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Stress redistribution and void growth in butt-welded canisters for spent nuclear fuel

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STRESS REDISTRIBUTION AND VOID GROWTH IN BUTT-WELDED CANISTERS FOR SPENT NUCLEAR FUEL

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ABSTRACT

English

The stress redistribution in Cu-Fe canisters for spent nuclear fuel during waiting for deposition and after final deposition is calculated numerically. the constitutive equation modelling creep deformation during this time period employs values on materials parameters determined within the SKB-project on "Mechanical integrity of canisters for spent nuclear fuel". The welding residual stresses are redistributed without lowering maximum values during the waiting period. a very low amount of void growth is predicted for this type of copper during the deposition period. This leads to an estimated very large rupture time.

Swedish

Spänningsomfördelningen i Cu-Fe kapslar för använt kärnbränsle i väntan på slutdeponering och efter slutdeponering har beräknats numeriskt. Den konstitutiva equation som modellerar krypdeformationen under denna tidsperiod använder värden på materialparametrar, som bestämts experimentellt ur relaxationsförsök i SKB-projektet "Mechanical integrity of canisters for spent nuclear fuel". Restspänningarna i svetsen omfördelas utan att maximivärderna sjunker under perioden före slutdeponering. Mycket liten håltillväxt förutsägs under deponeringsperioden för denna typ av koppar. Detta leder till tiden till brott uppskattas vara mycket lång.

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ABSTRACT

The stress redistribution in Cu-Fe canisters for spent nuclear fuel during waiting for deposition and after the final deposition is calculated numerically. The constitutive equation modelling creep deformation during this time period employs values on material parameters determined within the SKB-project on "Mechanical integrity of canisters for spent nuclear fuel". The welding residual stresses are redistributed without lowering maximum values during the waiting period. A very low amount of void growth is predicted for this type of copper during the deposition period. This leads to an estimated very large rupture time.

INTRODUCTION

In a current proposal for the design of canisters for spent nuclear fuel, the canister will consist of two concentric cylinders, an inner steel cylinder containing the fuel and an outer copper cylinder. After placing the inner cylinder into the outer cylinder a copper end is butt welded to the outer cylinder by use of electron beam welding. Figure 1 outlines the geometry of the Cu-Fe canister proposed. The welding residual stress field caused by this welding process was calculated in a previous investigation [1].

For the case of a large gap, 2 mm, between the two cylinders, the shape of the welding residual stress field was found to be similar to that often reported after butt-welding of pipes. Hence, the vertical copper cylinder will contract radially during cooling after welding at a section just below the backing ring, see Fig. 1. For compatibility reasons, this deformation is combined with a small axial outward displacement of the copper end. The residual axial and hoop stress field, as extracted from [1], in the weld and backing ring region are shown in Figures 2a,b.

A case with a much smaller gap, 0.2 mm, was also studied in [1]. Contact was calculated between the two cylinders at the inner vertical surface of the backing ring resulting in a strongly disturbed welding residual stress field as compared to Figs. 2 a,b. However, in order to ensure a practically feasible loading process, it is believed that a gap of at least 2 mm is needed between the two (almost) 5 m long cylinders.

After completing the welding process the canisters will be placed in the final underground storage. Due to the heat generation in the spent nuclear fuel, the canisters will have a temperature of roughly 100 - 150 °C while awaiting its final deposition. The durability of this waiting period may be anything from some days to one year. It is well known that time dependent plastic, *creep*, strains will develop in copper, but not in steel, when loaded at temperatures of about 200 °C. One would therefore anticipate a stress redistribution in the canister during this waiting period. Moreover, when placed in the storage, the canister will be subject to an increasing pressure (with time) due to swelling of the surrounding clay barrier. This pressure load will cause a further redistribution of the stress field in the canister. One may note that the pressure may vary somewhat along the outer surface of the canister due to a varying geometrical constraint for the swelling clay barrier. However, this pressure variation is believed to be small.

Present investigation The stress redistribution in the canister during first the waiting period before deposition and secondly when deposited is calculated by use of the FE-code NIKE2D [2].

The canister has the total length 4850 mm and the outer diameter 880 mm, see Fig. 1. The wall thickness of each of the two cylinders is 50 mm. The thickness of the backing ring is also 50 mm. The steel material is an ordinary C-Mn steel and the copper material is a Cu-P copper alloy with the room temperature virgin yield stress 50 MPa. As indicated above only one gap is studied here, 2.0 mm. Note that the gap is measured for a heated inner cylinder. The same FE-mesh as used in [1] is employed here.

The waiting period is assumed to extend for 100 hours, after that stresses will change only marginally as seen below. After deposition the stress redistribution during 10 years is studied. The pressure caused by swelling in the clay barrier is assumed to increase to 10 MPa during this time period.

MATERIAL DATA

In the FE-calculations the copper material is assumed to be thermo-elasto plastic, with the plastic strains treated as time-dependent, *creep*, only. This means that time-independent *plastic* strains are not considered during the waiting and pressure loading phase. The steel material is taken as thermo-elastic. Values for the thermal and elastic material properties are taken from [1].

During the waiting period the canister will be subject to prescribed deformation rather than precribed loads. Thus material properties should preferably be determined from relaxation tests instead of, standard, creep tests. With no such material data available from the literature, uni-axial creep relaxation tests in the temperature range 75 °C to 150 °C were performed [3] within the SKB project "Mechanical integrity of canisters for spent nuclear fuel". The recorded creep relaxation was here modelled with the commonly used Nortons law extended to multi-axial stress states by assuming isotropic creep deformation, hence

$$\dot{\varepsilon}_{ij}^{c} = B\,\sigma_{eff}^{n-1}\,s_{ij} \tag{1}$$

where σ_{eff} is the von Mises effective stress and s_{ij} is the stress deviator. The parameters B and n in Eqn (1) have been determined by using linear regression in a $\log(-\dot{\sigma}/E)$ - $\log\sigma$ plot. Figure 3 shows the regression obtained for the case T = 100 °C and the prescribed initial strain chosen such that the initial stress was 87 MPa. The prescribed strain rate during loading of the specimen was given a high value, $\dot{\varepsilon} = 1\cdot10^{-3}\ s^{-1}$ to ensure a low amount of creep deformation during this loading phase. For this temperature one obtains $B = 3.5\cdot10^{-41}$ and $n = 20.0$ ($[t]$ = h and $[\sigma]$ = MPa). These results were taken as representative for the temperature range that the canisters are subjected to while waiting the final deposition.

Figure 4 shows the calculated stress relaxation together with recorded stress reduction (for the case of the initial stress 87 MPa). Metallurgically, this relaxation process seems to be caused by a dislocation glide mechanism. More complex constitutive relations may be employed, but their potential is restricted by difficulties in obtaining values for the entering material parameters. For the present loading case, it is believed that an accurate modelling of primary creep is not motivated. One may note that the stress reduction predicted by use of parameters B and n determined from creep tests reported in [3,4] will be much too low.

As seen in Fig. 4 the time period when the stress is reduced is surprisingly low, less than 1000 h or roughly one month. This means that almost all stress reduction will take place before the canister will be deposited in the underground storage, or at least well before a swell pressure from the clay has been built up.

The parameters B and n determined from stress relaxation tests can not be used to model, the long time, creep deformation in the deposited canister. Based on the creep tests performed in [3,4] and on deformation maps in [5] the governing deformation mechanism is most likely volume diffusion with a typical value $n = 5$ for the Norton-Bailey exponent. Hence, for this time period Eqn (1) will also be used but entering material parameters are taken from creep tests reported in [3,4] at pertinent temperatures, around 100 °C and stress levels, around 100 MPa. One finds $B = 2.7 \cdot 10^{-20}$ and $n = 5.0$ ($[t]$ = h and $[\sigma]$ = MPa). Note that, for very long times, when both the temperature and the stress have decreased considerably the dominant deformation mechanism may change to surface diffusion, see [5].

MECHANICAL ANALYSIS

The short time, waiting, period of 100 hours was divided into 48 time steps and the deposition period of 10 years was divided into 108 time steps in the mechanical FE-analysis. The theory for large strains and the automatic stepping algorithm available in NIKE2D [2] were employed. The same convergence criteria as in [1] was used.

CALCULATED RESULTS

It is found that, during the first 100 hours after welding, the copper end will contract axially and eventually come in contact with the steel end at the canister center line. This leads to a radial increase of the copper cylinder at the location of the weld. The axial stresses at the weld will be redistributed without reducing the maximum magnitudes. The very high hoop stresses in the backing ring are both redistributed and reduced (the maximum hoop stress is reduced from 140 MPa to 70 MPa). The through thickness variation of the axial stress in the copper cylinder at a cross section just below the backing ring is seen to change completely leading to tensile axial stresses near the outer surface. The total accumulation of plastic strain (plastic + creep) was found to be 1 - 2% which is less than the 5% accumulated during the welding process. Figures 5 a,b show calculated axial and hoop stresses in the weld region and Figure 6 shows the displacement field for the upper part of the canister after the waiting period. Note that the maximum and minimum hoop stresses are found at the upper and lower surface of the copper end at the centre line. This part of the copper end is not shown in Fig. 5b.

The loading situation present when the canister is placed in the storage is simulated by subjecting the canister to a linearly increasing external pressure which reaches the peak value 10 MPa after 10 years. The long time creep parameters are then employed. During this time period stresses are reduced marginally without changing its distribution. The stress and displacement fields present after the deposition period are shown in Figures 7 a,b and 8. It is seen that stresses are somewhat reduced during the deposition period. Figure 9 shows calculated effective plastic strain in the weld and backing region after the waiting period. The accumulation of creep strain occurs mainly during the waiting period. As the stress field remains approximately constant with rather low values during the deposition period, see Figs. 5 and 7, there will be almost no accumulation of plastic strain during this period. The maximum plastic (plastic + creep) strain accumulated in the, possibly brittle, HAZ zone is 6 - 7 % which seems to be well below the reported, [3], ductility for the Cu-P copper proposed.

VOID GROWTH IN COPPER CYLINDER

The creep tests reported in [3] at temperatures round 100 °C show that Cu-P copper seems to have a sufficiently high ductility. This high ductility results in a low development of voids both within the grains and possibly in the grain boundaries. The few tests performed reveal a ductility of about 30% and transgranular fracture. The following equations are proposed in [5] for this deformation and void growth mechanism.

$$\dot{\varepsilon}^c = B\left(1 - \beta + \frac{\beta}{(1-\omega)^n}\right)\sigma_{eff}^n \qquad (2)$$

$$\dot{\omega} = B\,\beta\left(\frac{1}{(1-\omega)^n} - (1-\omega)\right)\sigma_{eff}^n \qquad (3)$$

where the factor β can account for combined axial and hydrostatic loadings. In the uni-axial case β = 0.6 and ω is a scalar damage parameter describing the volume fraction of voids formed.

The void growth during the waiting and deposition period was calculated numerically based on growth relations proposed in [5], Assuming that the stress state is constant during the deposition period (see Figs. 5 and 7) formulas for the rupture time under constant stress in [5] can be employed. Hence,

$$t_{rup} = \frac{1}{\beta\,(n+1)\,\sigma_{eff}^n}\ \ln\left[\frac{1-(1-(\omega_c))^{n+1}}{1-(1-(\omega_i))^{n+1}}\right] \qquad (4)$$

Here ω_i and ω_c is the initial and final value for the damage respectively. Taking ω_i = 0.00001 and ω_c = 0.25, see [5], and σ_{axial} = 95 MPa and σ_{hoop} = 45 MPa for a tensile loaded point in the HAZ at the outer surface one obtains, roughly, the rupture time $t_{rup} = 1 \cdot 10^5$ years.

DISCUSSION

The present calculations are based on several assumptions regarding the loading history (and values for entering material parameters). However, the short duration of the creep relaxation observed in the experiments in [3] justify the separation of the time history into a waiting period and a deposition period.

During the final cooling after the welding, the copper material will be subject to elevated temperatures. The duration of this cooling phase is short, but perhaps sufficiently long for some creep relaxation to take place. The effect of creep relaxation on the build-up of welding residual stresses should therefore be investigated.

During the autumn 1992 an alternative clay design have been proposed in which the swell pressure will increase to the maximum value, about 10 MPa, very rapidly, that is within some months [7]. It is not believed that use of the alternative approach will alter the results of the deposition period considerably.

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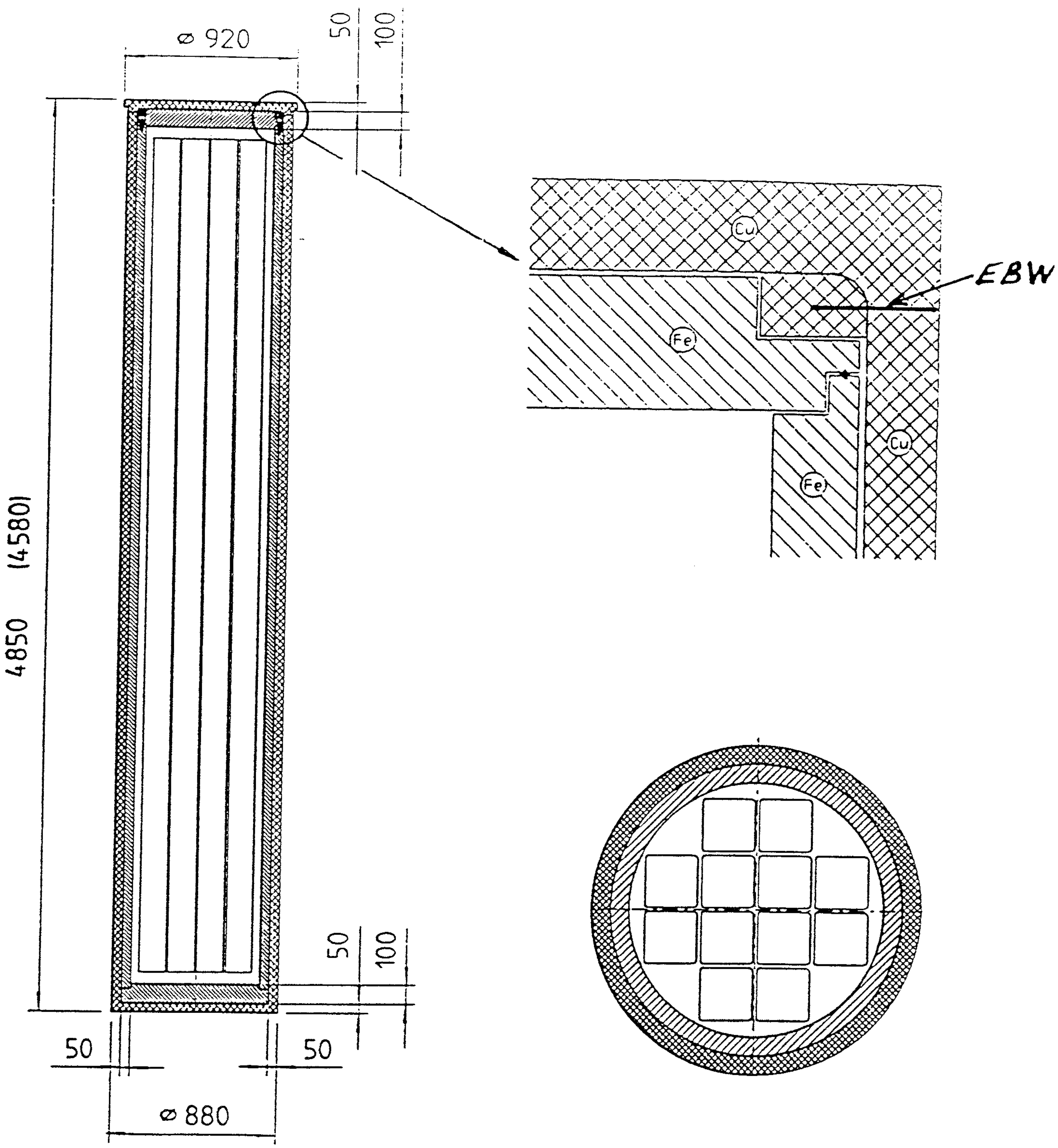

Fig 1 Geometry of the canister

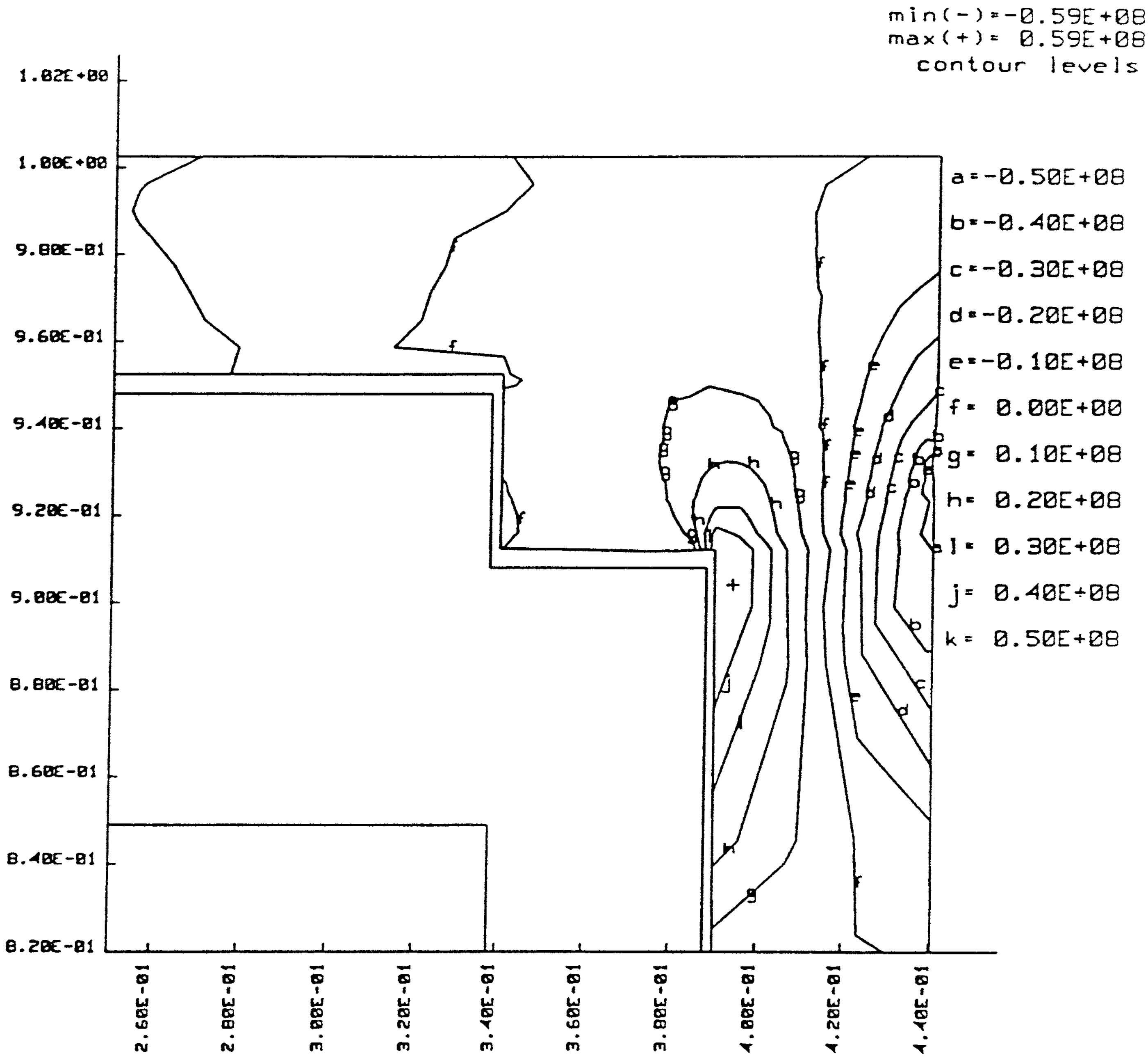

Fig 2a Calculated isolines for welding residual axial stresses for the large gap 2.0 mm.

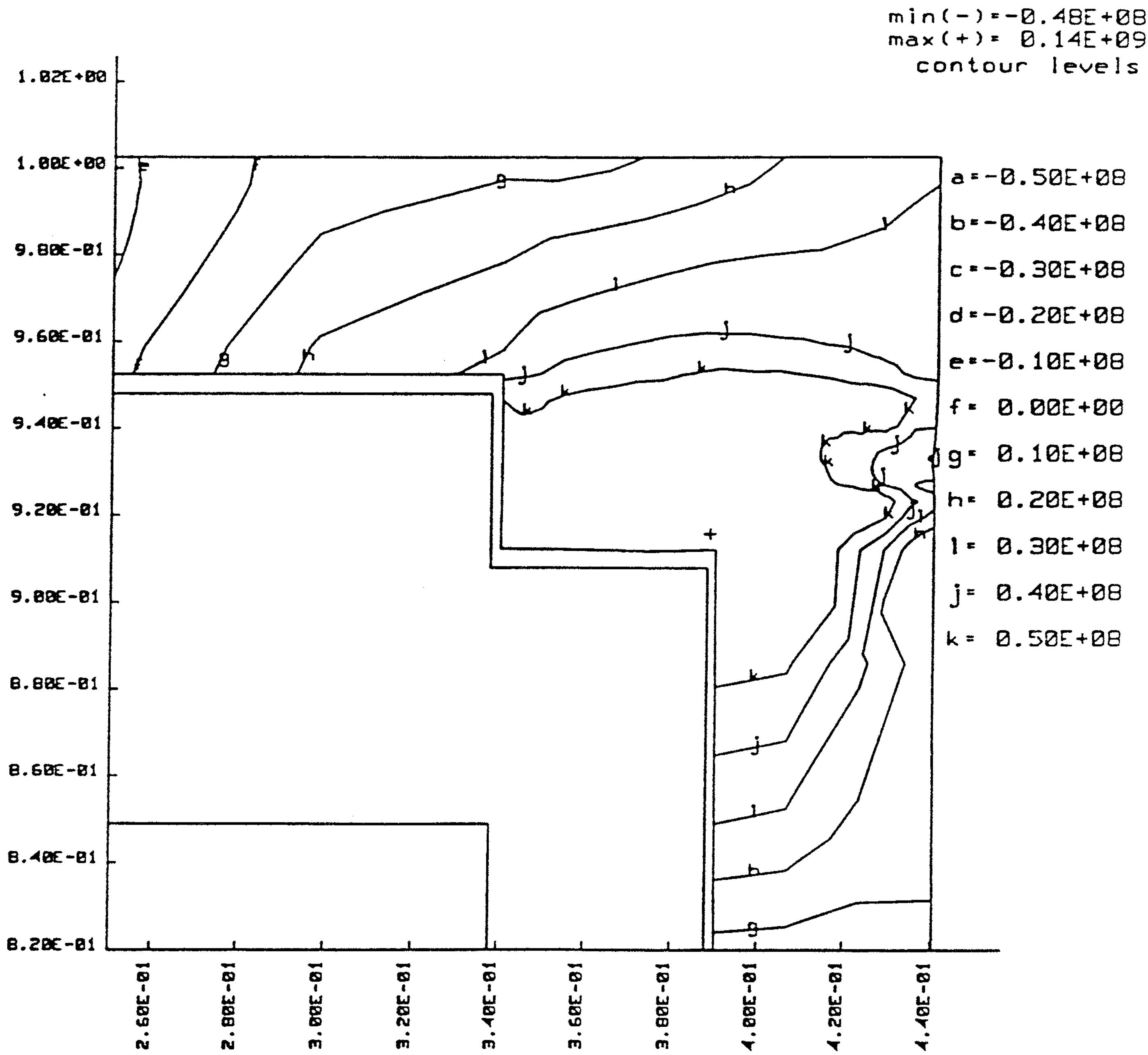

Fig 2b Calculated isolines for welding residual hoop stresses for the large gap 2.0 mm.

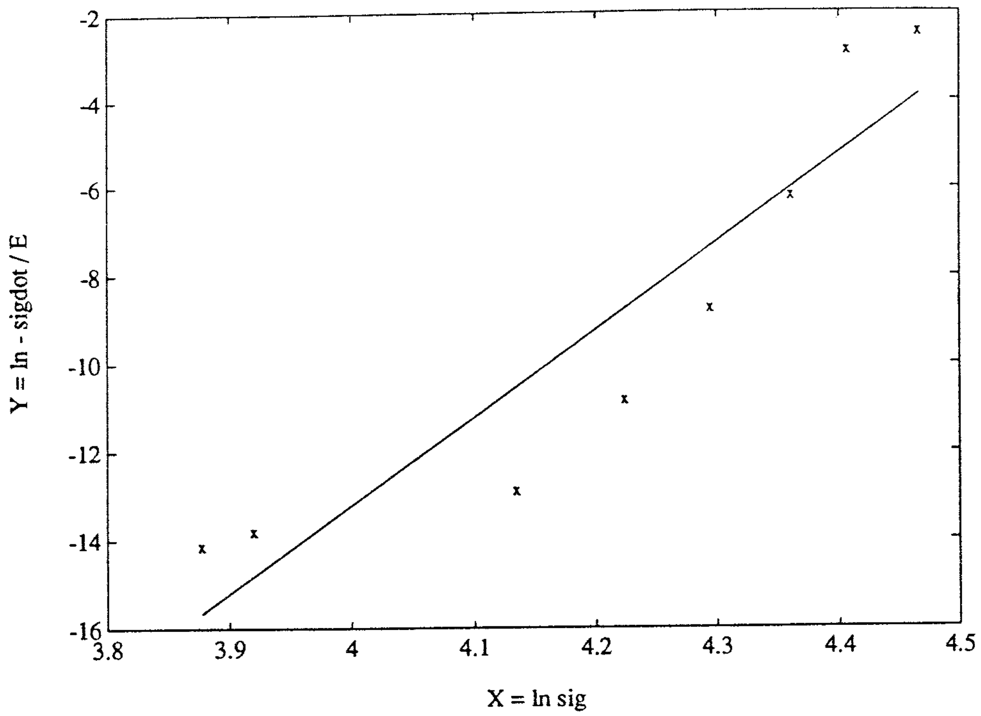

Figure 3 Linear regression of log σ vs log $(-\dot{\sigma}/E)$ for relaxation test 21 in [3] at 100 °C and with initial stress 87 MPa. Experimental results are marked with +.

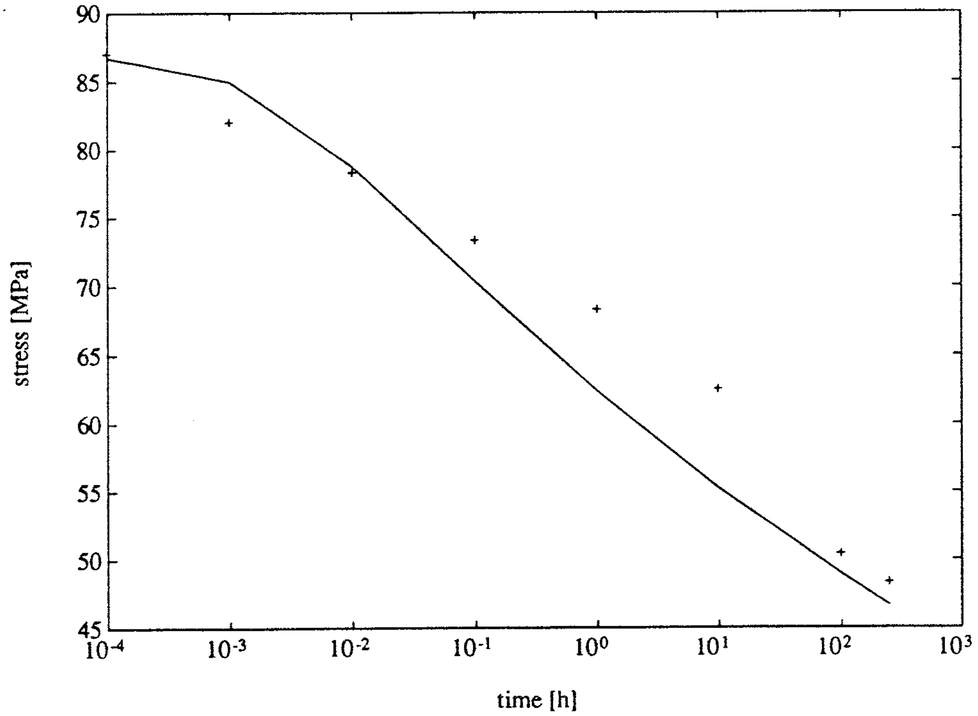

Figure 4 Calculated relaxation curve for initial stress 87 MPa together with experimentally determined relaxation. Experimental results are marked with +.

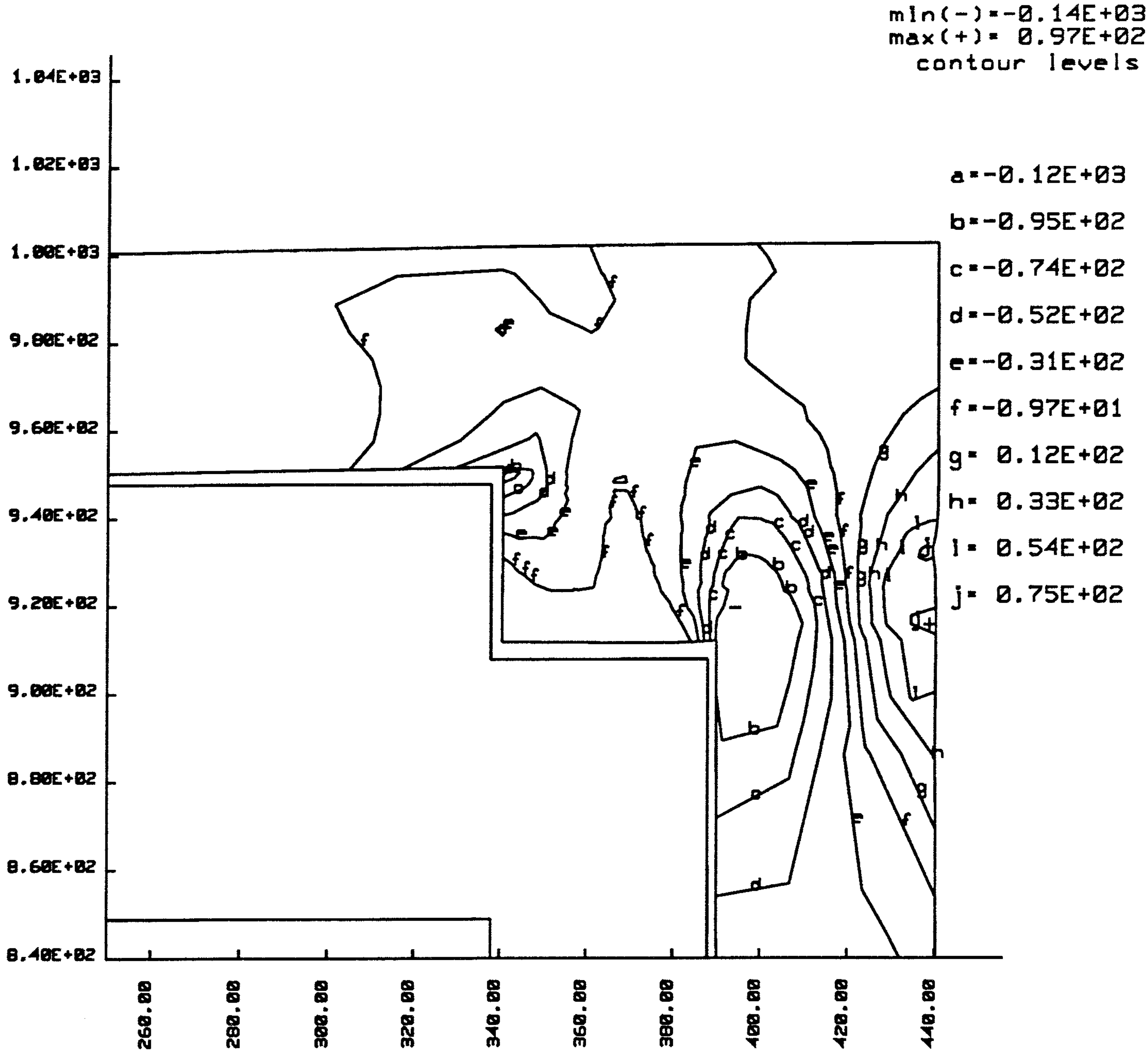

Figure 5a Calculated axial stresses after 100 h of creep deformation using short time creep constants.

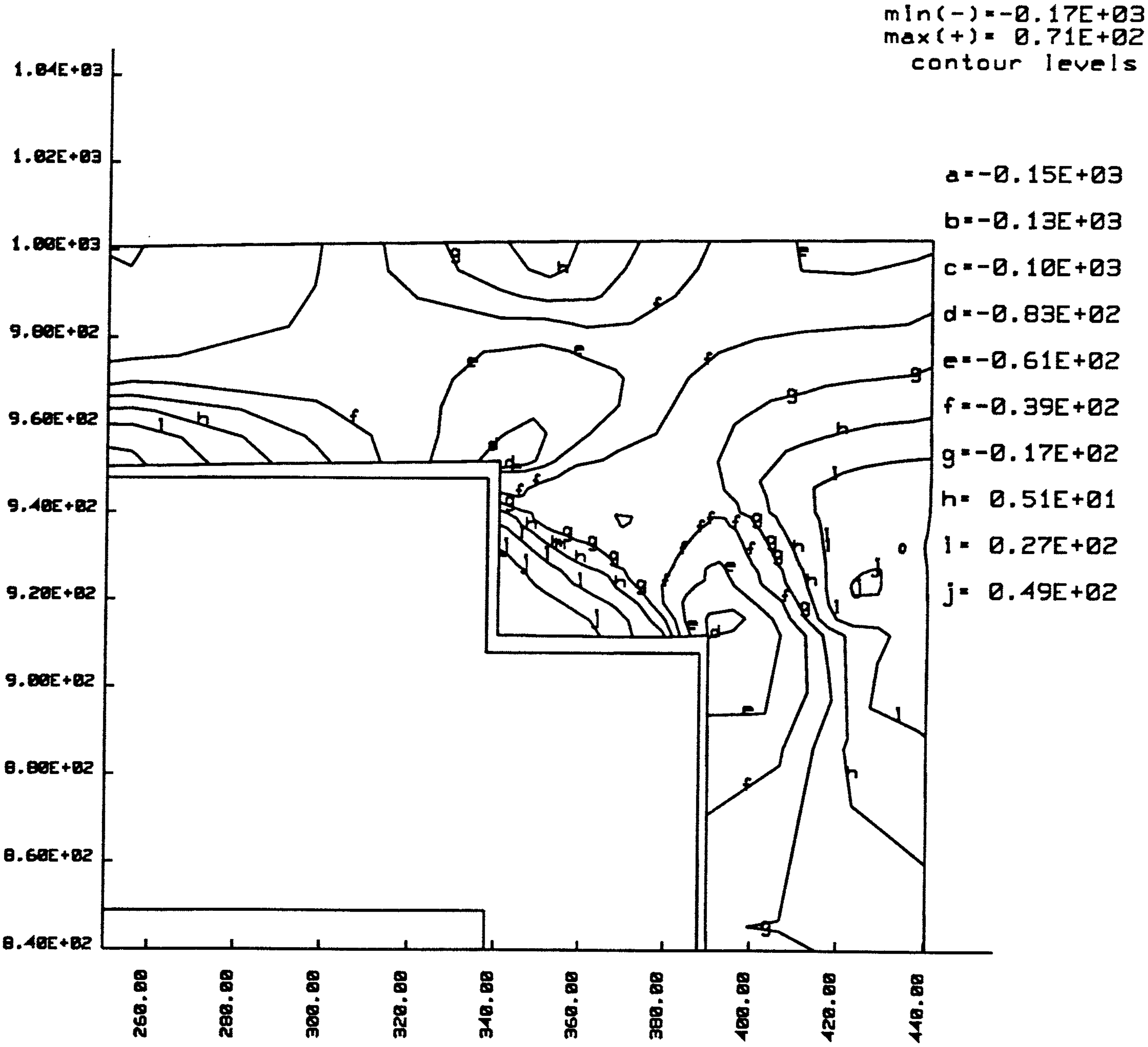

Figure 5b Calculated hoop stresses after 100 h of creep deformation using short time creep constants.

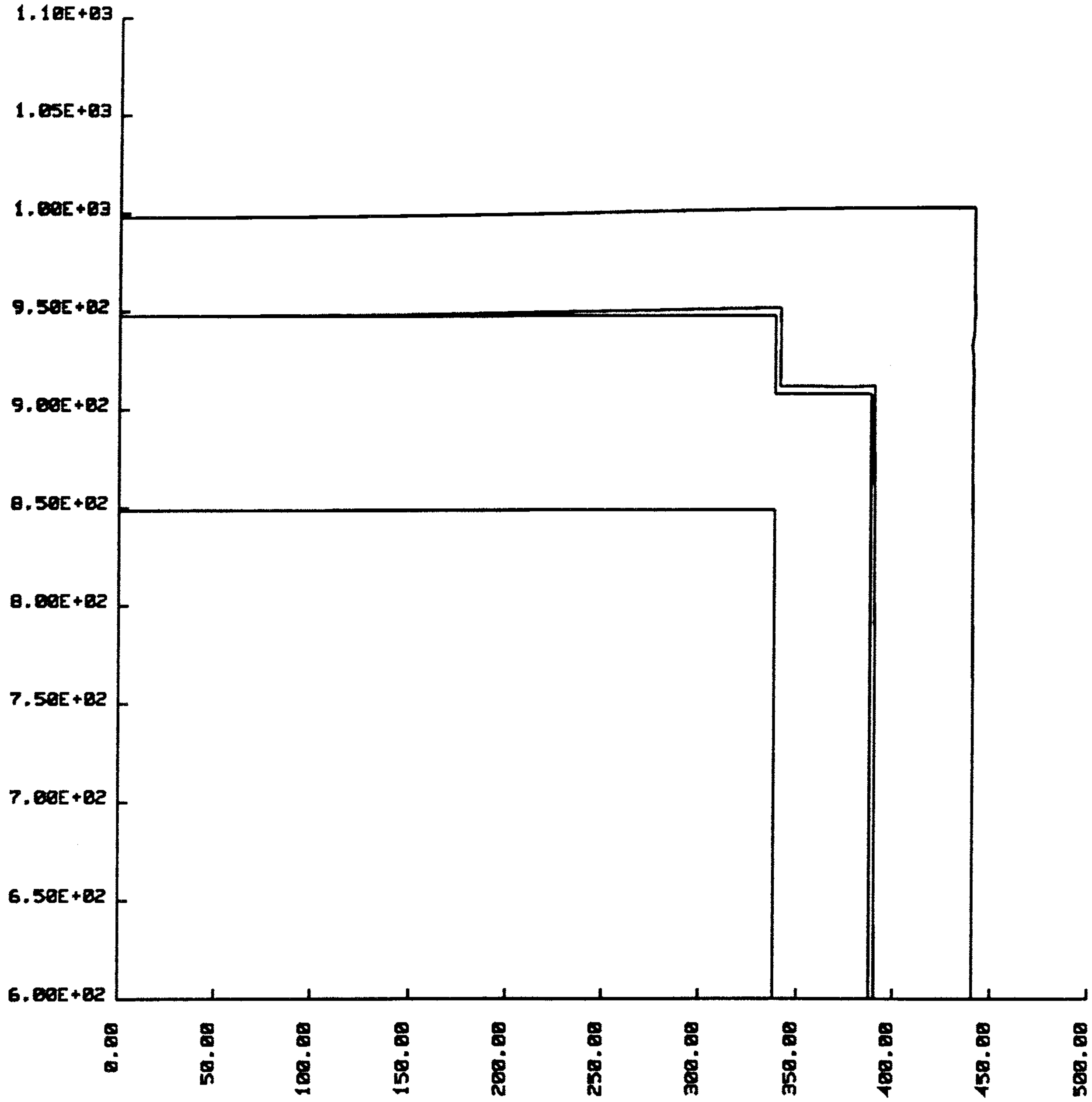

Figure 6 Calculated displacement field after 100 h of creep deformation using short time creep constants.

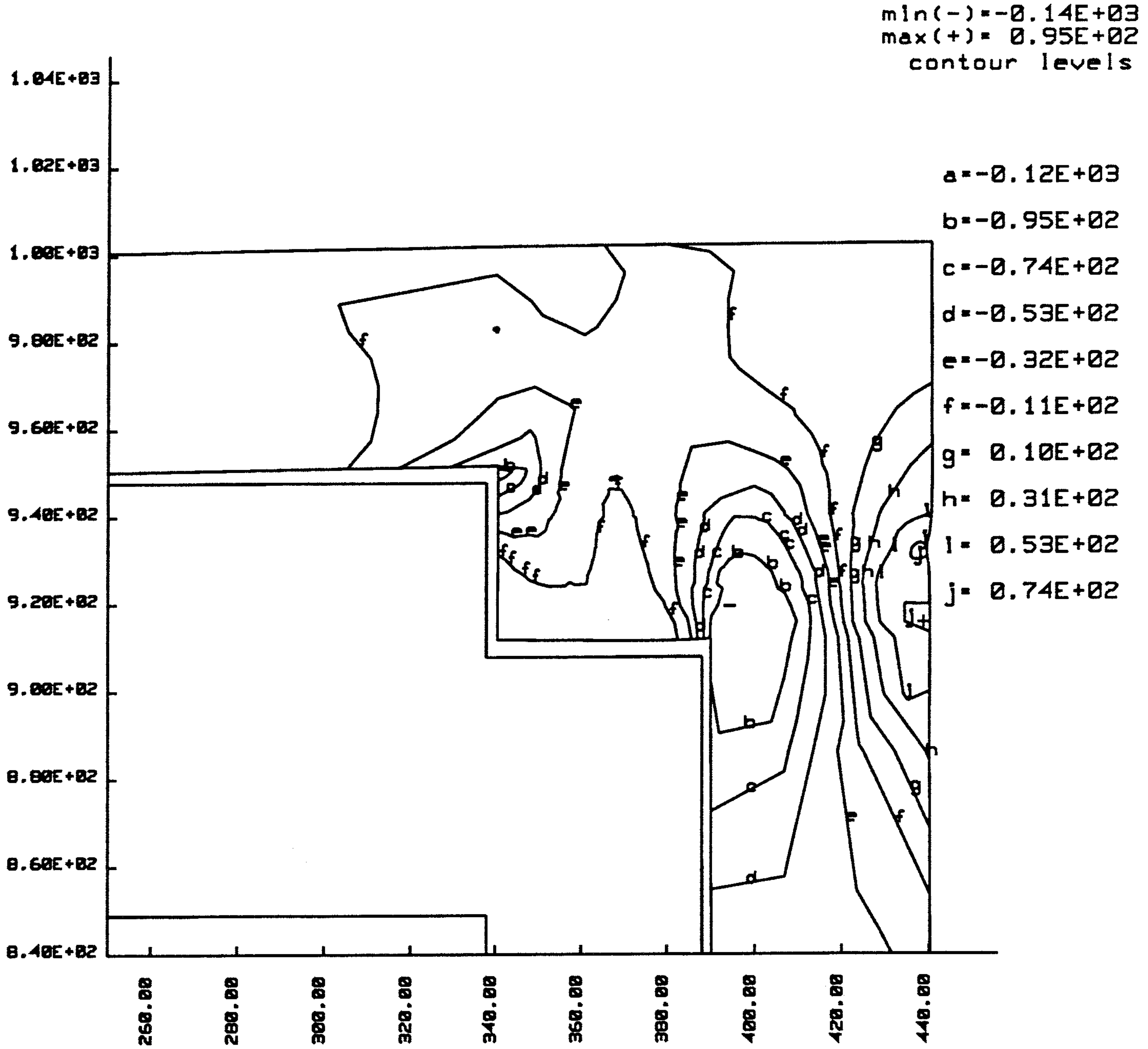

Figure 7a Calculated axial stresses after 10 years of creep deformation using long time creep constants.

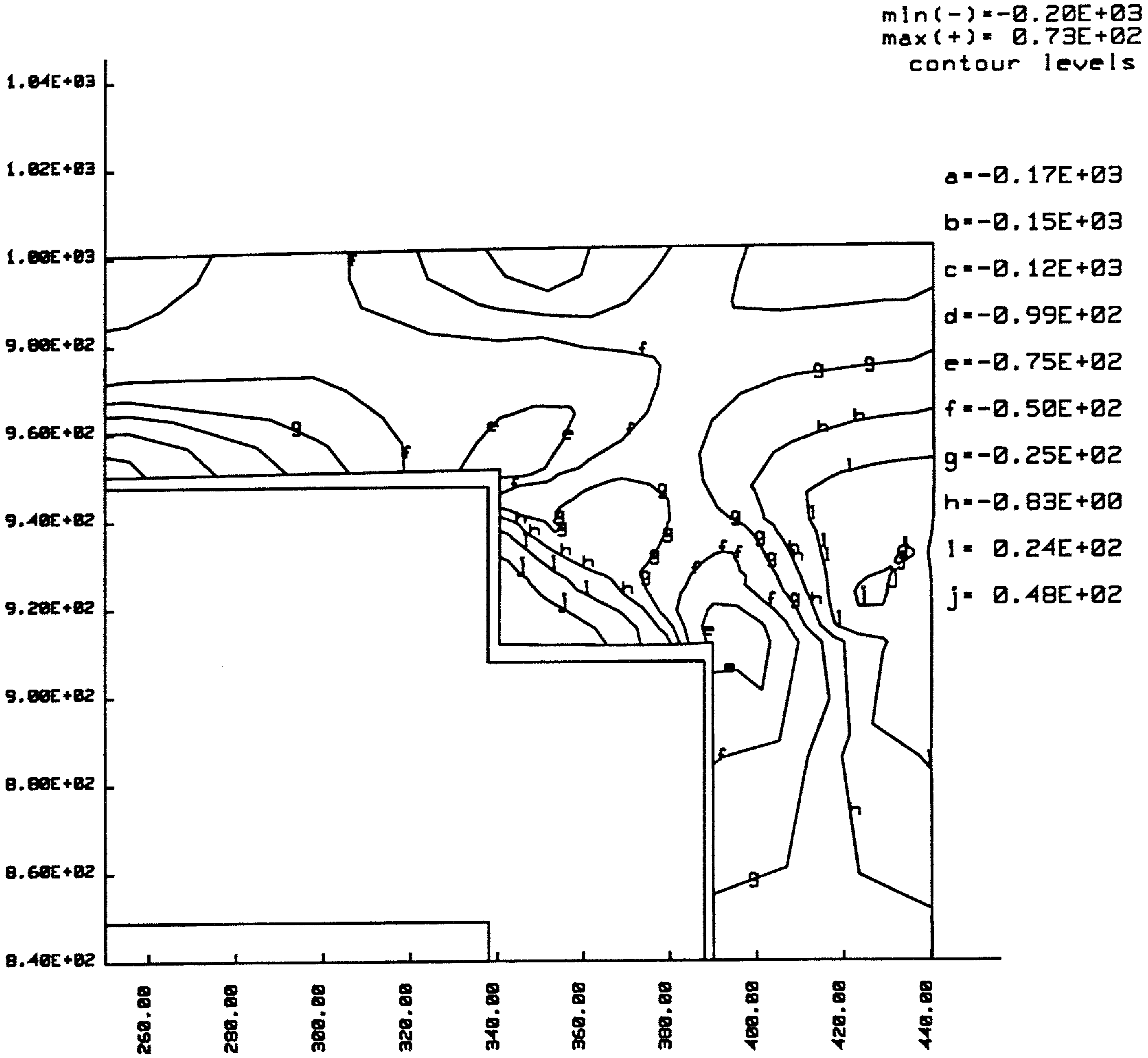

Figure 7b Calculated hoop stresses after 10 years of creep deformation using long time creep constants.

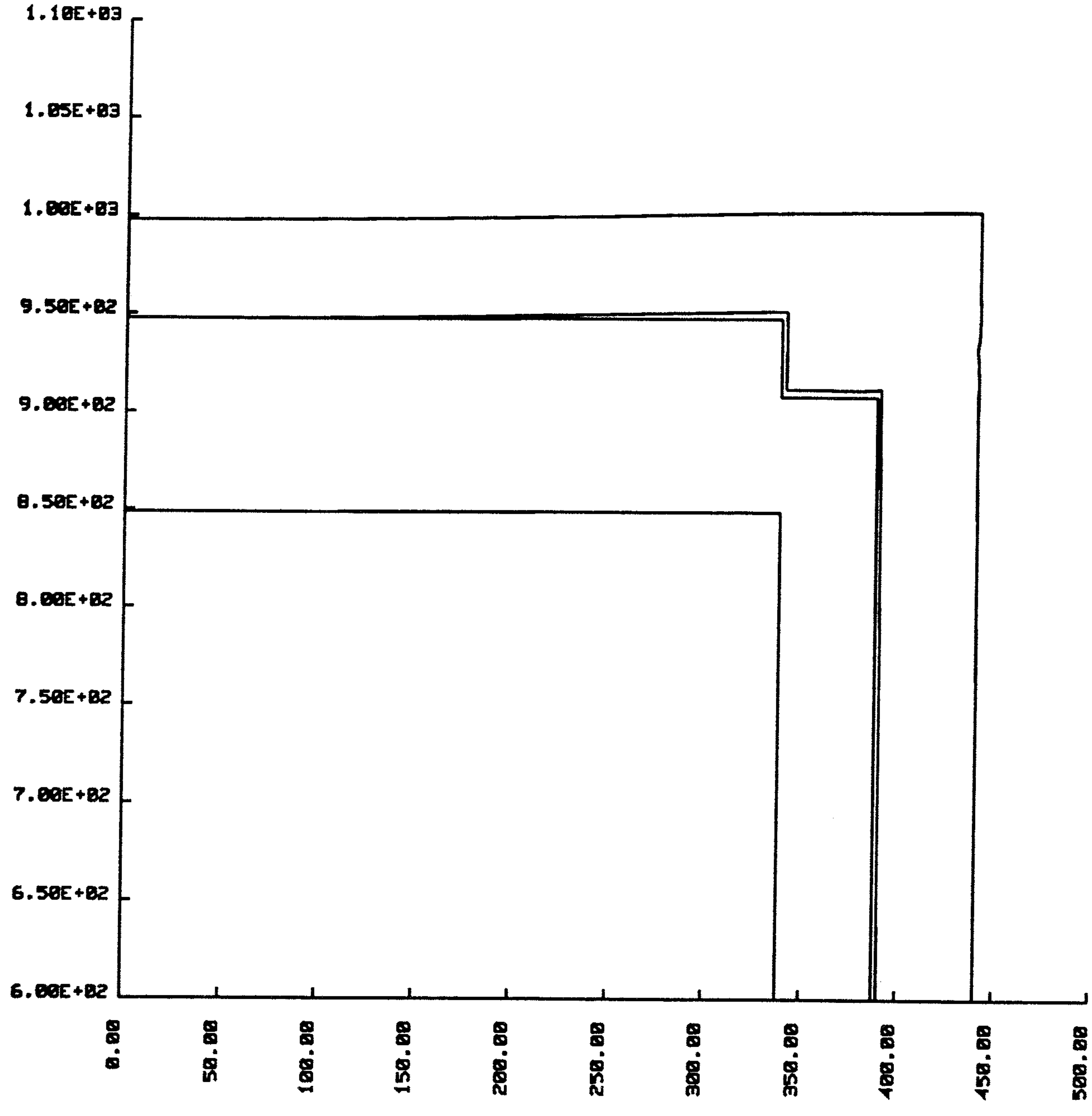

Figure 8 Calculated displacement field after 10 years of creep deformation using long time creep constants.

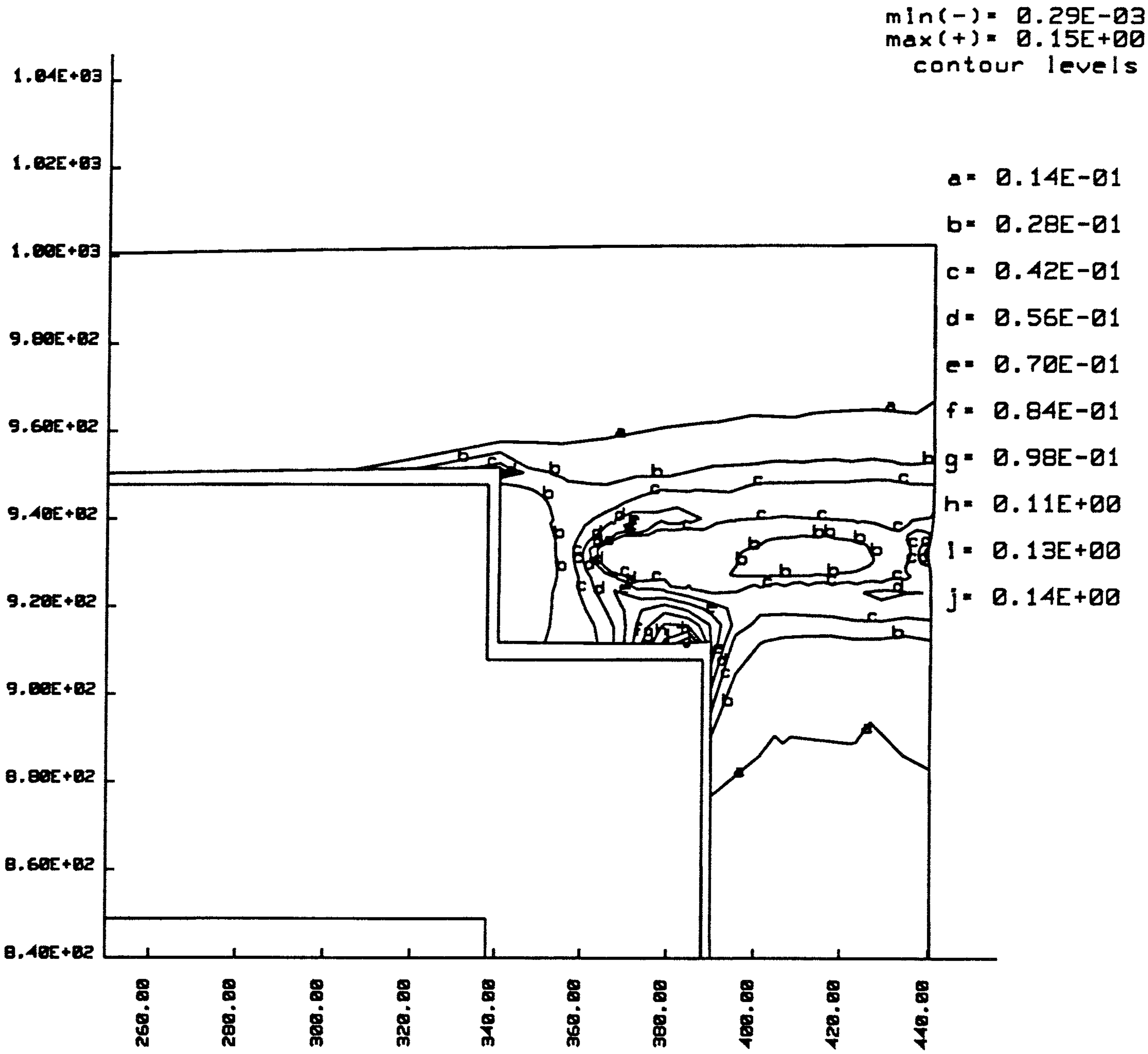

Figure 9 Calculated plastic and creep strain in weld and backing ring region after 100 h of creep deformation using short time creep data

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