Thermal Hydraulic Analysis of the TPX Plasma Facing Components*

C.B. Baxi, E.E. Reis, K.M. Redler, E.E. Chin, R.H. Boonstra, K.M. Schaubel
P.M. Anderson, E.H. Hoffman
General Atomics, P.O. Box 85608, San Diego, California 92186-9784

ABSTRACT

The purpose of the tokamak physics experiment (TPX) is to develop and demonstrate steady state tokamak operating modes that can be extrapolated to reactor conditions. TPX will have a double null divertor with an option to operate in a single null mode. The maximum input power will be 45 MW and the pulse length will be 1000 s. The major and minor radii will be 2.25 m and 0.5 m respectively. The material of plasma facing components (PFCs) will be carbon fiber composite (CFC). The cooling will be provided by water at an inlet pressure of 2 MPa and inlet temperature of 50°C. The heat flux on the PFCs will be less than 0.2 MW/m^2 on line of sight shields to 7.5 MW/m^2 on divertor surfaces. The maximum allowable temperature on the divertor surface is 1400°C and 600°C on all other PFCs. The attachment method, the type of CFC, the coolant flow velocity and the type of coolant channel is chosen based on the surface heat flux. In areas of highest heat flux, heat transfer augmentation will be used to obtain a safety margin of at least 2 on critical heat flux.

An extensive thermal flow analysis has been performed to calculate the temperatures and pressure drops in the PFCs. A number of R&D programs are also in progress to verify the analysis and to obtain additional data when required.

The total coolant flow rate requirement is estimated to be about 50 m^3/min (12000 gpm) and the maximum pressure drop is estimated to be less than 1 MPa.

INTRODUCTION

A new steady state tokamak facility called "Tokamak Physics Experiment" (TPX) has been proposed [1]. The purpose of this machine is to develop and demonstrate long pulse and advanced tokamak operations.

A view of the TPX with the plasma facing components is shown in Fig. 1. The vacuum vessel of the TPX will be made from titanium alloy, Ti-6Al-4V, to reduce the activation. The plasma facing components (PFCs) will be made from carbon fiber composites (CFC). The PFCs will be cooled by water. The TPX machine will be designed for initial baseline design of 18 MW of input power and later upgraded to operation at 45 MW. However, all PFCs will be designed for the 45 MW operation from the beginning. Table I shows the expected peak heat fluxes on different plasma facing components of TPX.

Table I
Heat Flux Distribution on Plasma Facing Components

Type of PFC	Peak Steady State Heat Flux (MW/m^2)
Inboard Limiter	Most areas 0.4, NB shine through areas 1.7
Lower & upper inboard passive plate	0.4
Lower & upper inboard divertor target	7.5
Lower & upper center divertor target	4.0
Lower & upper outboard divertor target	7.5
Lower & upper outboard passive plates	0.4
Poloidal Limiters	0.4
NB outer wall shine through armor (1 beam)	2.7
NB inner wall shine through armor (1 beam)	1.45
Line of sight shield (peak on vertical part)	0.20
Outboard toroidal limiters	0.4
Ripple armor	1.75

DESIGN CRITERIA

The PFCs will be cooled by water at an inlet pressure of 2 MPa and an inlet temperature of 50°C. Following limits on maximum temperatures of PFCs and structural materials are warranted by material properties and lifetime considerations:

Divertor PFCs	1400°C
All Other PFCs	600°C
Belleville Washers	400°C
Titanium Manifolds & Bolts	400°C
Copper Cooling channels in the divertor	300°C

The above criteria will be satisfied by using the simplest and cheapest possible attachment and cooling scheme for each of the components shown in Fig. 1.

In addition to the above thermal limits, an extensive stress analysis was undertaken (Ref. 2) to insure that stresses in the PFCs were within limits.

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-76CHO3073, Subcontract S03756-K.

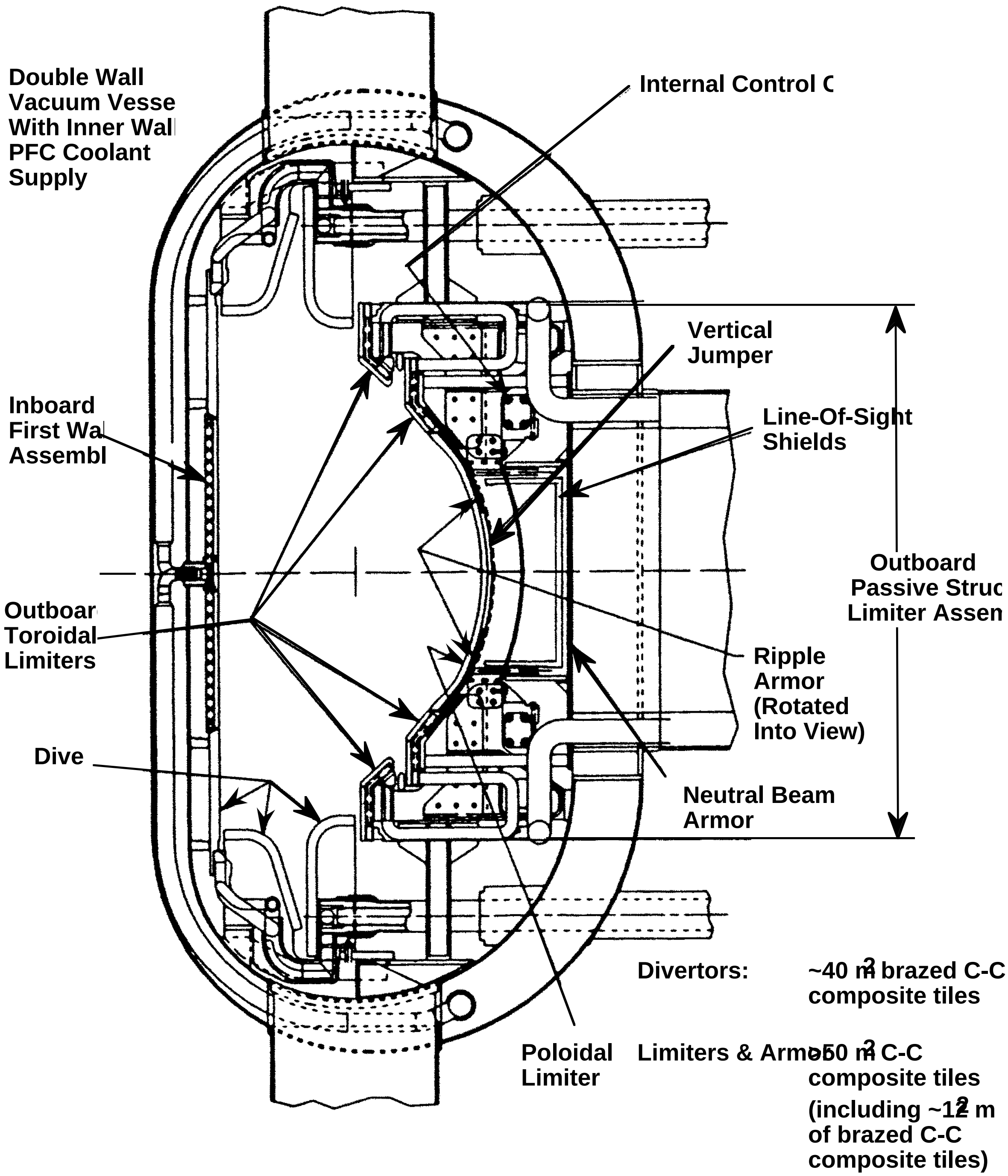

Fig. 1. TPX plasma facing components.

THERMAL ANALYSIS

Heat transfer coefficients during single phase and boiling heat transfer were calculated as a function of local wall temperature by using correlations recommended in Refs. 3 and 4. Figure 2 shows a typical variation of heat transfer coefficient calculated for a smooth channel and for a channel with swirl tape. The peak heat flux on the PFCs varies from 0.20 MW/m^2 on the line of shield to 7.5 MW/m^2 on the divertor (Table I). All these components can be designed by the four configurations discussed below.

Confinguration 1

Lowest heat fluxes occur on the line of sight shield. Heat flux distribution on this component was calculated by the view factor code FACET [5]. Line of sight shield will be made from titanium corrugated structure and coated by a suitable compound to avoid hydrogen embrittlement. A flow velocity

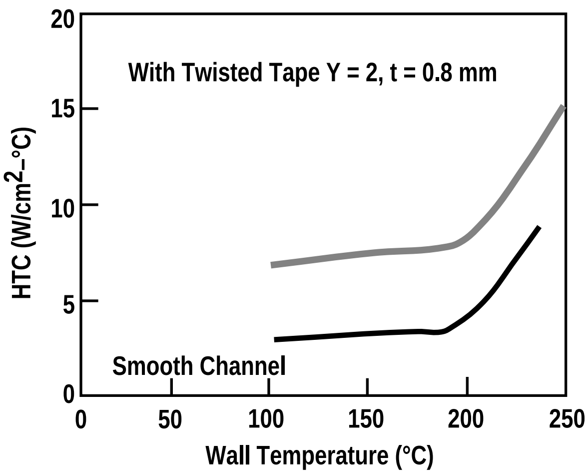

Fig. 2. Variation of heat transfer coefficient.

of about 2 m/s is adequate for these flux levels. Due to the corrugated structure the inlet pressure to this component will be limited to less than 0.5 MPa.

Confinguration 2

Inner and outer Passive Plates will be made from Cu-Cr-Zr alloy and need protection from heat flux radiated from the plasma. Since the peak radiated heat flux is 0.40 MW/m^2, a bolted tile design can be used. Bolted tile design is preferred over brazed design whenever feasible because the tiles can be replaced by remote handling machinery and because bolted components are much cheaper than brazed components. A compliant layer of GRAFOIL will be used between the CFC tiles and the water cooled copper plates to obtain adequate thermal contact conductance. Experiments [6] have shown that maximum contact conductance can be obtained at a GRAFOIL thickness of 0.1 to 0.2 mm. For a GRAFOIL thickness of 0.2 mm, chosen for this design, the relation between the contact conductance and the contact pressure can be described by the following equation [7]:

$$K = B\left\{1 - \exp\left(-p/po\right)\right\} \quad , \qquad (1)$$

where K = contact conductance, W/m^2–°C
B = 9730.0 W/m^2–°C
p = contact pressure, MPa
po = 0.104 MPa

Thus, at a contact pressure of 0.1 MPa (14.5 psi), a contact conductance of 6000 W/m^2-°C can be achieved which is sufficient for heat flux levels up to 1 MW/m^2, if the contact between the tile and the cooled coppper plate can be maintained over 100% of the area. A 2-D and 3-D finite element analysis was performed by COSMOS [8] and ANSYS [9] codes to verify that the design criteria can be satisfied by this concept. In areas where the tile contact can maintained over most of the area, the surface temperature of CFC tile was less than 450°C at the surface heat flux of 0.4 MW/m^2. In few locations (such as cutouts for remote handling tools and ports) where contact could be maintained only over 60% of the area, the peak tile temperature was about 600°C. For heat fluxes greater than 1 MW/m^2, use of brazed joints (Configuration 3) will be used.

Confinguration 3

CFC tiles brazed to water cooled Cu-Cr-Zr plates will be used for neutral beam armor, ripple plate armor and inboard limiter. A flow velocity of about 3 m/s is adequate to remove this heat flux level. As an alternative, the macro blocks developed for divertor cooling could be also used in this area. Due to a number of parallel channels in these components, a flow distribution analysis was performed with the code SNIFFS [10]. Minimum calculated velocities were used to calculate the heat transfer coefficients for input to in the finite element analyses. This analysis enabled design solutions (such as manifold and coolant channel sizes) to make the flow uniform in parallel channels. Fig. 3 shows a flow net work model used for such an analysis.

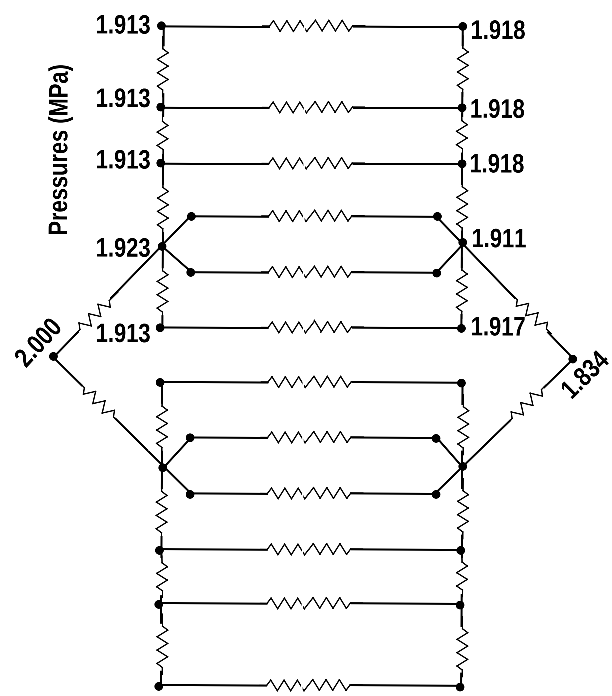

Fig. 3. Critical heat flux with and without enhancement

Confinguration 4

The highest heat flux of 7.5 MW/m^2 is expected in the divertor. In addition to keeping the surface temperature below 1400°C, it is important to insure that the critical heat flux (CHF) and concomitant tube burnout does not occur. Fig. 4 shows a typical relation between flow velocity and CHF for a geometry with a smooth channel and for geometry with heat transfer enhancement technique such as swirl tape insert. Since the required CHF can be achieved at a lower flow velocity, use of heat transfer enhancement results in a design with lower pumping power, less erosion of cooling tubes and less possibility of flow induced vibrations and cavitation. A review of heat transfer enhancement techniques indicated that the swirl tape insert was best technique

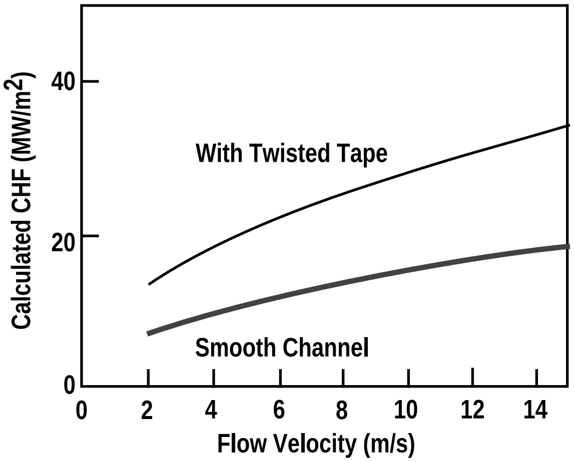

Fig. 4. Flow analysis model

available at present. A new correlation for CHF for swirl tape flow is described in Ref. 11.

Finite element analysis of the macroblock geometry selected for the divertor shows that the peak CFC temperature at a flow velocity of 6 m/s, is about 1200°C. A 3-D finite element thermal analysis of this geometry, which took into consideration the poloidal variation of heat flux indicated that the peak CFC temperature could be reduced by 150°C if a CFC with conductivity of more than 180 W/m-C (at room temperature) in that direction is used. The analysis took into consideration the variation of conductivity with temperature. All thermal analysis was followed by stress analysis reported in detail in Ref. 2.

FLOW ANALYSIS

The maximum flow rate, flow velocity and pressure drop is associated with the divertor. The divertor circuits were designed for a minimum flow velocity of 6 m/s and a maximum coolant outlet temperature of 110°C, if the inlet temperature is 60°C (50°C design value plus a margin of 10°C).

The pressure drops through the flow channels were calculated by using the friction factor and loss coefficient relations from Refs. 3 and 4. For the flow analysis of divertor, it was specified that the minimum flow velocity through coolant channels was 6 m/s and that the coolant channels are 16 mm diameter. Flow velocity in the feed lines was limited to 3 m/s. The flow distribution analysis was performed with SNIFFS code to insure that the minimum required flow velocity could be achieved in parallel channels. The coolant channels in the inner and outer divertor regions have swirl tape inserts due high peak heat fluxes, but the baffle part of the divertor does not require swirl tape insert. Flow requirements and pressure drops in all flow circuits are summarized in Table II.

CONCLUSIONS

1. Titanium panels can be used in areas with heat flux levels less than 0.20 MW/m^2.

Table II
Flow Requirement for PFC Cooling

Component	Inlet Pressure (MPa)	Pressure Drop (MPa)	Flow Required (m^3/min)
Lower Divertor	2.0	0.4	12.6
Upper Divertor	2.0	0.4	12.6
Inner Passive Plates	2.0	0.1	2.5
Outer Passive Plates	2.0	0.1	2.1
Poloidal Limiters	2.0	0.1	0.66
NB Inner Wall Shine Through	2.0	0.2	0.15
Ripple Armor	2.0	0.2	5.6
Neutral Beam Armor	2.0	0.2	0.5
Line of sight shield	0.5	<0.1	5.0
			42.17 m^3/min (11283.0 gpm)

2. A bolted tile design is adequate to cool PFCs with a heat flux less than 1 MW/m^2.

3. Tile brazed to water cooled copper plates will be used in areas with heat flux between 1 to 5 MW/m^2.

4. For divertor cooling with peak heat fluxes of up to 7.5 MW/m^2, flow at a velocity of 6 m/s, outlet temperature of less than 110°C, and twisted tape with a twist ratio of 2 provides a margin of 2.5 over the critical heat flux.

5. A pressure drop of 1 MPa is sufficient to provide the necessary flow in all cooling circuits.

REFERENCES

[1] G.H. Neilson *et al.*, “Design of a super conducting advanced tokamak,” presented at Symp. on Fusion Technology 1992, pp. 1636-1640.
[2] E. Reis, C.B. Baxi, E. Chin, K.M. Redler, “Thermal and structural analysis of TPX divertor,” this conference.
[3] S.T. Yin *et al.*, “Assessment of a heat transfer correlations package for water cooled plasma facing components in fusion reactors,” presented at Nureth 5, Salt lake City, September, 1992.
[4] W.M Rohsenow *et al.*, “Handbook of heat transfer fundamentals,” editors, McGraw-Hill Book Co., New York, 1983.
[5] A.B. Shapiro, “FACET- A radiation view factor computer code for axisymmetric, 2-D planer, and 3-D geometries with shadowing,” University of California Report UCID- 19887 (1983).
[6] N. Noda *et al.*, “Present status of design and R&D Of PFCs in LHD,” presented at ASME winter annual meeting, San Francisco, California, November 1995.
[7] J.C. Chervenak, “Report on effective thermal conductivity of PAPYEX-N,” Holometrix, RN- SAD-19, November 1988.
[8] “COSMOS, a finite element analysis code,” Structural Research, Santa Monica , California.
[9] “ANSYS finite element analysis code,” Swanson Analysis System, Inc., Houston, Pennsylvania
[10] G.M. Baccaglini, “SNIFFS- single phase nonisothermal fluid flow simulator,” General Atomics Report GA-A14501, 1977.
[11] C.B. Baxi, “Comparison of swirl tube and hypervapotron for cooling of ITER high heat flux components,” this conference.