DESIGN OF THE PLASMA FACING COMPONENTS FOR THE NATIONAL SPHERICAL TOKAMAK EXPERIMENT (NSTX)*

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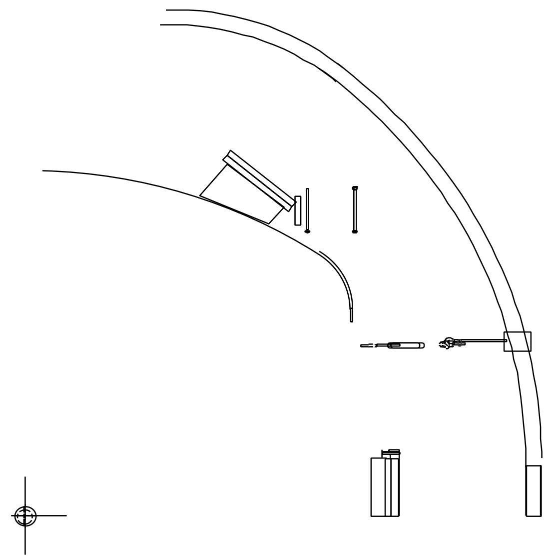
ABSTRACT

The NSTX device plasma facing components [PFC] consist of inboard divertors, outboard divertors, primary passive plates, secondary passive plates, a center stack casing [CSC], and the heating/cooling fluid distribution system. The PFC surfaces are protected by 3584 individually mounted carbon tiles. Surfaces exposed to high heat flux and/or high loads utilize composite carbon-carbon graphite and the remainder utilize less costly ATJ graphite. A variety of diagnostics are incorporated into the PFCs including thermocouples, Langmuir probes, Mirnov coils, and Rogowski coils. The NSTX device is designed to be operated in a pulse mode of five seconds on followed by five minutes off. Its PFC components are also required to be baked out to 350 C. During operation the PFC tiles are permitted to ramp up thermally and then cool sufficiently between shots to prevent ratcheting during subsequent shots. The CSC tiles are required to be thermally isolated from the CSC so that the primary heat loss is radiation to the other PFC components. The other PFCs are thermally coupled to water cooled plates by conductive gaskets. Special mounts are required which permit thermal expansion and can withstand disruption loads while maintaining thermal contact.

The tiles and mounts for the CSC are required to fall within a total radial space allotment of only 14 mm. A unique design for mounting graphite tiles to the CSC was developed which utilizes drift [shear] pins and Inconel brackets. Installation is accomplished via hidden fasteners accessed through very small holes in the tile faces. Analyses of the CSC mounting structure were performed and pull tests were performed on assemblies which simulated the attachment geometry in an attempt to determine the ultimate strength of the configuration and the mechanism of failure.

INTRODUCTION

The PFC components are shown in figure 1. The PFC surfaces are required to be baked to 350 C while maintaining the vacuum vessel at 100 C. The CSC is constructed of Inconel 625 and contains a layer of Microtherm[1] insulation to limit heat transfer to the central solenoid. Coolant channels are provided to carry away the resulting small heat load. All other portions of the CSC and other PFCs are cooled by conduction. The horizontal ring at the top and bottom of the CSC serve as Inner Divertors.



The Outer Divertor mounting structure consists of coolant traced copper plates attached to stainless steel grill structures. The attachments use belleville washers to permit expansion during bake out and operation. The inner and outer Passive Plates are also mounted on coolant traced copper plates but the attachment scheme is much more elaborate. The plates are mounted to U shaped ears on the Passive Plate electrical jumpers which flex elastically during thermal expansion. The jumper mounts are attached via a system of pinned and slotted brackets, again designed for thermal expansion. The CSC tiles are contour machined but the Outer Divertor and Passive Plates are machined flat [faceted].

Two composite materials were considered during the development program ; FMI's Coarse Weave 4D carbon-carbon composite and product 865-19-4, a carbon-carbon composite developed by Allied Signal[AS]. The FMI product was favored for its perceived higher strength and more isotropic structure but was it was also costly and its exclusive use would have exceeded the NSTX PFC budget

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allotment. The development program proved the adequacy of the AS material, in fact showed it to be superior in strength when oriented in an optimal direction to the grain and it was adopted in lieu of the FMI material.

CSC DESIGN

The baseline rail tile design is shown in figure 2. The rail tile assembly is attached to the CSC by Inconel weld studs and captured allen head nuts. The nuts are tightened through small [3.8 mm] access holes in the face of the tiles. The design utilizes four, 3.2 mm diameter, Inconel drift pins to retain the tile. A step in the rail tile permits lapping adjacent [cover] tiles and serves to retain them, thereby halving the number of mounting studs required. Wave springs under the cover tiles serve multiple functions; they pre-load the cover tiles to the rail tiles, cushion them against disruption loads, and permit thermal expansion. Radiation shields are used behind the cover tiles to prevent excessive heat transfer to the center stack column. Inner and Outer

DIVERTOR AND PASSIVE PLATE DESIGN

The envelope for divertors and passive plates is 2.54 cm which permits a more conventional mounting scheme. The tiles are attached by captive button head screws and Inconel T-bars to structural copper plates. Belleville washers under the screw heads permit thermal expansion. See figure 3. A composite graphite gasket [Grafoil] [2] assures good thermal contact with the copper. The T-bar permits thermal expansion in longitudinal and transverse directions while distributing the clamp up load into the gasket. The attachment screws are accessed through a small [4.6 mm] hole in the tile face.

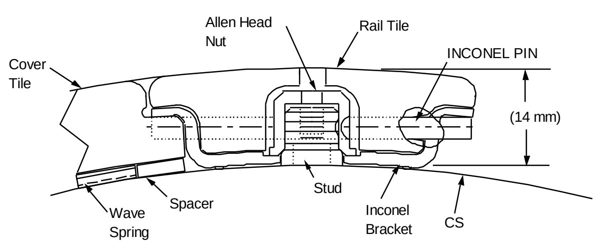

Figure 2. Cross section through CS Tile Assembly

DIAGNOSTICS

A large number of diagnostics are built into the graphite tiles. Space does not permit going into detail about the individual designs but they are designed to mount in typical manner to conventional tiles and the leads are routed in miters or channel provided along the edge of the tiles.

THERMAL STUDIES

Thermal analysis was performed on the center stack and divertor tiles. A one dimensional, transient heat transfer program [TILE.TEMP.1] was written in QUICKBASIC to derive the temperature vs. time, in graphite tiles. The BASIC program was designed to give a rough approximation of the thermal profile of a 1-D tile. It allowed quick turnaround and served as a guideline during conceptual design of the tiles and, later, as a litmus test to validate thermal analyses done with P-THERMAL[3] code. The thermal response of a CSC tile is shown in figures 4, 5.

The outer divertor heat flux approached 2 kW/cm^2 and temperatures were found to exceed the allowable [1200 C] for graphite. The maximum average heat load that could be sustained for 5 seconds was found to be 700 w/cm^2. Studies were done to determine means of limiting the temperature. These included alternate materials, geometry changes, varying tile thickness, plasma sweeping, and moving the x-point location. Details of the analyses are shown in a thermal report [4].

STRUCTURAL ANALYSIS

Analyses were also performed to determine the forces on the PFC components. During disruption events a distributed load of approximately 0.7 Mpa (100 psi) was assumed to be applied to the graphite, in a direction radially away from the central column. This load is transmitted as a shear load through the drift pins into the rail bracket. With a

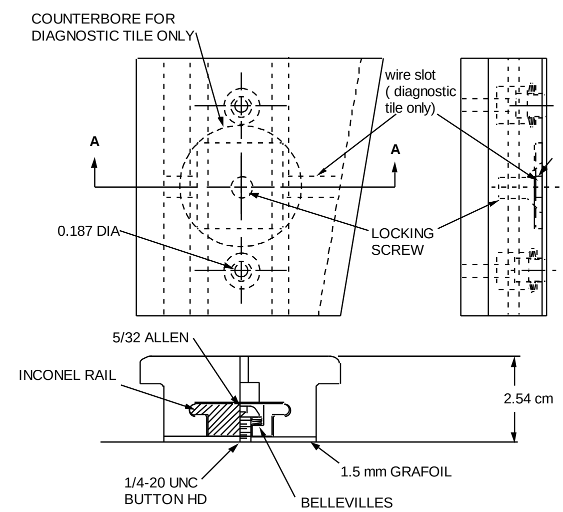

FIGURE 3 PASSIVE PLATE/OUTER DIVERTOR TILE MOUNT DESIGN

nominal 5 cm x 15 cm tile this equates to 2.07 Mpa (300 lbs) per pin. The pin diameter and edge distance are geometrically constrained ; they must clear the tile offset and the rail return leg. Early designs utilized a pin centerline to graphite edge distance of 5.05 mm and a 2.4 mm diameter pin; maintaining a centerline to edge distance of at least 2 diameters as recommended by strength of material handbooks for fasteners in pure shear. This criteria was dropped as a result of the testing program results.

TESTING

Nonlinear stresses occur in the tiles due to pin bending, anisotrophic grain structure, and stress concentrations at the edge of the tile ,therefore, actual failure loads and failure modes could not be accurately predicted without testing. The two candidate composite graphites were evaluated in pull tests in which the variables were the

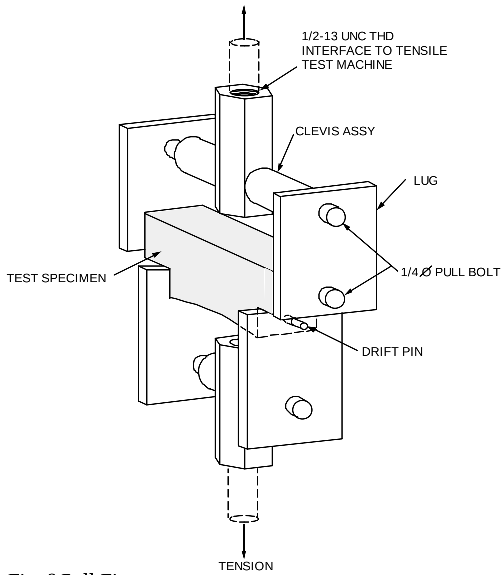

Fig. 6 Pull Fixture

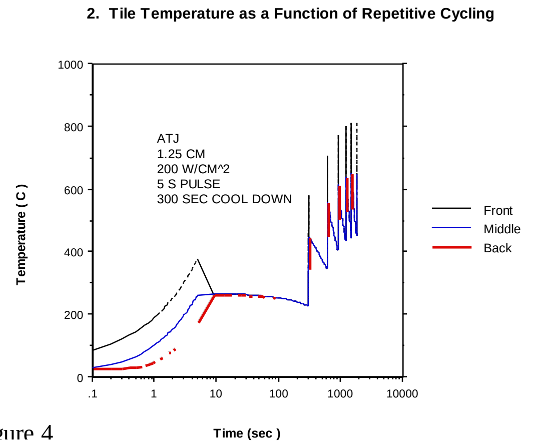

Figure 4

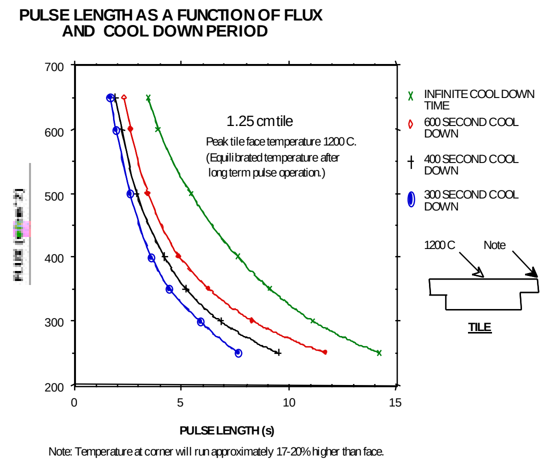

Figure 5

mounting pin diameter, the number of pins, and the direction of the pin relative to the grain direction of the specimens. Specimens duplicated actual dimensions of typical tile sections. The pull fixture is shown in figure 6. All tile failures initiated as cracking at the edges of the holes. Flexibility in the pin/graphite transferred the load to the ends, resulting in stress concentration and premature failure. Increasing the pin diameter and chamfering the hole edge to prevent localized pin contact resulted in increased load capacity [factor of 1.7 with AS material] even though the edge distance was not increased. The material and its grain orientation determined the failure mode [direction] and the ultimate load value. Only the Allied Signal material was able to meet the design criteria with any margin of safety. A compromise pin diameter of 3.2 mm was adapted for the rail bracket design. Details of the testing may be found in a test report [5].

bakeout temperatures and low viscosity, even at the operation temperature of 38 C.

<u>Power Loading Assumptions</u> - cooling

	Outer Divertors <u>@ 1.7 Mw</u>	Secondary Passive Plate <u>@ 0.45 Mw</u>	Primary Passive Plate <u>@ 0.45 Mw</u>	Total Cooling <u>Circuit Power</u>
Peak Power (MJ) (after 5 s pulse)	0.708 ea	0.187 ea	0.187 ea	2.16 MJ
Average Power (kW) (during cool down)	2.36 ea	0.625 ea	0.625 ea	7.22 kW

THERMAL HYDRAULICS

Dowtherm A[6] was chosen as the medium for both bakeout and heat removal between shots. It combines the favorable characteristics of low vapor pressure at elevated

The heat losses during bakeout due to conduction into the attachment structure and radiation to the torus wall were estimated at 5.2 to 8 kW, depending on the surface finish of the components. More detailed thermal analyses are documented in a report. [7]

Test Series 3

Key

AS	Allied Signal
FMI	FMI material
T	Tensile failure, top split off
TO	Shear failure, tear-out of material

Run No.	Pin Dia (inch)	Fail. Load (lbs)	Fail. Mode	Pin Orientation to Z axis
BN-12(AS)	0.125	350	T	Perpendicular[1]
BN-13(AS)	0.125	410	T	Perpendicular[2]
BN-14(AS)	0.125	668	TO	Parallel [3]
BN-15(AS)	0.125	570	TO	Parallel[4]
BN-16(FMI)	0.125	375	TO	Perpendicular[5]

Notes
1. Brittle fracture
2. Brittle fracture
3. Ductile fracture
4. Ductile failure. Load was cycled once before failure.
5. Ductile failure. Load released after edges split.

CONCLUSIONS

Calculations done after the Peer Review determined that the magnetic loading on the CSC will not be as high as expected and, in fact, the higher loads never manifest as tensile loads, i.e., radially away from the center column. As a result, the bracket and tile design is very conservative and no other testing is deemed necessary. The reduced loads also permitted substitution of less expensive Inconel in place of molybdenum alloy earlier planned for the CSC wave springs and rail pins. AS carbon material is used for the CSC rail tiles only. ATJ is used on all other PFC surfaces and is considered adequate for early operation; upgrade operation may require replacement of some of the divertor tiles with the AS material. To date the AS material has not been tested for thermal shock and it is not known whether it will perform as well as the FMI, the material of choice for very high heat flux applications. In view of its economic advantages this is an area which should be tested for future fusion applications.

REFERENCES

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