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THE TPX VACUUM VESSEL AND IN-VESSEL COMPONENTS

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ABSTRACT

The Tokamak Physics Experiment (TPX) is a superconducting tokamak with double-null divertors. TPX is designed for 1000-second discharges with the capability of being upgraded to steady state operation. High neutron yields resulting from the long duration discharges require that special consideration be given to materials and maintainability. A unique feature of the TPX is the use of a low activation, titanium alloy vacuum vessel. Double-wall vessel construction is used since it offers an efficient solution for shielding, bakeout and cooling. Contained within the vacuum vessel are the passive coil system, Plasma Facing Components (PFCs), magnetic diagnostics, and the internal control coils. All PFCs utilize carbon-carbon composites for exposed surfaces.

I. INTRODUCTION

Since the conceptual design review in March, '93, a number of design refinements have been proposed. This paper describes the design of the vessel and in-vessel components as presently planned. The major refinements include the adaptation of a homogeneous borated water shielding design, improvement of the passive coil structure, and detailed changes to the inner armor and limiter designs to improve space utilization. Figure 1 is a cross-section of the vacuum vessel showing in-vessel components.

II. VACUUM VESSEL

A. Vacuum Vessel Design Overview

The double-walled vacuum vessel of titanium alloy provides an efficient solution to the design requirements and considerations outlined above. The outer wall is connected by ribs to the inner wall of the vacuum vessel, creating a trapped volume or jacket around the inner chamber. There are several advantages to this arrangement. The ribbed, double-wall construction provides stiffness. The jacket provides a convenient way to maintain the vacuum vessel at 150 C during operation via circulation of pressurized water and to heat the jacket to 350 C during bakeout via superheated steam.

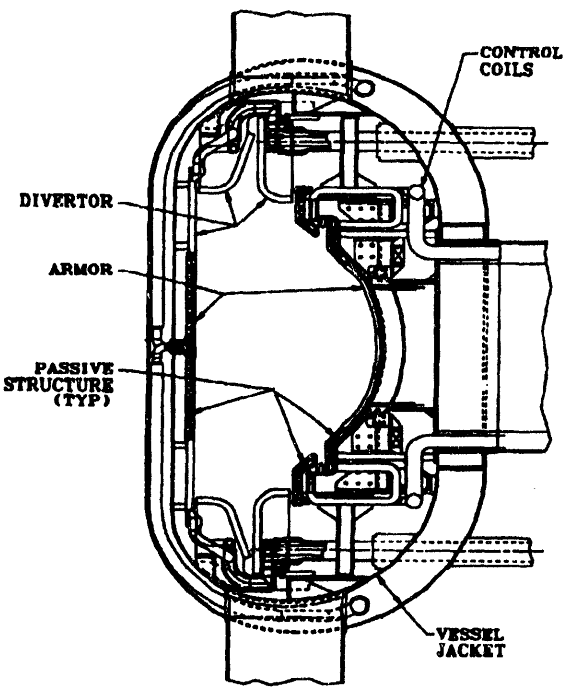

FIGURE 1. TPX VACUUM VESSEL AND IN-VESSEL COMPONENT DETAILS

The jacket also provides the basis of an efficient solution to the shielding requirements. The vessel coolant

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water is borated to provide shielding. In comparison, the conceptual design utilized boron carbide/leaded glass tiles in conjunction with the water in the coolant jacket. TPX has a peak neutron source rate capability of 7.5 x 10^{16} DD neutrons and 2.3 x 10^{15} DT neutrons. The homogeneous shield reduces the neutron-induced heating of the superconducting TF coils to an acceptable level and permits hands-on maintenance of components external to the vessel within 2 weeks of shut-down.

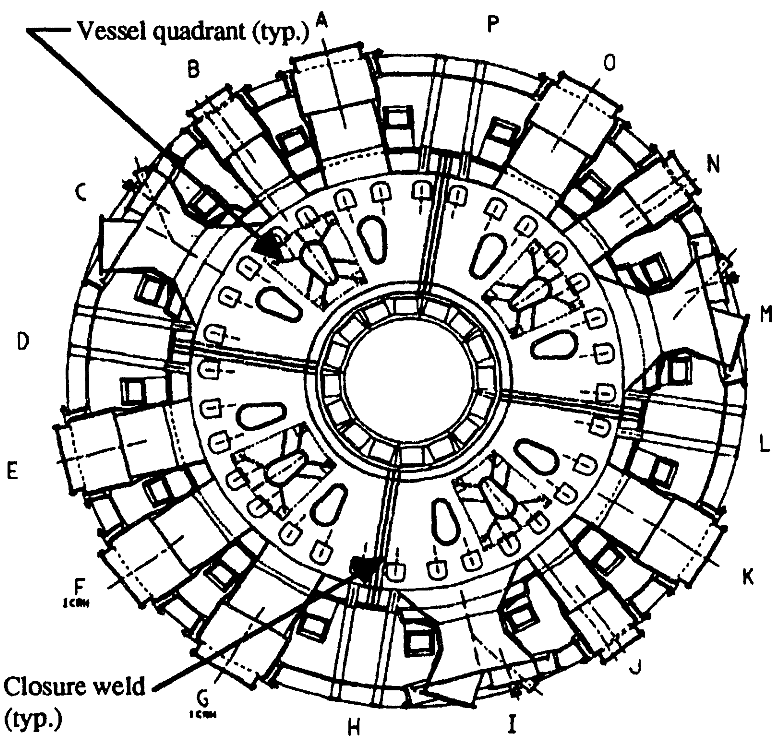

FIGURE 2. PLAN VIEW OF TPX VACUUM VESSEL

Figure 2 is a plan view of the vacuum vessel. The vessel has a major radius of 2.2 m, a height of 4.1 m, and weighs approximately 24000 kg. The vessel is fabricated in quadrants which are welded together during final machine assembly to form the toroid[1]. Quadrant segmentation is also beneficial for fabrication and transportation.

B. Material Selection

Ti-6Al-4V was chosen because of its good mechanical properties (especially at elevated temperatures), high electrical resistivity, a well established data base, good vacuum properties, good manufacturing characteristics, the requisite low activation characteristics and reasonable costs.

Ti-6Al-4V holds 50% of the market for titanium alloys [2] and is widely used in aerospace applications. Consequently its mechanical, forming, and welding properties are very well characterized. The "Extra Low Interstitial" or ELI grade, will likely be used for TPX because of its more controlled composition and higher ductility. It has an ultimate strength of 830 MPa (120 ksi) and a yield strength of 760 MPa (110 ksi). During the conceptual design phase, concern was expressed about the possibility of hydrogen embrittlement of the Ti-6Al-4V. The conclusion of specialists convened on this topic [3] was that glow discharge cleaning at either 150 or 350 C should not cause embrittlement problems. However, it was recommended that shields be provided which, together with the other PFCs, will avoid any exposure of the vessel walls to energetic charge exchange neutrals from the plasma which could cause embrittlement. Consequently, line-of-sight shields are now included in the PFC work scope.

The TPX maintenance requirements demanded the selection of a low activation material. There are two phases to TPX's operation. In the first phase, the first two years of operation, TPX will operate to a neutron budget that limits activation of the vessel and in-vessel components to levels that permits hands-on maintenance. In the second phase, neutron yields are much higher and remote handling is required.

The neutron budget is 0.5 x 10^{20} DD neutrons and 0.5 x 10^{18} DT neutrons for the first year of operation with corresponding budgets of 2.5 x 10^{20} and 3.75 x 10^{18} for the second year. ; The background radiation in the vessel is dominated by the copper used in internal components. Following a 2 week cool-down after two years of operation, the titanium alloy has a contact dose rate of ~3 mR/hr. The copper would have a contact dose rate of ~ 30 mR/hr. These levels are low enough to permit hands on maintenance to be performed within PPPL's dose exposure limits of 1 R/yr., and 600 mR/quarter. During this phase, a gradual transition will be made from primarily hands on maintenance to primarily remote handling maintenance.

The neutron yields and consequently component activation levels are much higher in year 3 and beyond. Remote handling is necessary for maintenance inside the vacuum vessel. Additionally it is required that the vessel interior be accessible for hands-on maintenance following a one year shutdown during which activated in-vessel components are removed. This requirement is designed to accommodate in-vessel reconfigurations or unanticipated hardware failures. This is the primary reason for the selection of Ti-6Al-4V. Following a 1-year cool-down and ten years of DD operation with a total neutron yield of 4×10^{22} DD neutrons and 8×10^{20} DT neutrons, the contact dose of the titanium would be ~5mR/hr. The titanium alloy is also a significant advantage for eventual decommissioning.

II. IN-VESSEL COMPONENTS

The PFCs are structurally supported from the vacuum vessel via titanium alloy brackets or struts. Magnetic diagnostics are located in the space between the vacuum vessel wall and PFCs. They attach either to the vacuum vessel wall or the back side of the PFCs. The internal control coils are located behind the outer toroidal limiters on the limiter support struts. Remote maintenance, described in detail in Reference 4, will be provided for all components requiring routine maintenance. All PFCs are required to withstand loads due to plasma disruptions characterized by a possible vertical displacement, thermal quenches occurring in 0.1 to 1 ms, current quenches occurring in not less than 4 ms. and halo currents up to 500 kA (25% of I_p). All in-vessel components are compatible with the TPX vacuum vessel environment -- i.e., a vacuum level of $\leq 10^{-9}$ torr for impurity gases, operating temperature of 150 C, and bakeout temperature of 350 C.

A. Magnetic Diagnostics

Magnetic diagnostics include the following [5]:

- Flux loops/voltage loops. Fifty-two one-turn continuous loops are planned to measure the one-turn plasma voltage.
- Magnetic field probes. Two poloidal arrays of 78 will be provided for position control.
- Mirnov coils. Two poloidal arrays of 8 and one toroidal array of 8 will measure MHD activity.
- Rogowski coils. Two poloidal loops helically wound at 180 degrees toroidal spacing to measure I_p.
- Locked mode coils. Four picture frame coils at 90 degrees of toroidal spacing to measure MHD activity.
- Diamagnetic loops. Two continuous poloidal loops at 180 degree toroidal spacing to measure plasma pressure.
- Saddle loops. Two partial poloidal arrays at 180 degree toroidal spacing with 10 rectangular coils in each array to measure differential poloidal flux.

B. Divertor

TPX utilizes a double null slot divertor configuration. Single null capability is also available. A modular design is used to facilitate maintenance. Figure 3 shows one of 16 modules which make up a toroidal array. Each module is further subdivided into inner (inner target) and outer (baffle & outer target) assemblies to facilitate remote maintainability. Plasma density is controlled by pumping through 8 vertical pumping ports in each divertor. Gas feeds are provided for gas target/radiative divertor operation.

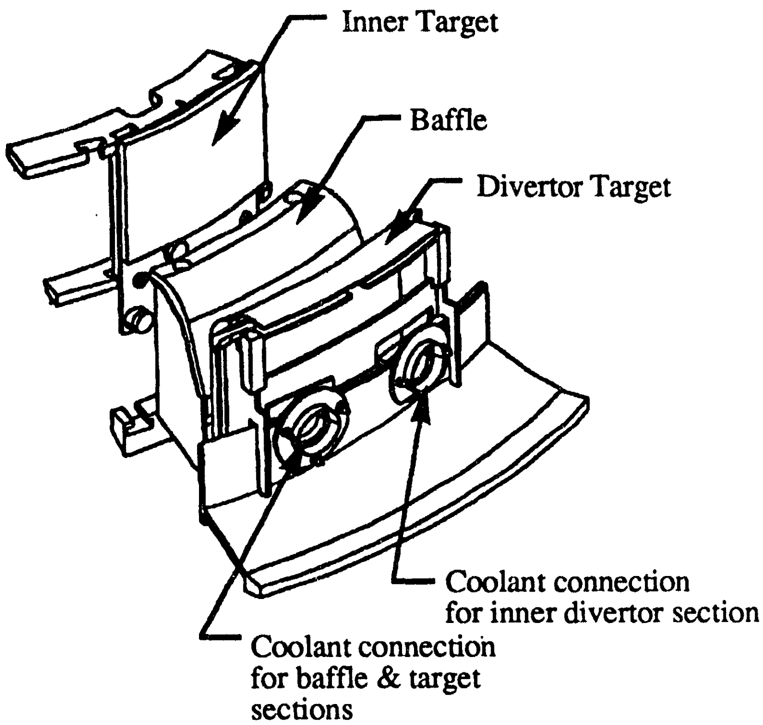

FIGURE 3. TPX DIVERTOR MODULE

The divertor targets are designed for a peak heat load of 7.5 MW/m^2 with a peak carbon temperature of 1400 C. Low activation materials are used to the maximum extent possible. The divertor structure and manifolds are made of Ti-6Al-4V; carbon-carbon composites will be used for the high heat flux surfaces; dispersion strengthened copper will be used for the coolant tubes. A monobloc or saddle block configuration is expected to be used.

C. Poloidal Limiters

Three outboard poloidal limiters are provided for plasma startup and to protect the RF antennae. For startup, each limiter must handle a heat load of 2 MW for 1 to 2 seconds. For steady state operation, each limiter must handle 0.25 MW. The limiter consists of carbon-carbon composite tiles bolted to a titanium heat sink.

D. Passive Stabilization Structure / Toroidal Limiters

The passive stabilization structure, with armor tiles attached, also serves as the toroidal limiters. TPX's highly elongated plasma is vertically unstable. To provide vertical stability, passive stabilization is required to slow the vertical motion to the extent that active feedback control can take over. Furthermore, passive structures must be provided for kink mode stabilization to enable TPX to attain high beta values. The passive stabilization cage, shown in Figure 4, evolved since the conceptual design to satisfy both vertical and kink stability.

The outer stabilization structures consist of upper and lower rings of dispersion-strengthened copper with single resistive toroidal breaks (to assist plasma initiation) and 13 vertical current jumpers between them. This "cage" configuration allows toroidal currents to flow for vertical stabilization along with quasi-helical eddy current patterns to interact with helical MHD modes. Three of the vertical jumpers are incorporated into the poloidal limiters discussed above. Tiles are attached to the plasma facing surfaces of the copper to withstand the 0.4 MW/m^2 radiation heat load from the plasma. The In-Vessel Vehicle (IVV) used for maintenance will ride on tracks; the upper and lower rings each have a toroidal gap for access to the tracks which are mounted behind the rings

The inner passive stabilization structure consists of (16) modular panels of water-cooled, dispersion strengthened copper attached to the inner vacuum vessel wall. The panels are joined to adjacent panels along the top and bottom to form belts; a resistive joint is provided at a single location to assist plasma initiation. This configuration permits toroidal currents and quasi-helical eddy currents to flow. Carbon-carbon composite tiles are attached to permit the limiter to withstand radiation heat loads of 0.4 MW/m^2. Areas that serve as armor for neutral beam shine-through protection is designed for 1.7 MW/m^2.

An important feature of the design is the avoidance of electrical insulators in the vacuum vessel for improved reliability. The relatively high electrical resistivity of Ti-6Al-4V used for the vessel and the passive cage supports, compared to the low electrical resistivity of the copper employed in the passive cage elements, make this approach feasible.

E. Armor

Armor is required to protect the vessel walls and the passive stabilizer structure. The armor consists of carbon-carbon tiles bolted or brazed, depending on heat flux, to water-cooled heat sinks.

The vessel walls must be protected from heat radiating from the plasma, neutral beam shine-through, and from energetic charge exchange neutrals which could cause

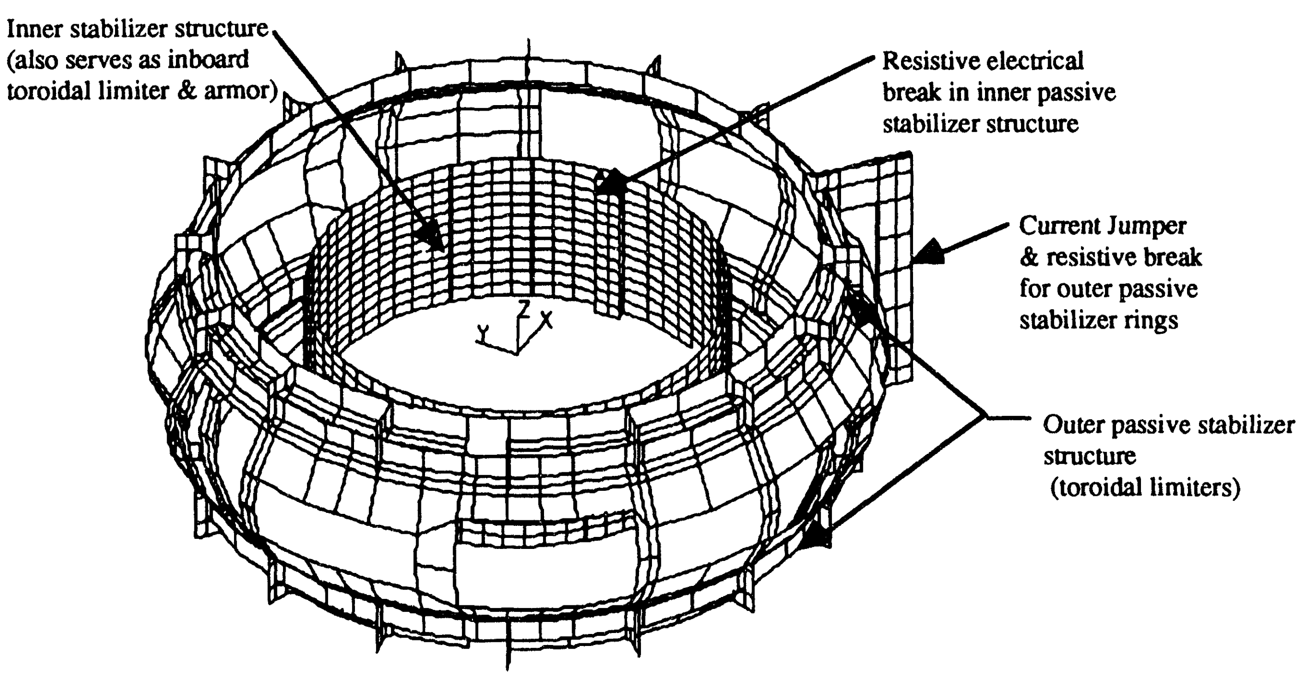

FIGURE 4. FINITE ELEMENT MODEL OF TPX PASSIVE STABILIZER STRUCTURE

hydrogen embrittlement of the titanium. The heat load due to radiation from the plasma is 0.4 MW/m^2. The heat load due to neutral beam shine-through is 1 to 3.8 MW/m^2 depending on location. Armor is located on the outer vessel wall to protect against neutral beam shine-through, in ports to protect the port walls from both scrape-off and shine through, on the inner vessel wall to protect the vessel from neutral beam shine-through. The inner wall armor is incorporated into the modular inner wall panels discussed above in Sect. D. The tiles in these regions are brazed to the dispersion-strengthened copper panel. The outer wall armor panels consist of carbon-carbon composite tiles brazed to water-cooled heat sinks.

F. Internal Control Coils

Active feedback control is provided to control random vertical disturbances leading to $\delta Z \sim 1$ cm RMS displacements from the mid plane. Recently the option of using the internal control coils for fast radial position control arising from random magnetic perturbations ($\delta R \sim 1$cm RMS), ELMs (periodic thermal dumps), heating, plasma ramp-up and ramp-down, and minor disruption was also examined. Such control is needed to maintain the distance between the plasma and antennae for heating and current drive and to prevent the plasma from impacting on the outboard or inboard limiters. This work is ongoing, but indicates that a single set internal control coils can be used to control both vertical and radial disturbances. Radial control, however, requires significantly more coil strength than vertical control--100 kAt (200 kAt peak for occasional minor disruptions) versus 40 kAt for vertical control only.

The internal control coils consist of MgO insulated, titanium jacketed water-cooled copper multi turn coils located symmetrically about the mid-plane behind the outer toroidal limiter (passive plate). A plan view is shown in Fig. 5. The coil is assembled from quarter turn segments, with current jumpers connecting the segments. This arrangement assists in initial assembly and makes it possible to optionally power the coil in segments.

CURRENT STATUS

At the time this paper was written, contract awards for the Preliminary and Final Design phases and associated research and development for vacuum vessel and PFCs were imminent.

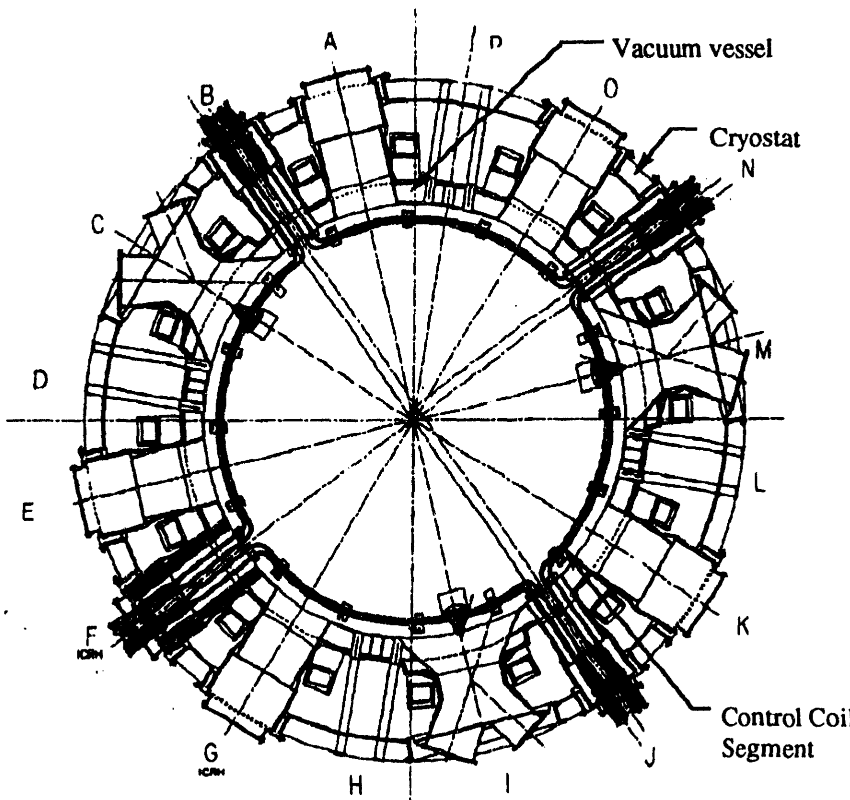

FIGURE 5. PLAN VIEW OF THE TPX INTERNAL CONTROL COILS

ACKNOWLEDGMENTS

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