

# Elastic-Plastic-Creep Analyses of Brazed Carbon-Carbon/OFHC Divertor Tile Concepts for TPX\*

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## ABSTRACT

The 7.5 MW/m<sup>2</sup> heat flux requirements for the TPX divertor necessitate the use of high conductivity carbon-carbon (C-C) tiles that are brazed to annealed copper (OFHC) coolant tubes. Significant residual stresses are developed in the C-C tiles during the braze process due to large differences in the thermal expansion coefficients between these materials. Analyses which account for only the elastic-plastic strains developed in the OFHC tube may not accurately characterize the behavior of the tube during brazing. The elevated temperature creep behavior of the copper coolant tubes intuitively should reduce the calculated residual stresses in the C-C tiles. Two divertor tile concepts, the monoblock and the archblock, were analyzed for residual stress using 2-D finite element analysis for elastic-plastic-creep behavior of the OFHC tube during an assumed braze cooldown cycle. The results show that the inclusion of elevated temperature creep effects decrease the calculated residual stresses by only about ten percent when compared to those analyses in which only elastic-plastic behavior of the OFHC is accounted for. The primary reason that creep effects at higher temperatures are not more significant is due to the low yield stress and nearly flat-top stress-strain curve of annealed OFHC. Since high temperature creep plays less of a role in the residual stress levels than previously thought, future scoping studies can be done in an elastic-plastic analysis with confidence that the stresses will be within approximately ten percent of an elastic-plastic-creep analysis.

## INTRODUCTION

During the brazing process, the elevated temperature creep of the OFHC copper heat sinks bonded to C-C plasma facing material intuitively should reduce the calculated residual stresses in the C-C tiles. In fact, analyses of all concepts using dispersion strengthened copper tubes, which did not creep, (with and without a compliant layer) showed negative margins of safety. In order to verify the reduction of stress through creep, both the monoblock and archblock divertor tile concepts were analyzed for residual stress using 2-D FEM for elastic-plastic-creep behavior of the OFHC tube during an assumed braze cooldown cycle. Subsequent thermal loads were not analyzed since the residual stresses in the C-C tiles are decreased during steady-state operation.

The inclusion of creep with the effects of the elastic-plastic behavior of the OFHC tube for the monoblock and archblock concepts were performed for an assumed braze cooldown cycle using the ANSYS code. The residual stress results are then compared to the results for an elastic-plastic analysis without the inclusion of creep effects.

## MONOBLOCK CONCEPT

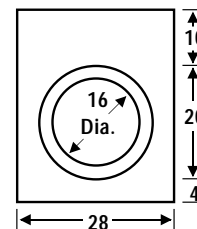
The monoblock design shown in Fig. 1 was used for the analyses. The analyses were performed for Hercules 3-D Pan Fiber C-C brazed to annealed OFHC tube. The graphite was assumed to behave in an elastic manner.

The temperature-dependent elastic-plastic material properties for annealed OFHC were based on data from Refs. [1-5.] The stress/strain curves for the copper were assumed to be adequately represented with a bilinear relationship in which a tangent modulus ( $E_t$ ) defines the stress/strain behavior after yielding has occurred. The material data for OFHC used in the analyses is provided in Table I.

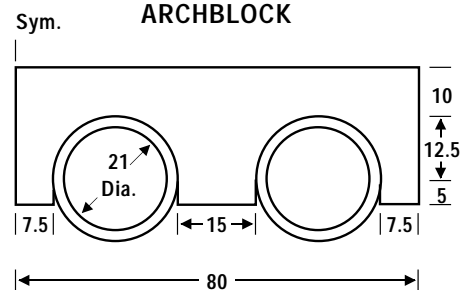
Table I  
Material Properties of Annealed OFHC

T (°C)	E (GPa)	$\nu$	$\alpha$ (10 <sup>6</sup> /°C)	$\sigma_y$ (MPa)	$E_t$ (GPa)
20	96.6	0.33	16.8	34.5	1.31
200	91.8	0.33	17.4	27.6	0.97
400	82.8	0.33	18.1	19.3	0.65
600	69.0	0.33	18.8	13.8	0.34
650	65.5	0.33	19.0	12.4	0.28
750	57.3	0.33	19.7	10.4	0.17

## MONOBLOCK



## ARCHBLOCK



Dimensions in mm

Fig. 1. Geometry of Monoblock and Archblock Tile Concepts.

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Data for the steady-state (secondary) creep strain rate of annealed OFHC at elevated temperatures (to 886°C) was found in Refs. [6–9]. There was considerable scatter in the collected data and linear regression fit of the data over selected temperature ranges was performed to obtain the creep constants required for input to ANSYS code. The secondary creep strain increment  $\Delta \epsilon_{cr}$ , as a function time,  $t$ , is computed in ANSYS by the following equation:

$$\Delta \epsilon_{cr} = \dot{\epsilon} \Delta t$$

where the secondary creep strain rate is:

$$\dot{\epsilon} = A \sigma^B e^{-C/T}$$

- and  $\sigma$  = equivalent stress
- $T$  = absolute temperature
- $e$  = natural log base

The material creep constants over the selected temperature ranges are:

	497° to 886°C	260° to 497°C
A	$2.792 \times 10^{-2}$	$5.91 \times 10^{-4}$
B	4.303	3.429
C	$1.878 \times 10^4$	$7.27 \times 10^3$

Log-log plots of the calculated secondary creep rates versus the various creep rate data are shown in Fig. 2. These show good correlation between published data and a calculated data. The idealized line indicates scattering in the data. It was assumed in this analysis that the creep strains developed below 260°C are negligible compared to those developed at higher temperatures.

The following braze cooldown cycle was used in the elastic-plastic creep analysis assuming a “lock-up” temperature of 750°C. The 50°C temperature drops occur in 36 s. The transition from 500° to 20°C occurs in 5 h.

Hold Time (min)	Temperature (°C)
0	750
60	700
60	650
60	600
60	550
60	500
0	20

Results for the residual stresses at 20°C in the y direction in the C-C monoblock are shown in Fig. 3. The ultimate tensile and compressive strengths of the Hercules 3-D C-C are +240 MPa and -97 MPa. The minimum factor of safety is 1.14 based on the maximum compressive stress developed during the braze process. The copper tube is excluded in the plot to emphasize the C-C stresses. A plot of the maximum equivalent stress (Von Mises) in the OFHC tube versus time in Fig. 4 shows the creep relaxation of copper stress during the braze cycle hold times. It is seen that the stress in the tube relaxes substantially above 500°C, but that the final cooldown to 20°C results in stresses that are in the plastic range. The end result for the OFHC tube is that it is fairly

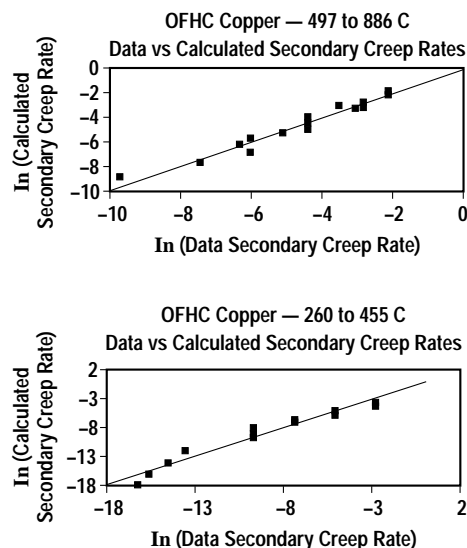


Fig. 2. Log-Log plots of calculated vs. data for secondary creep of annealed OFHC.

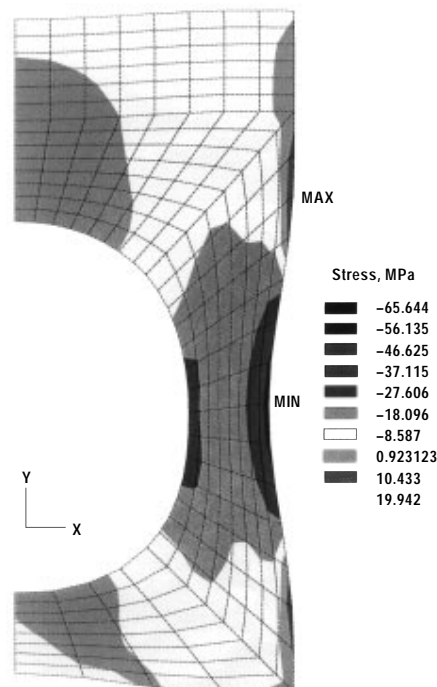


Fig. 3 Residual stress distribution in Y direction in Monoblock.

uniformly stressed to 45 MPa when the stiffness is based on the tangent modulus of the material at room temperature. The final residual stress state in the C–C is primarily a function of the final stress and stiffness state of the tube.

Plots showing the development of the maximum creep strain, plastic strain, and elastic strain components in the OFHC are shown in Fig. 5. The development of the maximum tensile residual stresses in the vertical direction in the C–C throughout the braze cycle is shown in Fig. 4.

The residual stresses in the C–C are nearly identical with or without the inclusion of creep. Comparison of the maximum

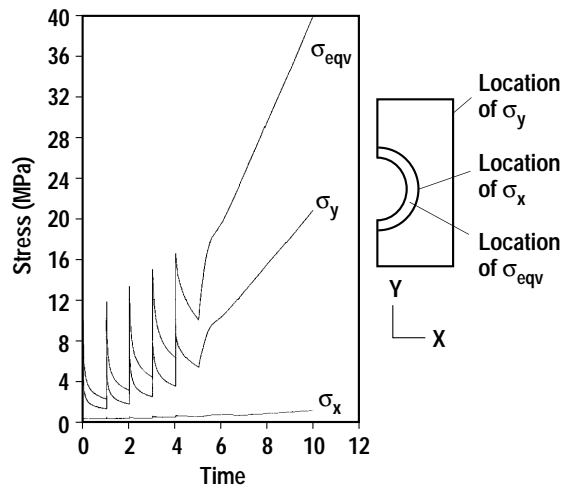


Fig. 4. Development of maximum equivalent residual stresses in Monoblock vs. time.

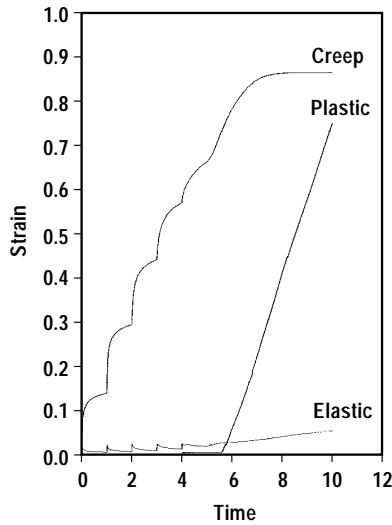


Fig. 5. Development of creep strain, plastic strain, and elastic strains in Monoblock vs. time.

and minimum residual stresses in the C-C with and without creep are shown in Table II. Comparing the 750°C lockup cases, it is seen that accounting for creep effects at the elevated temperatures results in residual stresses that are only slightly less (about 10%) than those when accounting for elastic-plastic behavior only. This somewhat surprising result can be explained by:

- 1) The monoblock design OFHC tube is almost uniformly stressed well into the plastic range during braze cooldown.
- 2) The total strains in the OFHC tube are limited by the temperature range of the braze cycle, i.e., they are secondary strains and are self-limiting.
- 3) The total strains developed in the OFHC tube are therefore about the same whether achieved by an elastic-plastic path or a combined elastic-plastic-creep path.
- 4) The low yield stress and nearly flat-top stress strain curve of annealed OFHC results in a tube uniformly stressed to its

yield stress and a stiffness characterized by its tangent modulus. Therefore, any assumed lock-up temperature of the braze which will cause the OFHC tube to be in the plastic range should produce the same residual stresses in the C-C monoblock tile.

Table II  
Calculated Maximum Residual Stresses and Strains in Monoblock (maximum and minimum stresses given)

Analysis Type	Elastic-Plastic	Elastic-Plastic-Creep	Elastic-Plastic
Lockup temperature (°C)	750	750	500
$\sigma_x$ in C-C (MPa)	+14.5 -91.9	+13.3 -84.8	+13.5 -87.0
$\sigma_y$ in C-C (MPa)	+21.9 -72.0	+19.9 -65.5	+20.5 -67.3
$\sigma_{eff}$ in OFHC	48.5	44.5	45.8
Plastic strain in OFHC	0.025	0.018	0.017
Creep strain in OFHC	—	0.009	—

In order to check the above theory, an elastic-plastic analysis of the monoblock was performed in which a lockup temperature of 500°C was used. These results show stresses in the C-C that are within the range of the other analyses which used a lockup temperature of 750°C. Note that the non-linear strain in the OFHC is much less than that calculated in the other two analyses. Since creep plays less of a role in the residual stress levels than previously thought, future scoping studies can be done in an elastic-plastic analysis with confidence that stresses will be within ~10% of an elastic-plastic-creep analysis.

It is theorized from this study that it is important to account for low temperature creep effects on the residual stresses in the monoblock tile. The residual stresses in the tile will decrease due to creep near room temperature as the stress in the copper relaxes below its yield stress. This would be difficult to study analytically because the creep strain rate of OFHC is small at lower temperatures, requiring longer computation times.

### ARCHBLOCK CONCEPT

The archblock divertor tile design shown in Fig. 1 has been selected as the preferred concept for the highest heat flux areas of the TPX divertor. This design consists of a wide FMI 3-D fine weave C-C brazed to four OFHC tubes. Although this 3D C-C was selected for this analysis, other C-C materials are still under consideration. This combination of materials provides the highest safety factor against the ultimate for residual stresses due to brazing in a 2-D analysis. Also, the use of hold-downs anchored in the tile and bolted to the Ti backing plate make the use of a 3-D C-C highly desirable.

An elastic-plastic-creep analysis of the archblock was performed for the same braze cooldown cycle as was used for the monoblock. The lock-up temperature was taken to be 750°C. The materials properties input to the ANSYS code for the OFHC are shown in Table I. Also, the creep constants for the OFHC used in the analysis of the monoblock were used here.

Results for the residual stresses in the X and Y directions in the archblock tile are shown in Table III. It is to be noted that the peak tensile stresses occur at the tangency point between the copper tube and the tile. The peak tensile stress (in the X direction) which would initiate a crack at the braze interface is 40 MPa. This provides a high factor of safety of 4.4 against the ultimate tensile stress for this 2-D analysis. However 3-D analyses indicates high stresses at the end of the tile.

The plot of the development of the residual stresses in X and Y directions at a point in the tile is shown in Fig. 6. It would appear from this plot that the inclusion of creep effects into the analysis would result in calculated stresses lower than analyses which account for only the elastic-plastic behavior of the OFHC material. An elastic-plastic analysis (without creep) was performed for the archblock design. The stress contour plots for this analysis were very similar to those in which creep included. However, as shown in Table III, the maximum and minimum stresses are about 10% greater than those in which creep was not included. The redistribution of inelastic strains to the elastically stressed part of the copper tube was not as great as expected. The minimum factor of safety for the FMI 3-D fine weave C-C is 1.77 based on its ultimate compressive strength.

Table III  
Calculated Maximum Residual Stresses and Strains in Archblock  
(maximum and minimum stresses given)

Analysis Type	Elastic-Plastic	Elastic-Plastic-Creep
$\sigma_x$ in C-C (MPa)	40.8 -46.2	40.0 -43.9
$\sigma_y$ in C-C (MPa)	75.6 -65.3	70.3 -62.0
$\sigma_{eff}$ in OFHC (MPa)	48.5	44.5
Plastic strain in OFHC	0.0197	41.9
Creep strain in OFHC	—	0.0085

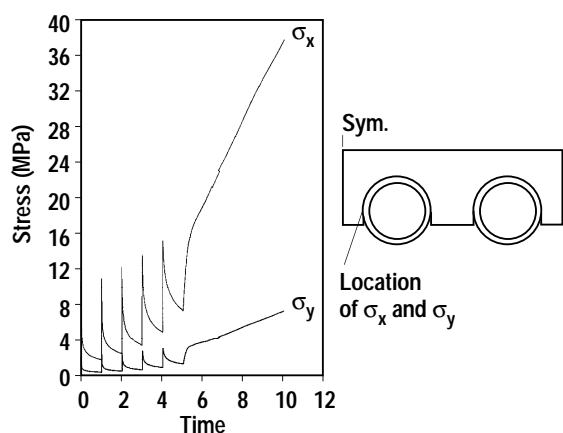


Fig. 6. Development of residual stress vs. time in Archblock.

## SUMMARY

These results show that the inclusion of elevated temperature creep effects decrease the calculated residual stresses by only about ten percent when compared to those analyses in which only elastic-plastic behavior of the OFHC is accounted for. The primary reason that creep effects at higher temperatures are not more significant is that the total strains developed in the OFHC tube are about the same whether achieved by an elastic-plastic path or a combined elastic-plastic-creep path. This is due to the low yield stress and nearly flat-top stress-strain curve of annealed OFHC. It is theorized that it is important to account for low temperature creep in the OFHC in estimating the final residual stress state in the tiles.

A 2-D analysis shows that the archblock with 3-D fine weave C-C develops acceptable residual stresses after the braze cooldown cycle. Based on compressive strength, the factor of safety is 1.77. More importantly, the stress to initiate a crack at the braze interfaces gives a factor of safety of 4.4. A 3-D model of the archblock will be analyzed in future work for residual stresses near the singularity points at the free edge of the tile in the direction of the tube axis.

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