing specimens.

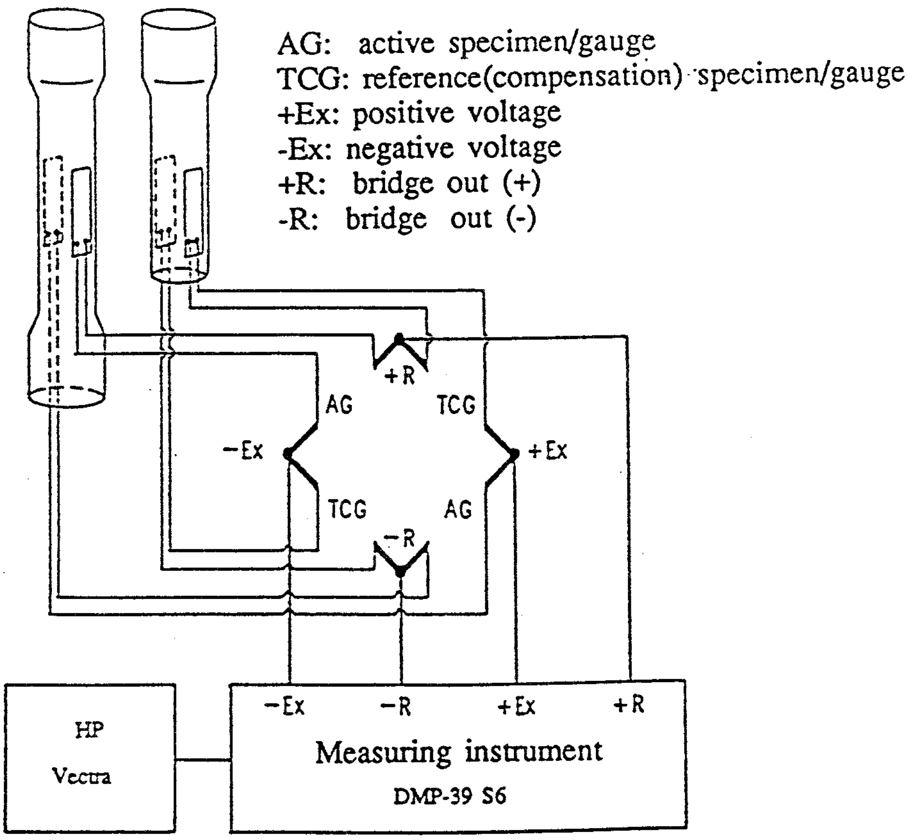


Fig 2. The strain gauge measurement configuration for one of the 16 channels of the measuring system.

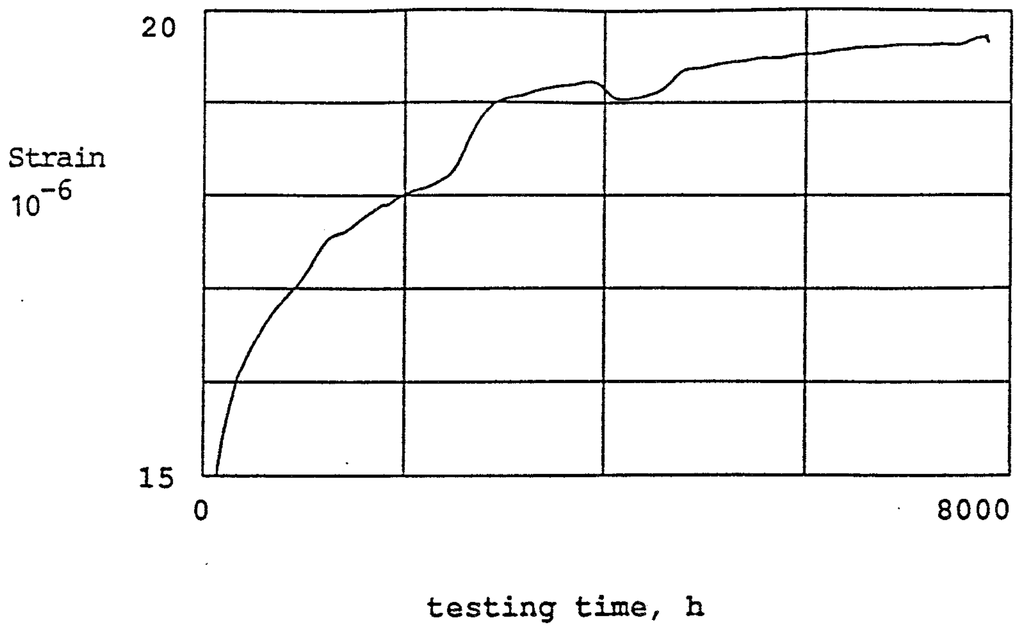


Fig 3. Strain (smoothed recording) as a function of testing time for the x-direction of CuAg0.1 (5% cold work) at 76.3 MPa stress. Note that initial strain was deducted from strain readings (as in following Figs as well).

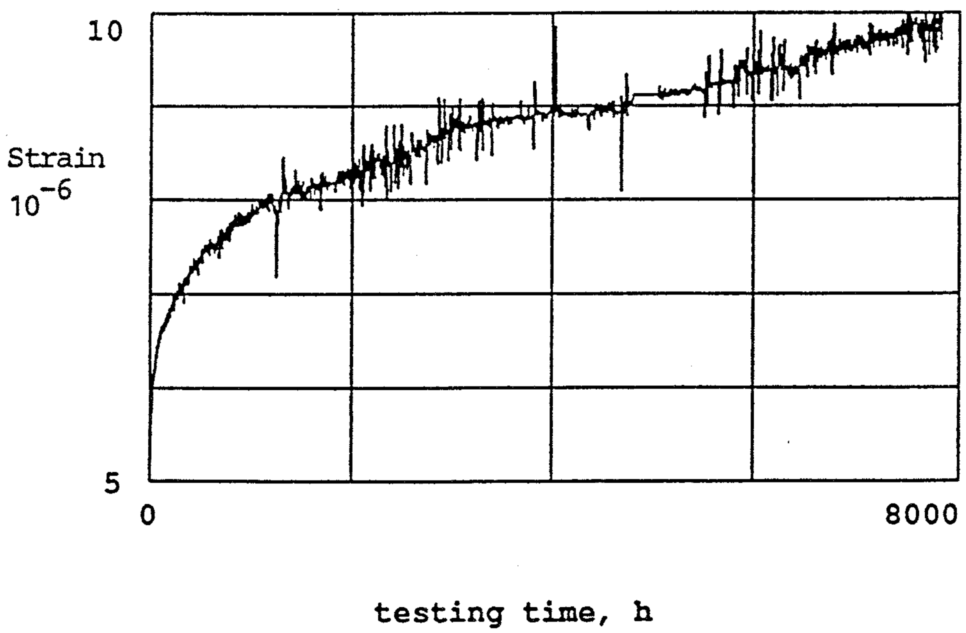


Fig 4. Strain (original recording) as a function of time for the y-direction of the same specimen as in Fig.3.

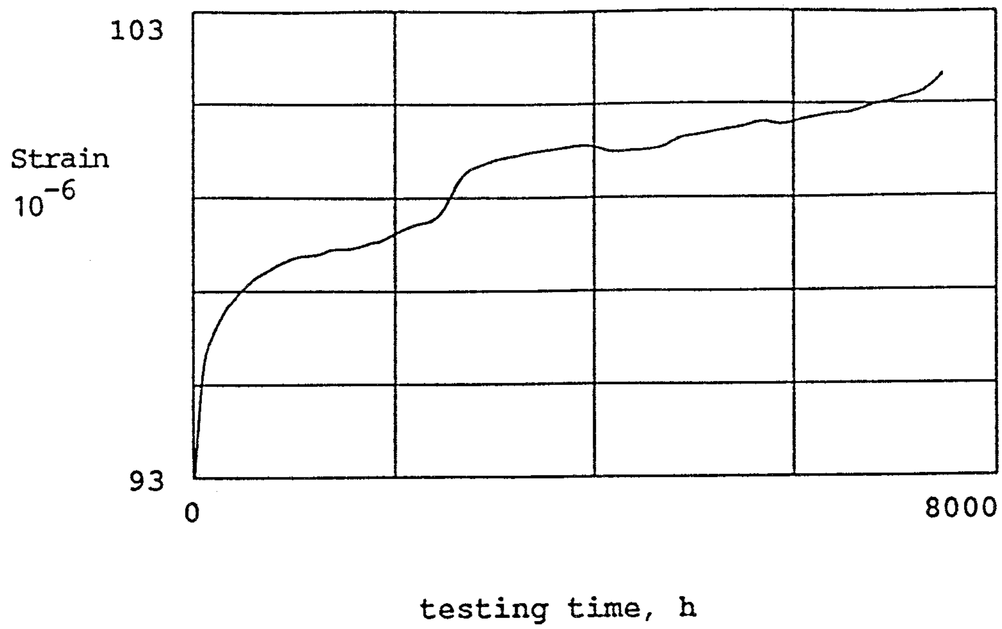


Fig 5. Strain (smoothed recording) as a function of time for the x-direction of CuAg0.1 (5% cold work) at 51.5 MPa stress.

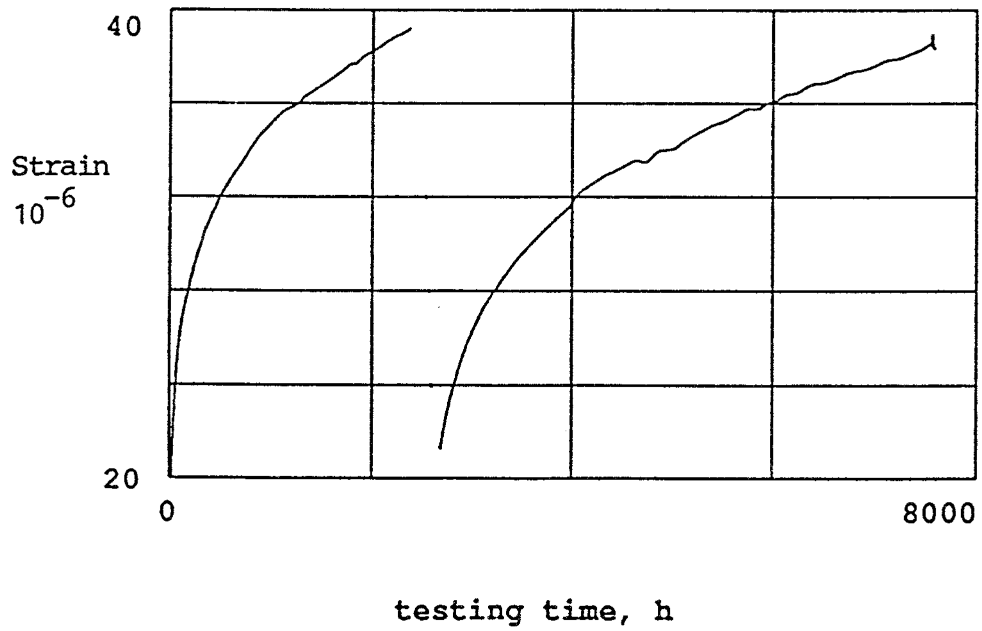


Fig 6. Strain (smoothed recording) as a function of time for the x-direction of CuAg0.1 (15% cold work) at 51.5 MPa stress.

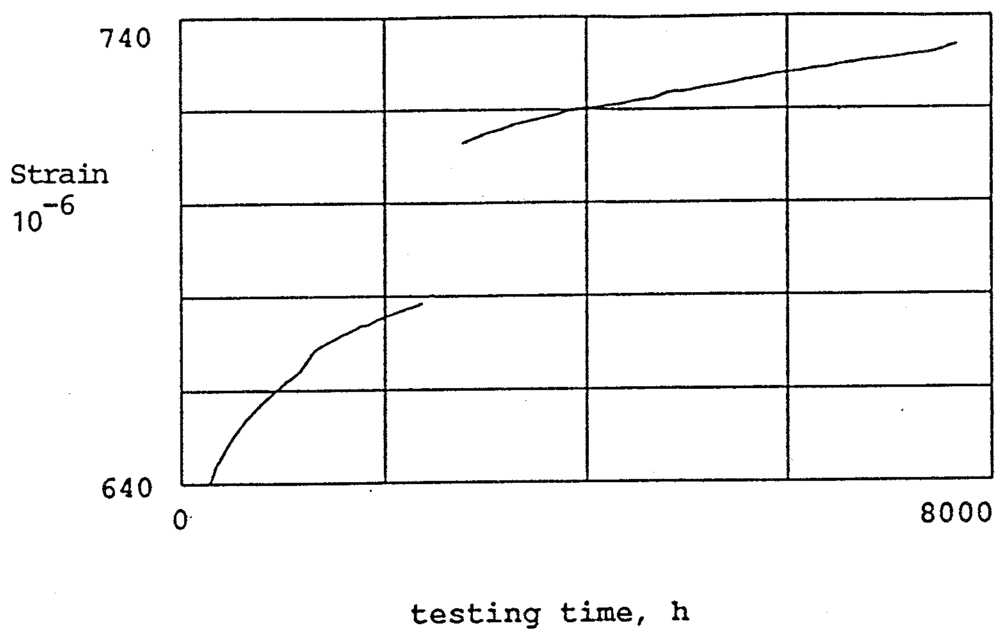


Fig 7. Strain (smoothed recording) as a function of time for the x-direction of OFHC copper (5% cold work) at 43.6 MPa stress.

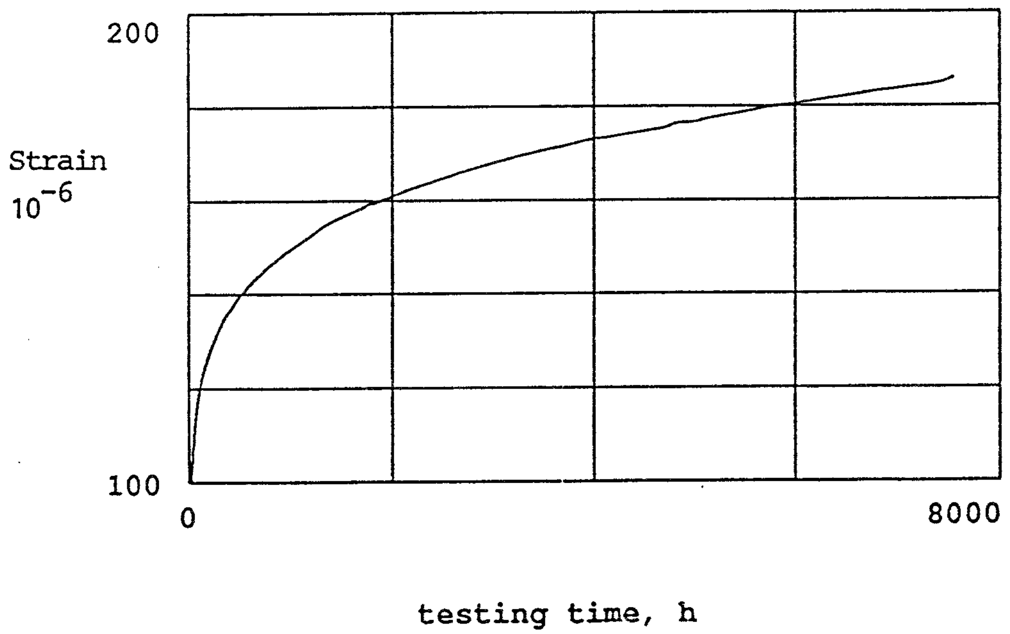


Fig 8. Strain (smoothed recording) as a function of time for the x-direction of OFHC copper (15% cold work) at 51.4 MPa stress.

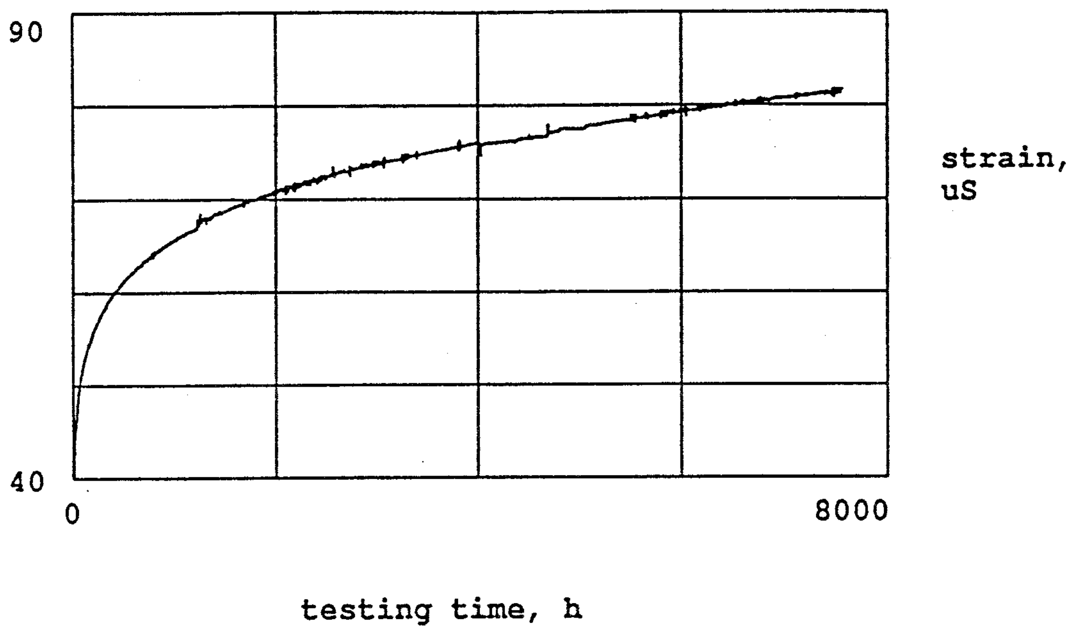


Fig. 9. Strain (original recording) as a function of time for the y-direction of OFHC copper (15 % cold work) at 51.4 MPa stress.

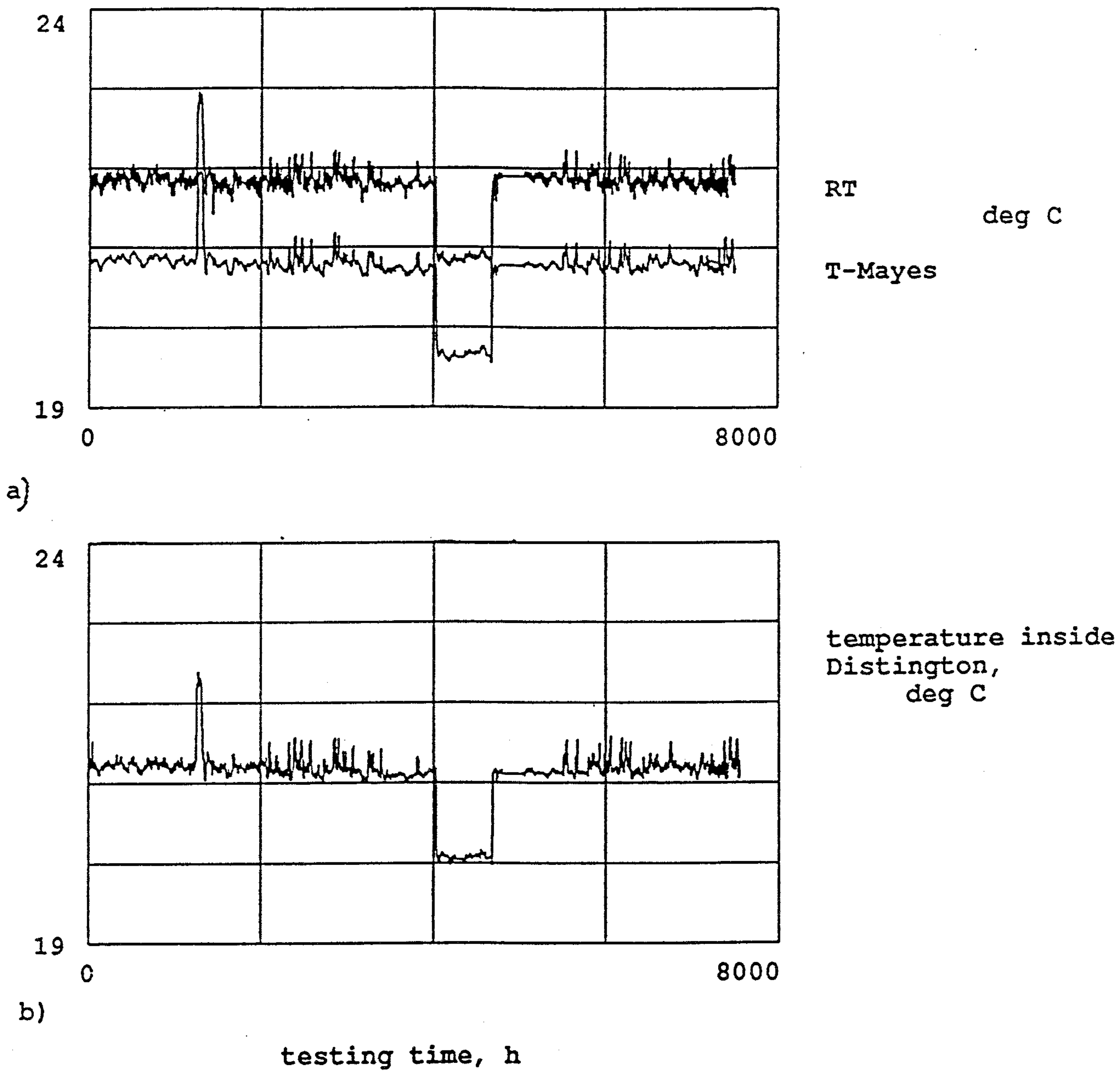


Fig 10. Temperature recordings for a) room temperature (uncalibrated, RT) outside the testing chambers and inside the single specimen (Mayes) testing machine chamber; b) inside the four-specimen (Distington) testing machine chamber.

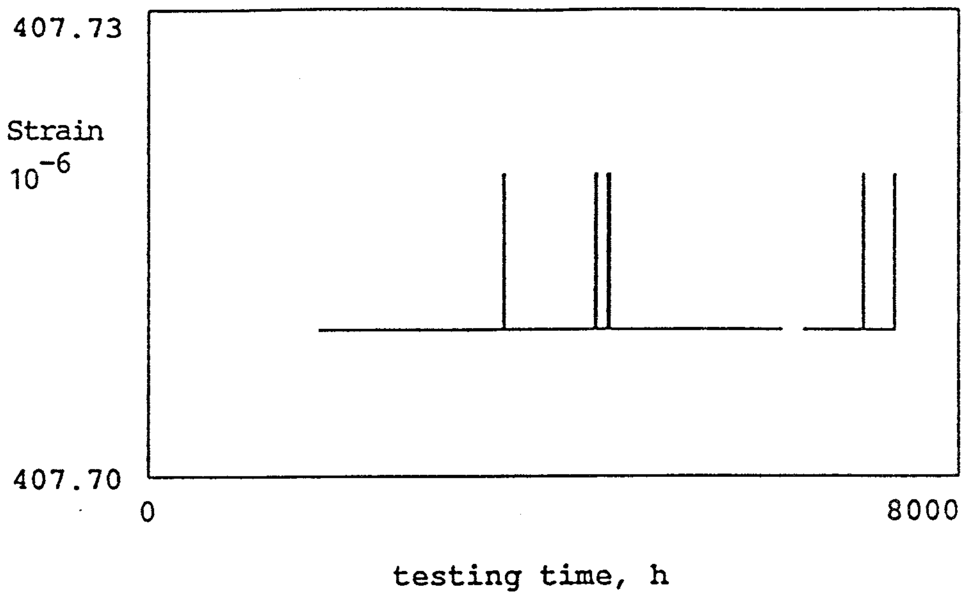


Fig. 11. Recording of the reference voltage, converted to microstrains (positive side).

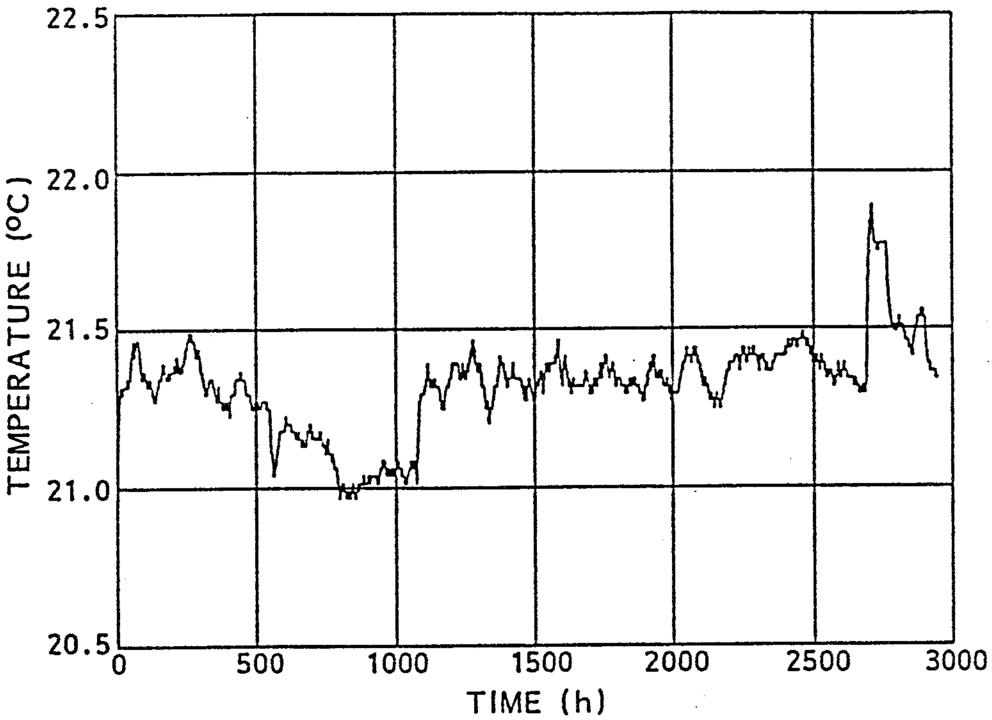


Fig 12. The temperature inside the single specimen testing chamber during the additional second phase of creep testing. Note the period between 1090 and 2 660 hours, showing a temperature fluctuation of about ± 0.1 °C.

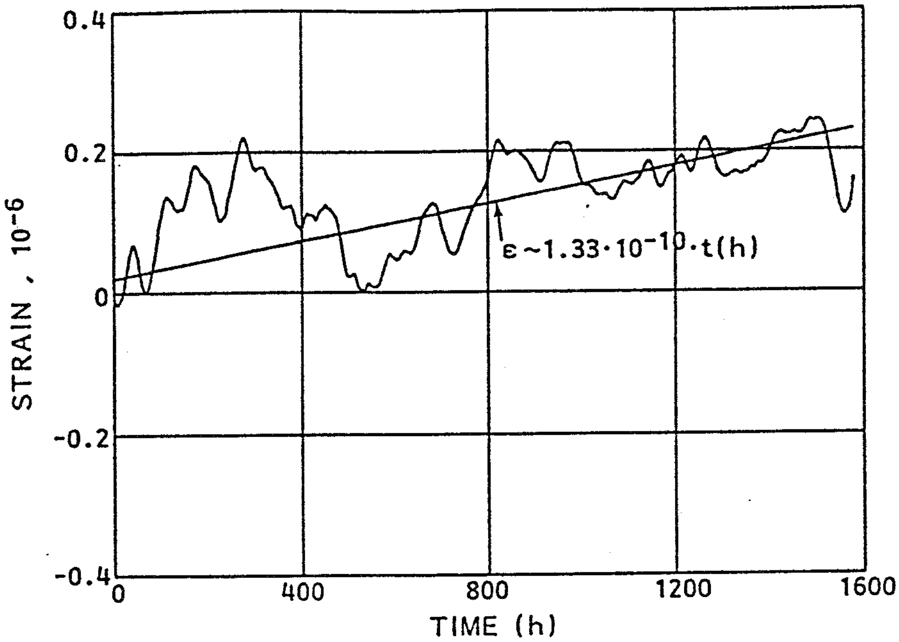


Fig 13. The average longitudinal (x-direction) strain increment from the six strain gauges of CuAg0.1 (5% cold work, 76.3 MPa), during the period of 1570 hours of relatively stable temperature (cf. Fig 12) in the second phase of testing.

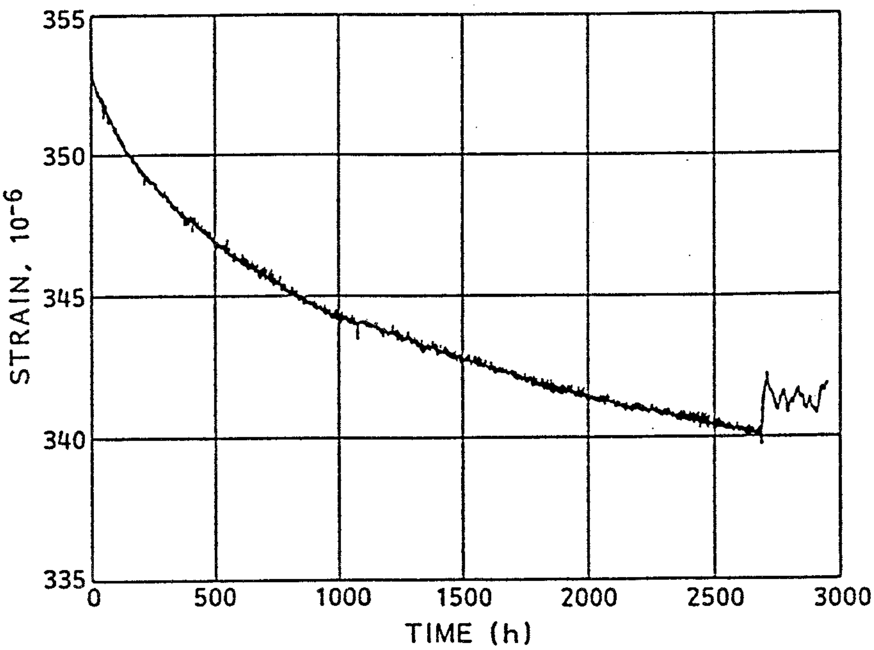


Fig 14. The strain indication of the OFHC copper specimen with 5 % cold work after load removal (initially 8 000 h at 43.6 MPa) during the second phase of testing.

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[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
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[2]SKB AB
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[2]Clay Technology AB
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