Tokamak Physics Experiment Divertor Design*

P.M. Anderson
General Atomics
P.O. Box 85608, San Diego, California 92186-9784

ABSTRACT

The Tokamak Physics Experiment (TPX) tokamak requires a symmetric up/down double-null divertor capable of operation with steady-state heat flux as high as 7.5 MW/m^2. The divertor is designed to operate in the radiative mode and employs a deep slot configuration with gas puffing lines to enhance radiative divertor operation. Pumping is provided by cryopumps that pump through eight vertical ports in the floor and ceiling of the vessel. The plasma facing surface is made of carbon-carbon composite blocks (macroblocks) bonded to multiple parallel copper tubes oriented vertically. Water flowing at 6 m/s is used, with the critical heat flux (CHF) margin improved by the use of enhanced heat transfer surfaces. In order to extend the operating period where hands on maintenance is allowed and to also reduce dismantling and disposal costs, the TPX design emphasizes the use of low activation materials. The primary materials used in the divertor are titanium, copper, and carbon-carbon composite. The low activation material selection and the planned physics operation will allow personnel access into the vacuum vessel for the first 2 years of operation. This 2-year period will allow final in-vessel checkout of the remote handling equipment. The remote handling system requires that all plasma facing components (PFCs) are configured as modular components of restricted dimensions with special provisions for lifting, alignment, mounting, attachment, and connection of cooling lines, and instrumentation and diagnostics services. Alignment of the plasma facing surface to the as-built magnetic field and to neighboring modules is critical to limit peak temperatures and limit carbon impurities in the plasma. Both local edge-to-edge and overall alignment of the divertor is accomplished using a machined alignment ring system. This ring system maintains the modules in a circular array and is adjusted during machine assembly to align with the as-built magnetic field. The macroblocks have 10 mm of carbon-carbon protection for the copper tubes, of which 7 mm is considered erosion allowance.

INTRODUCTION

The general arrangement of the Tokamak Physics Experiment (TPX) divertor system is shown in Fig. 1. Each divertor consists of three water cooled carbon-carbon (C-C) composite heat flux panels for the inner, baffle, and outer divertor. A distributed gas injection system is incorporated to provide for radiative divertor operation to reduce the peak heat flux to the divertor. Particle pumping is provided through eight vertical ports for each divertor to control the plasma density. Each divertor system is comprised of 16 toroidal sectors of 22.5° each. A 22.5° sector of the lower divertor attached to divertor mounting rings is shown in Fig. 2. This paper describes the design of the TPX divertor midway through the Preliminary Design phase.

The materials used for the divertor are titanium for the structure and water manifolds, oxygen-free copper (OFC) for water cooling tubes and C-C composite for the plasma facing surfaces. Low activation materials are used where possible in order to preserve hands on maintenance during the first two years of operation. Activation levels are predicted to preclude manned access later in the operational program.

DIVERTOR DESIGN REQUIREMENTS

The divertor is designed for steady-state thermal operation with pulse lengths of 1000 s or more. Impurity generation rates and C-C erosion allowance limit the peak acceptable localized surface temperatures to 1400°C. The divertor is to be designed for the TPX upgrade heating power of 45 MW. The inner and outer divertors are required to handle a peak heat flux of 7.5 MW/m^2 from particle impingement and radiative heat. The baffle is designed for a peak of 4 MW/m^2 of radiative heat. Maximum power applied to a heat flux panel is 12 MW for the outer divertor, 7.5 MW for the baffle, and 5 MW for the inner divertor.

All divertor hardware including divertor modules, water coolant lines, diagnostic instrumentation, and gas lines for radiative divertor gas supply are required to be connected/disconnected and handled remotely.

Radiative divertor operation requires that a target gas be introduced in the throat area of the divertor. This is accomplished with several independently controlled gas feed lines which are routed to supply gas through the plasma facing tiles on all three of the divertor plasma facing surfaces.

The divertor system will be subjected to halo currents which flow poloidally through the plasma and divertor. The maximum halo current is defined to be 40% of the 2 MA plasma current with a toriodal peaking factor of 2.

Module edge-to-edge alignment is critical to limit peaking of the heat flux on the C-C surface. This alignment must be within 1 mm and is achieved using mounting rings to form a common surface for aligning and mounting of the modules. The machined mounting rings shown in Fig. 2 will be installed and aligned to the measured magnetic field to distribute the intense heat flux uniformly.

---

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-76CH03073, Subcontract S03756-K.

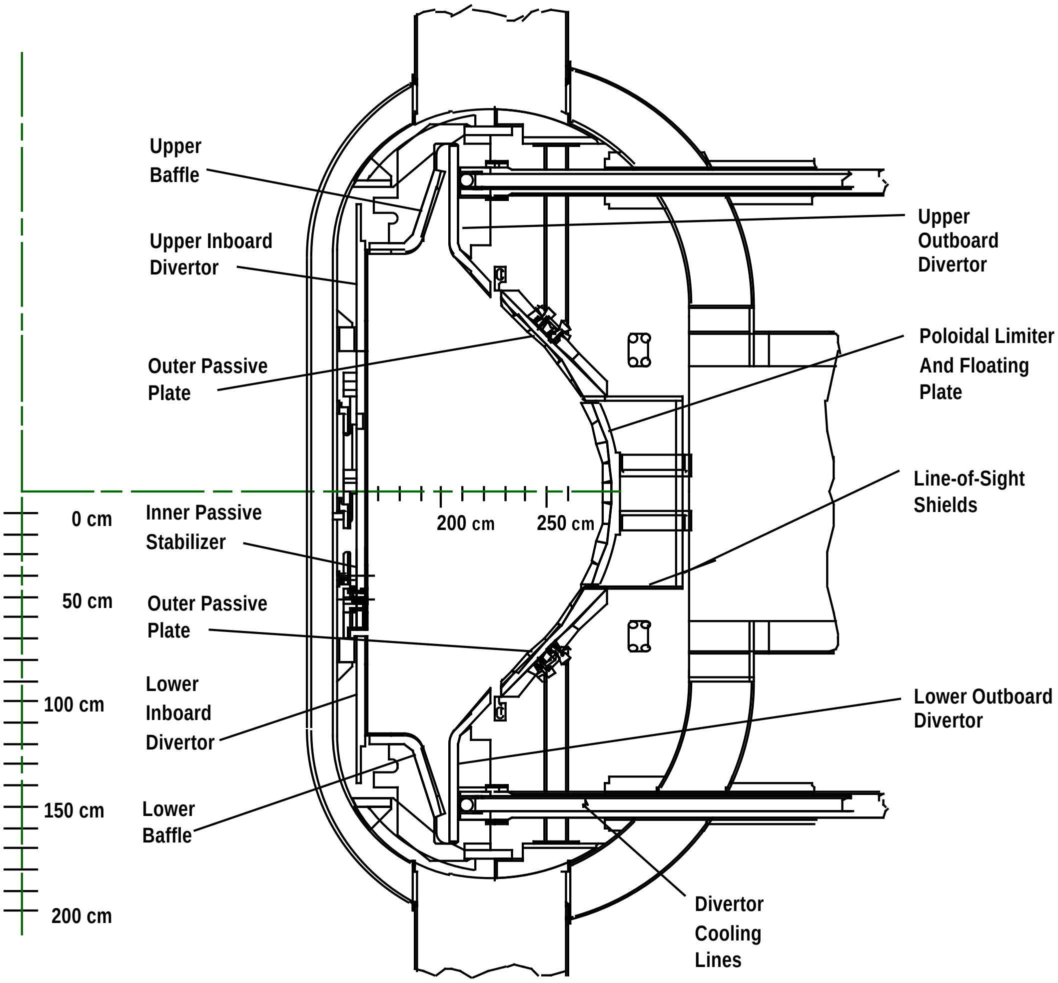

Fig. 1. General arrangement of the tokamak physics experiment (TPX) divertor system

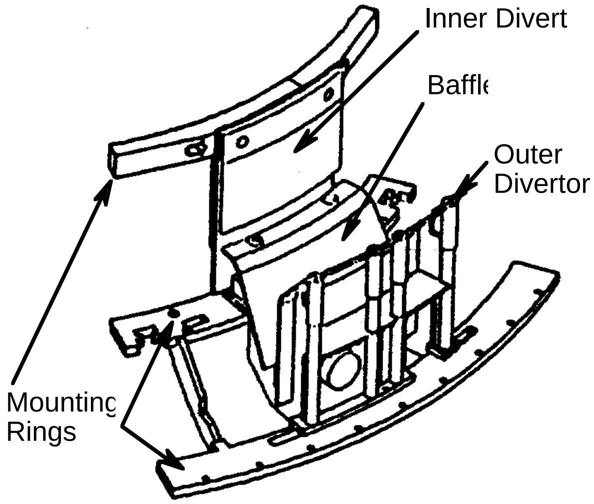

Fig. 2. Divertor sector on mounting ring.

Erosion of C-C will occur at progressively higher rates at the operating temperatures above 1000°C. The total operating time for TPX is 5 x 10^6 s. The C-C is required to have an erosion allowance of 7 mm.

The divertor modules must form a sealed system with a leakage allowance of 8500 l/s of neutral particles which otherwise might re-enter the plasma and degrade performance. This has been accomplished with secondary particle shields to restrict the neutral particle movement.

Divertor diagnostics require direct views into the slot formed by the baffle and outer divertor surfaces in four areas of the upper and lower divertor. The divertor is required to accept a diagnostic module in these areas.

DESIGN DESCRIPTION

Due to activation accumulated over the operational life of the TPX tokamak, the divertor and all other plasma facing components (PFC's) are required to be installed and removed remotely using the in-vessel maintenance vehicle. The General Atomics supplied end effectors, along with the Oak Ridge National Lab designed in-vessel vehicles, will assist in initial installation of the divertors in TPX. The divertor sector (22.5° toroidally) has been designed into two modules which are the inner divertor module and the baffle/outer divertor module as shown in Fig. 2. This was done to allow for installation/removal of the divertor within the space limitations of the TPX plasma chamber and ports.

The plasma facing flux surfaces on each module are comprised of C-C composite brazed to poloidal cooling tubes to meet heat transfer and mechanical support requirements. Macroblocks are relatively large C-C or graphite blocks with one or more cooling tubes bonded into holes. Braze materials exclude silver to limit component activation. Macroblock construction has been chosen which uses five OFC tubes in each block as shown in Fig. 3. Macroblocks were selected over monoblock and multi-arch block designs due to their robust thermal and structural characteristics. Five tubes per block were specified to allow for an adequate number and distribution of attachment hardware as determined by spatial requirements of the divertor frame, cooling lines, and attachments.

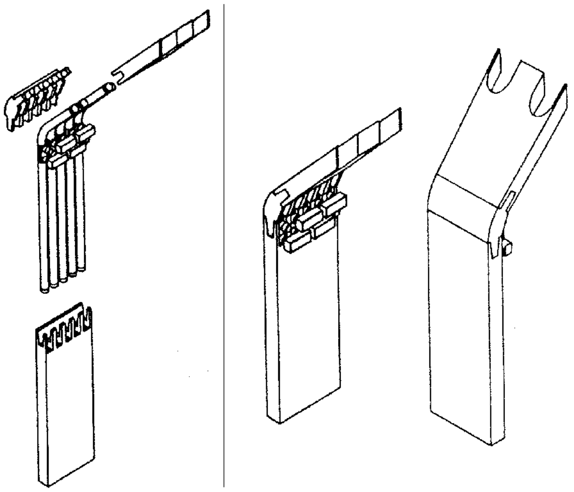

Fig. 3. Five tube macroblock concept for divertor.

The coolant tubes are 20 mm o.d. and 16 mm i.d. Thermal performance is enhanced by a twisted metal tape inside the tube. The tape twists the water flow one turn every 64 mm of tube length. This twisting action doubles the critical heat flux compared to conventional tubes.

The coolant flow enters near the midpoint of each coolant tube and flows up and down on either side of the twisted tape. Horizontal flow connections direct the coolant to the next tube within a macroblock as shown in Fig. 3. A similar flow circuit utilizing concentric tubes is an alternate to the twisted tape design. Both designs have similar thermal and hydraulic performance.

The 16 divertor modules top and bottom are aligned such that the vertical gap between adjacent modules is centered over one of 8 vertical pumping ports in the top or bottom of the vacuum vessel. The conductance for divertor pumping should be similar for all modules which should produce a uniform toroidal pressure distribution.

The attachment of the tube/tile assembly to the titanium backing plate will be made using fasteners through the backside of the support plate which attach to a tee bar imbedded in the C-C as shown in Fig. 4. There will be approximately 100 tile fasteners per outer divertor module to provide proper mechanical support for halo current and disruption loads.

The macroblock attachment shown in Fig. 4 uses multiple fasteners threaded into a nut bar which is installed into slots in the backside of the macroblock. Belleville washers are used to maintain preload throughout the life of the divertor. A Grafoil® sheet is sandwiched between the C-C and the titanium support plate to distribute the load and to facilitate differential thermal movements between the C-C and the titanium calculated to be about 1 mm during bakeout of 350°C.

The macroblocks will be assembled onto the titanium support plate individually and then connected to the inlet and outlet manifolds. A manifold arrangement is shown in Fig. 5 with the C-C and support plates deleted in order to highlight the flow circuit. The inlet manifold supplies five macroblocks connected in parallel. Each macroblock has two parallel flow paths within each vertical tube (flow from the center towards each end and return) and these five tubes are connected in series.

Because of the difficulties with remotely repairing damaged fastener threads located within the vessel, the divertor and other PFCs are utilizing quarter turn T bolts as shown in Fig. 6 for remote fasteners. These bolts clamp the hardware into place and all threads are removed with the modules. This eliminates the challenging in-vessel task of repairing damaged in-vessel threads using remote equipment. These fasteners are latched into place with a 90° turn of the T bolt. The nut is torqued onto the bolt with a remote powered wrench, with a torque up to 400 ft-lb. The reaction torque is directly reacted out through a spline interface between the wrench and the PFC as shown in Figs. 6 and 7. This spline interface eliminates high reaction forces from being applied throughout the remote maintenance equipment.

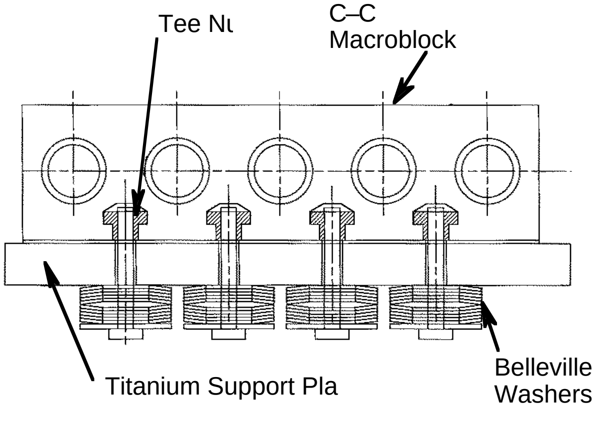

Fig. 4. Divertor macroblock attachment concept.

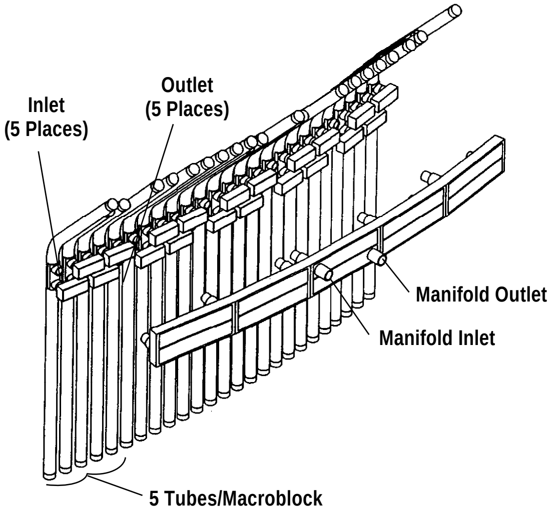

Fig. 5. Outer divertor coolant arrangement including supply and return manifolds.

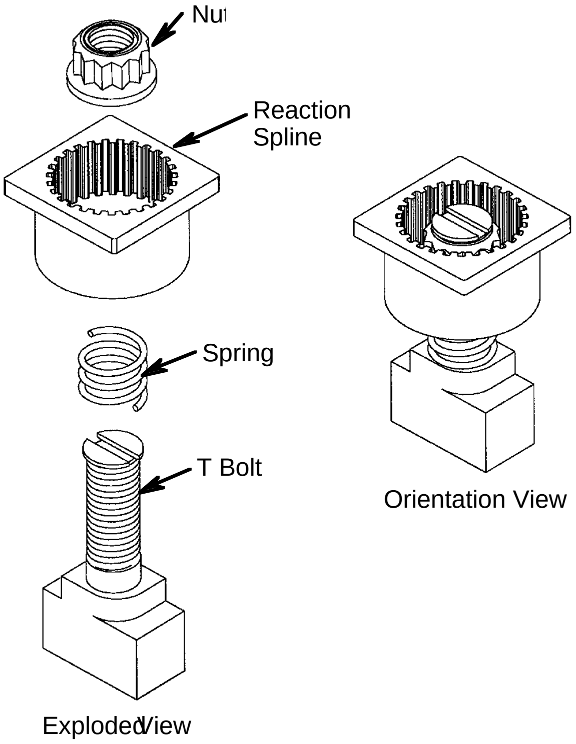

Fig. 6. Quarter turn bolts for remote fasteners.

The coolant flow is supplied to and returned from each divertor module through a set of concentric cooling lines. The inner line is a slip fit into the divertor and seals using a piston ring system. The vacuum to water seal on the outer line is made using a remote welding head inserted inside the tube from outside of the machine cryostat. Cutting of this outer tube for remote removal is accomplished by a roller cutter tool that is also inserted manually from outside of the cryostat.

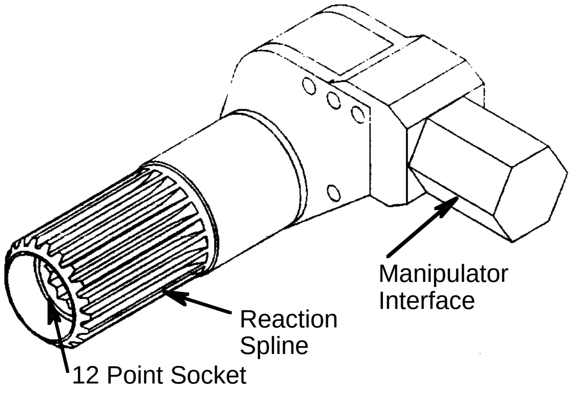

Fig. 7 Remote powered wrench.

Additional information on the welding tool is given in [1]. Divertor instrumentation and radiative gas feed lines are included in the concentric tube assembly. A remotely engaged electrical and gas lines connector is attached to the divertor end of the outer concentric tube. The electrical and gas lines are attached to the outside of the outer tube and are sealed using a conventional sealed connector at their exit locations at the outside of the cryostat. These lines and connectors are removed whenever the divertor is removed.

Eight of the outer divertor/baffle modules will be of modified design to provide for diagnostic viewing access. These modules will be located at 90° intervals located top and bottom with their module edge in line with the vertical diagnostic ports. The modules will be shorter in toroidal length by 3 cm by elimination of a single coolant tube and 3 cm of C-C macroblock. This 3 cm space between divertor modules will be replaced by a cooled diagnostic cassette installed through the vertical port.

The final surface contour of the C-C heat flux panel will be machined as an assembled set while mounted on a tooling plate simulating the actual ring structure.

FLOW ANALYSIS

The pressure drop through the flow channels is calculated by using friction factor and loss coefficients relations from [2]. Pressure drop in tubes with swirl inserts is 0.07 MPa/m at a flow velocity of 6 m/s.

The flow velocity of 6 m/s produces a critical heat flux margin greater than two against burnout for conditions of 7.5 MW/m^2 applied heat load. Flow velocity in the feed lines and manifolds is 3 m/s.

The flow rate, coolant temperature increase, and pressure drop in each divertor sector is presented in Table I. The inlet water temperature is 60°C with a pressure of 2 MPa.

Table I
Water Coolant Performance For Heat Flux Panels

	Max Heat Per System (MW)	Coolant Water Flow (l/s)	Temperature Out (°C)	Pressure Drop (MPa)
Outer Divertor	12.0	192.9	89.6	0.66
Baffle	7.5	154.3	83.1	0.66
Inner Divertor	5.0	154.3	75.4	0.66

THERMAL ANALYSIS

A scoping study was performed to evaluate the thermal and structural response of various tile materials and for the macroblock design using 2D thermal and elastic-plastic stress analyses. Based on a coolant water inlet temperature of 60°C and an outlet temperature of 110°C, room temperature thermal conductivities of 200 W/mK perpendicular to the macroblock surface and about 100 W/mK parallel to the surface are necessary to limit peak operating temperatures to below 1400°C. The thermal conductivity of C-C has been included as a function of temperature.

THERMAL STRESS ANALYSIS

Analysis has been done to evaluate the thermally induced stresses in the C-C due to the differential thermal expansion between C-C and the OFC tubes after braze cooldown. These stresses are acceptable and are reported in [3].

STRUCTURAL ANALYSIS

Halo currents not always develop during plasma disruptions. The circuit for these currents is through both plasma and conductive first wall elements. The poloidal current flow within the divertor C-C macroblocks and the divertor structure produces impulsive pressure type forces of up to six atmospheres. These loads must be handled by the following attachments: C-C macroblock to divertor structure attachments, the divertor structure to mounting ring, and the mounting ring to vacuum vessel.

The divertor structure to mounting ring attachments are 19 mm (0.75 in.) diameter titanium T bolts as shown in Fig. 6. Each bolt is preloaded to 122,000 N (27,400 lb). Six bolts mount the baffle and outer divertor to the mounting rings while three bolts are used to mount the inner divertor.

R&D TASKS

Research and development has started on characterization of C-C materials and on initial joining of C-C to OFC. The C-C to OFC joining task is a joint task by GA, McDonnell Douglas, and Rocketdyne Division of Rockwell International.

Other areas planned for R&D include:

1. Develop mass production and inspection techniques for high quality water cooled plasma facing surfaces fabricated from brazed OFC to C-C blocks.

2. Assure proper thermal, structural, and coolant flow performance of the divertor system, using full scale flow and vibration testing of a module.

REFERENCES

[1] Silke, G.W., “Remote welding equipment for TPX,” this conference.
[2] Idei’chik, I.E., “Handbook of hydraulic resistance,” AEC-tr-6630, Washington D.C.: U.S.Department of Commerce, 1966.
[3] Reis, E.E., *et. al.*, “Thermal and structural analysis of the TPX divertor,” this conference.