Thermal and Structural Analysis of the TPX Divertor*

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ABSTRACT

The high heat flux on the surfaces of the TPX divertor will require a design in which a carbon-carbon (C-C) tile material is brazed to water cooled copper tubes. Thermal and structural analyses were performed to assist in the design selection of a divertor tile concept and C-C material. The relevancy of finite element analysis (FEA) for evaluating tile design was examined by conducting a literature survey to compare FEA stress results to subsequent brazing and thermal test results. The thermal responses for five tile concepts and four C-C materials were analyzed for a steady-state heat flux of 7.5 MW/m^2. Elastic-plastic stress analyses were performed to calculate the residual stresses due to brazing C-C tiles to soft copper heat sinks for the various tile designs. Monoblock and archblock divertor tile concepts were analyzed for residual stresses in which elevated temperature creep effects were included with the elastic-plastic behavior of the copper heat sink for an assumed braze cooldown cycle. As a result of these 2D studies, the archblock concept with a 3D fine weave C-C was initially found to be a preferred design for the divertor. A 3D elastic-plastic analysis for brazing of the arch block tile was performed to investigate the singularity effects at the C-C to copper interface in the direction of the tube axis. This analysis showed that the large residual stresses at the tube and tile edge intersection would produce cracks in the C-C and possible delamination along the braze interface. These results, coupled with the difficulties experienced in brazing archblocks for the Tore Supra limiter, required that other tile designs be considered. Recent developments at Tore Supra and JET have shown that a robust divertor design can be achieved by a macroblock concept. This concept utilizes a large C-C plate in which multiple coolant tubes are brazed or cast by processes that greatly minimize defects at the C-C/copper interface. Thermal analysis results for a 2D C-C macroblock concept incorporating two coaxial counterflow coolant tubes are presented.

INTRODUCTION

The design of the divertors for the Tokamak Physics Experiment (TPX) consist of 16 toroidal modules of 22.5 degrees as shown in Fig. 1. The divertors are mounted at the top and bottom of the vacuum vessel by continuous ring structures to assure proper alignment of the heat flux surfaces. Each module has three heat flux surfaces for the inner, middle, and outer divertor. The high heat flux on the divertor surfaces will require a design in which carbon-carbon (C-C) tile materials are brazed to water cooled copper tubes. The brazing process produces the most severe stresses in the tiles due to the large difference in the coefficient of thermal expansion between the C-C material and copper tube. To assist in the selection of a divertor tile concept and C-C material type, a number of thermal and structural analyses were performed. This paper summarizes the conclusions from this analysis effort and describes the process leading to selection of the macroblock concept.

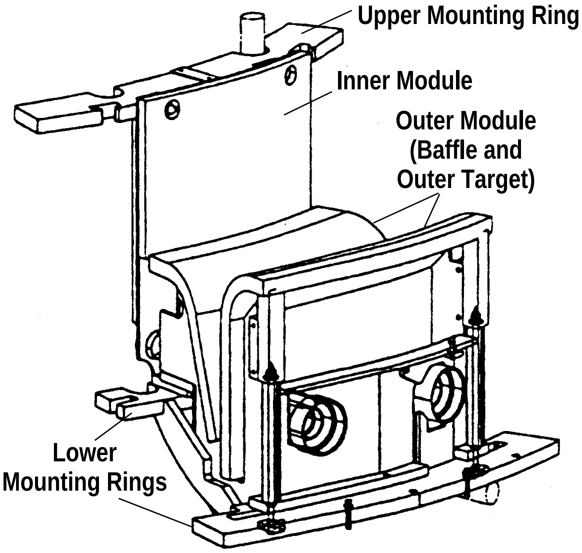

Fig. 1. TPX divertor module concept.

SELECTION OF TILE CONCEPTS

The divertor tile scoping studies were based on a maximum operating heat flux on the surface of the divertor tiles of 7.5 MW/m^2, a peak allowable surface temperature of 1400°C and a braze cooldown cycle with an assumed lockup temperature of 750°C. The scoping study included the tile concepts shown in Fig. 2. Three C-C materials were selected for structural analysis due to braze cooldown and thermal analysis during maximum steady-state operation: (1) Carbone-Lorraine A05-2CFC, (2) SEP N112 (1 + 2), and (3) FMI 3D fine weave with P55 fiber. All analyses are based on manufacturers nominal properties.

The elastic-plastic analyses of the five concepts were performed using the COSMOS/M finite element code. With the exception of the monoblock tile concept, all the finite element models required a very fine mesh at the free edge of the braze interface between the C-C tile and OFC heat sink.

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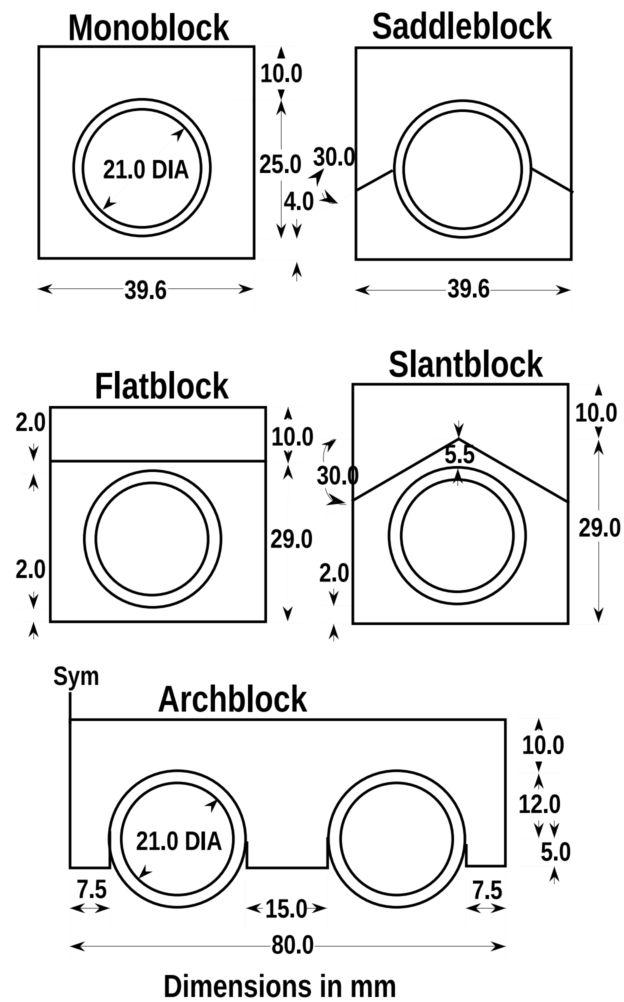

Fig. 2. Divertor concepts analyzed in scoping study.

The fine mesh is required due to the existence of a stress singularity at the free edge.

Table I summarizes the factor of safety based on manufacturer's properties for each concept based on maximum tensile stress at the braze interface. The table shows that the monoblock with SEP N112 C-C and the archblock with 3D fine weave C-C provide safety factors greater than 4.0 at critical tensile stress zones. Only the flatblock with Carbone-Lorraine A05 and SEP N112 C-C had calculated safety factors less than 1.0. The stresses reported are taken at two elements away from the singularity for the flatblock, saddleblock, and slantblock concepts. Previous studies have shown that finite element solutions of bi-material interfaces are accurate within two elements of the edge [1]. The stresses reported for the archblock are the maximum calculated values since they are due to a stress concentration rather than singularity effects.

The results from this study show that the archblock with 3D fine weave C-C is a strong candidate for being the preferred concept. In addition to having relatively low stresses due to brazing, the archblock has the large advantage of having adjacent tubes to help cool the C-C should one or more tubes have bad brazes. It should be noted that these 2D analyses do not include stress singularities along the tube length. 3D analyses of these concepts lead to different conclusions.

Table I
Braze Cooldown Factors of Safety[(a)]
(F.S. = $\sigma_{ult}/\sigma_{max}$) ($\sigma_{max}$ is tensile stress to initiate a crack at braze interface)

	Carbone Lorraine A05 - 2 CFC	SEP N112 (L1+2)	FMI 3D Fine Weave CFC
Monoblock	3.4	4.4	2.7
Saddleblock	1.9	1.8	2.0
Flatblock	0.75	0.77	1.88
Archblock	2.0	1.1	4.2
Slantblock	3.0	2.7	2.2

[(a)]Based on 2D analysis.

Thermal analysis of each of the five tile concepts and 3 C-C materials was performed for a steady-state surface heat flux of 7.5 MW/m^2. The analysis assumes a water velocity of 6 m/s at a pressure of 1 MPa and bulk temperature of 92°C. This is the coolant temperature at the end of the coolant channel for 35°C inlet temperature. Also, twisted tape (twist ratio, y = 2) is used in the copper tube to increase the heat transfer coefficient. The twist ratio, y, defined as number of diameters per 180° tape twist, is equal to 2. The heat transfer coefficient is calculated as a function of the wall temperature of the copper tube and accounts for the possibility of boiling.

The calculated peak surface temperature for each of the tile concepts and materials are given in Table II. The peak temperatures for all concepts are less than the 1400°C limit. The conductivity used in this analysis for the 3D fine weave C-C can be increased by using P100 fibers in lieu of the standard P55 fiber. Also, the temperature of the inside of the copper tubes does not reach the critical heat flux levels. The maximum wall heat flux in the coolant channel was about 50% of the critical heat flux at these flow conditions.

Table II
Maximum Temperature (C) of Carbon Tile, q" = 7.5 MW/m^2

	Carbone Lorraine A05 - 2 CFC	SEP N112 (L1+2)	FMI 3D Fine Weave CFC	MFC-1
Monoblock	1078	1116	1143	–
Saddleblock	1048	1113	1135	–
Flatblock	866	988	952	542
Archblock	1142	1141	1174	–
Slantblock	1179	1347	1391	–

During the brazing process, the elevated temperature creep of the copper heat sinks of C-C/OFC PFCs intuitively should reduce the calculated residual stresses in the C-C tiles. Both the monoblock and archblock divertor tile concepts were analyzed for residual stress using 2D FEM for elastic-plastic-creep behavior of the OFC tube during an assumed braze cooldown cycle using the ANSYS code. A complete description of this analysis is presented in Ref. [3]. 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.

ANALYSES OF STRESS SINGULARITIES

The preliminary selection of the archblock concept was partly based on the 2D elastic-plastic analyses in which a standardized mesh size was used to evaluate various concepts for the braze cooldown cycle. Typically, the mesh size at locations of possible stress singularities was taken to approximately the same as the unit cell size of the C-C material. Stress singularities cause very high localized stresses to be calculated at elements near the fee edges at the interface between dis-similar materials.

The location of the high tensile stresses in the archblock occurs at the intersection of stress concentration (at the tangency point) and the singularity at the tube extension. This agrees with the cracks observed in a similar design using pyrolytic graphite that was brazed at Sandia National Laboratory (SNL). Discussions with SNL emphasized the difficulties in fabrication of the archblock concept due to fitting and jigging of annealed OFC tubes during the braze process. They strongly discouraged acceptance of the archblock concept for TPX based on their experience with the limiter for Tore Supra.

The problem in attempting to analytically evaluate brazed C-C tiles is that there is no method for properly evaluating the high stresses calculated at singularity locations, particularity if the heat sink is allowed to yield. Depending on the material properties of the brazed components and the geometry at free edges, it is possible that the singularity disappears and is only a stress concentration. This determination can be made only by analyzing a given concept with at least three progressively finer mesh sizes around the singularity. This method, suggested by SNL, is used to calculate the strength and intensity of the singularity for a specific concept. There is no criteria for evaluating the singularity strength and stress intensity. However, lower values of both the strength and stress intensity indicates a preferred concept when comparing various designs.

The high tensile stress at the singularity points may not result in failure of the component since these stresses become compressive a short distance away from the free edge along the braze interface preventing a Mode I crack (tensile stress normal to crack) from propagating. However, the high shear stresses extend a considerable distance along the braze interface, suggesting that a small Mode I crack could propagate in a Mode II loading (shear stress in plane of the crack). Also, a crack formed during the brazing process may propagate during subsequent thermal and stress cycles. This type of failure has seen some experimental results [2].

There has been a great deal of development world-wide on C-C tiles brazed to OFC heat sinks. There are several papers which report stress analysis results indicating that residual stresses due to brazing should result in failure of the C-C tiles, but the actual concept survive brazing and subsequent thermal testing without damage. In an effort to resolve these differences between stress analysis and actual fabrication, a literature survey was conducted to compare finite element results to observed results after brazing and thermal testing. It is concluded from this survey that tile design which resulted in large calculated safety factors can be successfully fabricated and tested thermally to design loads for 1000 cycles. However, tile designs with safety factors near one or less than one sometimes survive fabrication, but in some cases fail as predicted by analysis.

MACROBLOCK CONCEPT

Collaboration with members of the international fusion community led to acceptance of the macroblock concept shown in Fig. 3 as the preferred concept for the TPX divertor. Recent development of the macroblock concept at Tore Supra and JET have shown very promising results for both the fabrication process and high heat flux testing [4,5]. The TPX macroblock concepts consists of five OFC tubes brazed inside a C-C plate. The pressurized assembly is then brazed and cooled down under pressure to reduce residual stresses through creep effects.

The macroblock design offers the following advantages:

1) A very reliable braze joint with no voids at the tube/ C-C interface. The coolant tubes are self jigging within the macroblock.

2) The C-C plates replaces a large number of tiles. Fewer parts translates to higher reliability.

3) Stress singularities exist only at the free ends of the macroblock, away from the high heat flux zones.

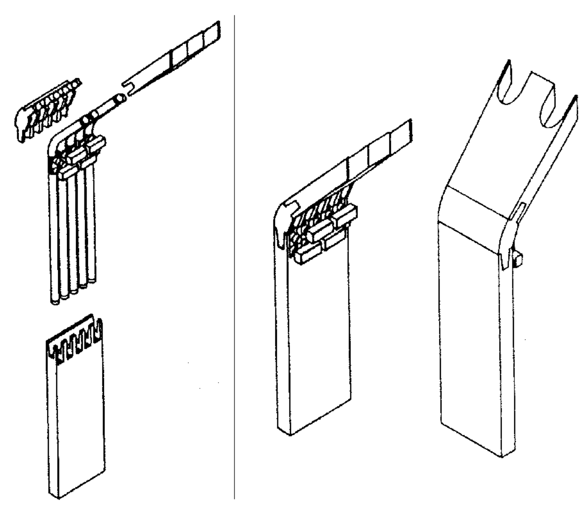

Fig. 3. Five tube macroblock concept.

4) The macroblock provides a robust structural element for attachment to a support structure. The electromechanical loads are not reacted through the annealed OFC coolant tubes.

5) The multiple brazed tubes provide redundant conductive heat flow paths in case of blocked coolant in one or more tubes.

6) Macroblock designs have been successfully built and thermally tested for more than 1000 cycles [4,5].

A 3D steady-state thermal analysis of the macroblock divertor concept was completed which incorporates the effect of an axially distributed heat flux profile along the axis of the tube. The axial heat flux profile peaks at 750 W/m^2, near the center of the macroblock and decreases with distance along the axis of the tube. Thermal results using this distributed profile were compared to results using a constant heat flux of 750 W/m^2. Coolant channels with and without swirl flow were analyzed. Table III shows the maximum temperatures in the C-C, at the top of the tube, and on the inner surface of the tube.

Table III
Thermal Results for Macroblock Concept

	2D Swirl Const. q"	3D Swirl Const. q"	3D Swirl Dist. q"	3D No Swirl Const. q"	3D No Swirl Dist. q"
Max CFC temp, °C	1146	1146	973	1232	1063
Top of tube temp, °C	252	252	236	291	276
Inside of tube temp, °C	193	194	186	232	226
Max inside wall q'' (W/cm^2)	1170	1193	1007	1200	1015

In comparing the constant heat flux profile case (quasi 2D) to the case with a distributed heat flux profile, the maximum wall heat flux is about 15% lower with the distributed heat flux. Also, the copper tube temperatures are lower by about 15°C.

A 3D elastic-plastic stress analysis of the macroblock tile concept was performed using the structural model for the standard braze cooldown of 750° to 20°C. The coolant tube was modeled as extending slightly beyond the free edge of the C-C plate. The results show that at the symmetry end, the residual tensile and compressive stresses satisfy the TPX stress criteria for C-C of 0.67 times the ultimate tensile strength and 1.0 times the ultimate compressive strength. The residual shear stress does not meet the allowable of 0.67 times the ultimate shear strength but is at the ultimate shear strength of the material. The fee radial contraction of the tube extension produces localized high radial stresses which may cause circumferential cracks to develop in the C-C material. In addition, the singularity stress condition at the free edge of the macroblock produces calculated stresses which would indicate debonding would occur over a short distance along the braze interface. Neither of these types of failure were observed in the actual fabrication of the macroblocks using SEP N11 C-C for testing by Tore Supra personnel.

CONCLUSIONS

The inability of finite element analyses to calculate residual stresses in C-C tiles brazed to OFC heat sinks limits the use of stress analysis for selecting a preferred divertor tile concept and C-C material. However, it is useful to use elastic-plastic finite element stress analyses to determine the stress intensity and strength of the stress singularity for comparison between various concepts and material combinations. The best solution is to avoid the stress singularity and stress concentration effects as much as is possible. This is achieved by the macroblock design where high residual stresses exist only at the braze interface at the ends of the plate away from high heat flux zones.

Accounting for creep effects at elevated temperatures in the OFC tubes results in residual stresses that are only about 10% less than those when accounting for elastic-plastic behavior only.

The five tube macroblock has been selected as the preferred concept for the TPX divertor. The design produces very reliable braze joints required for heat transfer. The use of swirl tape within the coolant tubes will limit peak surface temperatures on the divertor surface to about 1000°C. Also, the macroblock provides a robust structural element for reacting electromechanical loads through its attachments.

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