Design of the MkII Divertor with Large Carbon-Fibre Composite (CFC) Tiles

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1. INTRODUCTION

The MkII Divertor will be installed inside the JET torus over a six month period, starting before mid-1995. It will replace the MkI Divertor which has been in operation since February 1994.

The design of this new divertor has two main purposes. Firstly it aims to maximise the power handling capability of the plasma-facing surface which intercepts the magnetic field lines at very shallow angles with large, accurately aligned, CFC tiles. The alignment is controlled by pulling each tile down on to support pads at all four corners. These support pads are shared with the adjacent tiles, thereby ensuring accurate edge alignment and shadowing, particularly in the important toroidal direction.

The second main purpose of the design is to create a flexible system for studying different divertor geometries and concepts. This is achieved by constructing a water-cooled support structure in the shape of a U-channel above the divertor coils. This structure becomes a permanent fixture inside the torus. Carriers for supporting the plasma-facing CFC tiles are attached to the support structure. These carriers and tiles are cooled only through radiation and contact conduction to the support structure. Their exchange with a differently shaped set is therefore relatively straightforward. Figure 1 shows a poloidal cross-section through the design to be installed in mid-1995.

Impurity control is aided by the provision of a pumping gap with access to the in-vessel cryo-pump. Water-cooled louvres shield the cryo-pump from radiation loads.

De-contamination of the vessel interior, as carried out before the last shutdown, is no longer possible, owing to the large number of concealed areas and closed diagnostic conduits. Consequently all installation work for the MkII Divertor has to be carried out by personnel working in full protection suits supplied by air through flexible hoses. This prevents intricate assembly work taking place inside the vessel and the MkII design needs to take these limitations into consideration.

2. SUPPORT STRUCTURE

This is formed from three concentric rings consisting of a base plate plus inner and outer rings. The joints between these rings is made at the corners through flexible hinges which avoid bending stresses during disruptive and non-uniform loading of the structure. They also play a role during assembly of the structure inside the torus by allowing some flexibility between the assembled components.

The choice of 24 modules was dictated by the size of the largest single module that could fit through a torus horizontal port (17mm nominal clearance with the present design).

Figure 2 shows a CAD view of one of the 24 modules which is assembled from the three ring sections, corner hinges and water-cooled louvres. The joints between the modules are assembled with fishplates either side, located by dowels and bolts. Water-cooling of the structure is introduced through Ø8mm gun-drilled holes. Each module has a single cooling path with the water passing between the side rings and baseplate through the louvre pipes.

Support of the structure on to the divertor coils takes place at each of 32 main coil clamps. The original purpose of these clamps was to hold the divertor coils in position inside the torus and any load on to them passes into the wall of the torus. A T-slot locator is fitted between the baseplate and clamps to permit radial movement between them during high temperature baking but

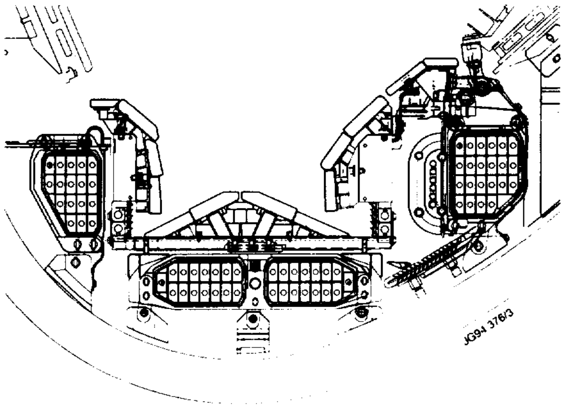

Figure 1. Poloidal section

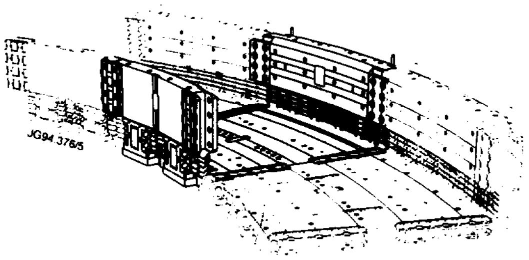

Figure 2. CAD perspective of module

restraint against forces in the vertical and toroidal directions.

The support structure has been designed to resist a variety of forces that are predicted to arise from plasma disruptions and halo currents (ref. 1). Figure 3 summarises the loading cases that have been studied using ABAQUS and NASTRAN computer codes.to arise from plasma The structure is manufactured almost entirely from Inconel 600 because of its high resistivity, stability and strength at elevated temperatures. Although the structure is cooled almost to room temperature during operation, vacuum conditioning takes place up to 350°C so elevated temperature material stability is animportant parameter. The structure also forms an electrically conducting ring inside the torus magnetic field and a high material resistivity is necessary to minimise induced electrical currents.

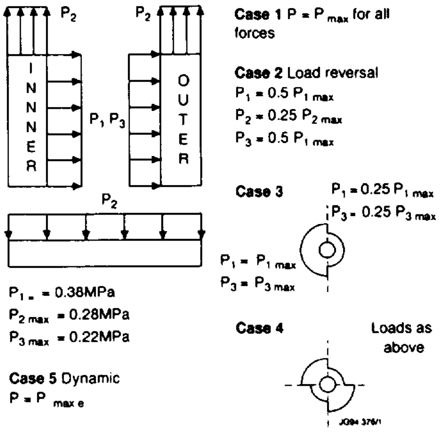

Figure 3. Downward, Upward, Mode 1, Mode 2.

Final assembly of the components to form the support structure will take place inside the torus. The manufacturing process has been chosen to ensure that all the modules fit together accurately and that the final set of locating dowels and bolts will locate correctly in the closing module. The manufacturers will assemble the complete structure on a vertical axis turntable inside the factory before machining the dowel and bolt holes in the fishplates. After bolting the structure together, the inside surfaces of the U-channel will be machined by turning to create the highly accurate mounting surfaces for the tile carriers. The slots for locating the carrier alignment dowels will be marked with the complete structure on the turntable and then have the final machining done after dismantling the modules. This procedure will lead to a final tolerance of ± 0.2mm between adjacent carriers.

3. TILE CARRIERS

The aim behind the carrier design is to create lightweight, rigid structures for locating the tiles accurately while providing support for diagnostics and their electrical connections. To this end, the carrier design has evolved into an assembly of tile support pads and mounting bosses, joined together with ribs. Each module is fitted with six different carrier designs, i.e. one pair each for the inner ring, outer ring and base. Each pair consists of one wide and one narrow carrier. Installation on to the support structure requires that the carriers alternate between wide and narrow versions around the torus. Figure 4 shows a CAD representation of the outer ring carriers where the wide carrier has the tile corner support pads built in. These pads provide the location for the tiles from the adjacent narrow carriers, ensuring that pads are shared to minimize the tolerance in tile-to-tile step heights. Location of the tiles on to the carriers takes place through a spring-loaded bar through the body of tile to pull it down on to the pads. Support pads at the ends of this bar give it a dumbbell appearance and apply the tile loads in line with the corner supports. This avoids a bending moment across the tile. Early trials at pulling down the tiles with a single central fixing point led to the initiation of longitudinal cracks along the tile centre line. Each tile position on the carriers is defined by three dowels that fit into matching slots in the rear tile face, i.e. one toroidal and two poloidal/rotational location dowels. The slots allow tile movement under thermal expansion. The pull down force of the tiles on to the carriers is set nominally at 1KN, determined by the need to deflect the tile until all four corner pads touch simultaneously, taking into account the build-up of tolerances.

Attachment of each carrier on to the support structure is achieved with spring loaded bolt assemblies. The spring loading is required to allow thermal expansion of the carriers with respect to the structure, the fixed references being dowel locations in the structure. For the base plate, one toroidal and two poloidal/rotational dowels are used. For the side rings, a single toroidal dowel is required with the vertical face and top edge of the rings providing the radial and poloidal references.

Manufacture of the carriers is suitable either through investment casting or welded assembly. The final dimensional tolerances are achieved through NC machining of the dowel holes, bolting locations and tile support pads with respect to the interface on to the support structure.

A wide range of diagnostics will be fitted to the MkII Divertor, many of which will be attached to the tile carriers. These include thermocouples, bolometers and Langmuir probes. Later stages of the MkII Divertor require the present set of carriers to be replaced by ones designed to create a different divertor profile. This exchange is planned for late 1996, after the next limited tritium experiment but before the torus has time to recover from the tritium loading and neutron radiation. Consequently any carrier exchange has to be carried out by remote manipulation and without personnel intervention into the torus. Lifting points and clearances have been taken into account for these purposes.

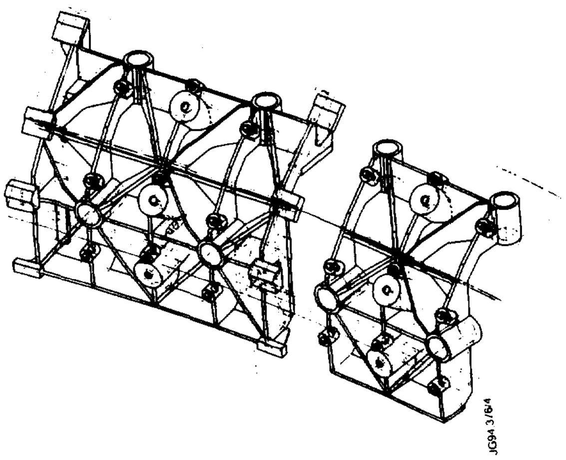

Figure 4. Outer ring carrier

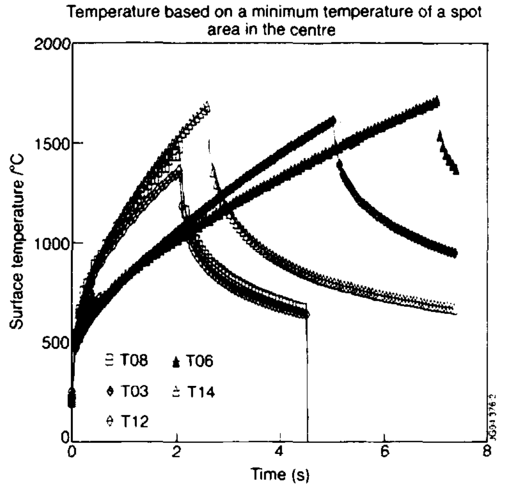

Figure 5. Thermal performance of tile material

4. TILES

4.1 Material properties

The three criteria for selection of the tile material were thermal conductivity, expansion coefficient and mechanical integrity.

The most important requirement was the thermal conductivity perpendicular to the tile plasma-facing surface. This should be as high as possible to maximise the time for the tile surface to reach any specified temperature.

The field lines impinge on the tiles at angles between 1° and 8°. This should be kept as low as possible to minimise the surface heat flux. Thermal gradients through the tile and toroidal expansion coefficient cause the tile to bow, thereby increasing the flux angle. Consequently the lowest toroidal thermal expansion coefficient is required.

For mechanical integrity, the tiles must be able to withstand both the thermal stresses and the mechanical loads imposed by the combination of magnetic fields and halo currents passing through the tiles during disruptions.

4.2 Thermal performance

Eight different materials from four different European suppliers were tested to rank them in terms of thermal conductivity and bowing under a neutral beam heat flux. Figure 5 shows the surface temperature as a function of time for five of these materials with a heat flux of $10MW/m^2$.

The best materials, when bowing was taken into account, were the 2D materials. These were oriented with the fibre plane direction running in the toroidal and away from the beam directions. One of these materials cracked along the lamination during testing with a surface temperature of 2400°C (much higher than the maximum expected at JET of 1800°C). To retain the best thermal solution, a method was developed for holding together 2D materials with metal tie rods.

Figure 6 shows a tile with the holes for the metal tie-rods and the tie-rods of Ø4mm Inconel 718 threaded into conical nuts. Prototypes had thicker rods spaced at twice the pitch of the existing and were tightened up to 6kN but it was later found necessary to tighten only to 1.5kN.

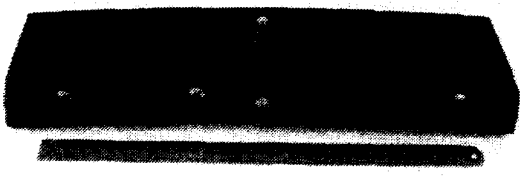

Figure 6. MkII tile

4.3 Thermal testing of prototype tile

Once the basic components of the tile had been determined, a prototype tile was tested. The tile was taken through ~ 200 pulses, 2 seconds long, at $15MW/m^2$, cycling between 600°C and 2000°C surface temperature. The bulk surface temperature did not exceed 600°C. No cracking of the material was observed.

4.4 Surface profile

The main criterion for the design of the tiles is that no edges are exposed either poloidally or toroidally. The thermal performance is defined to a large extent by the toroidal angle of the tile, α. To minimize α, tiles as long as possible are used and gaps are kept to a minimum. A schematic of the design of the tiles is shown in Figure 7. The adjacent gaps are different which means the tiles are stepped to gain the maximum performance. The centre line height difference between tiles is ~0.6 and the height difference at the end of the tiles is ~ 2mm.

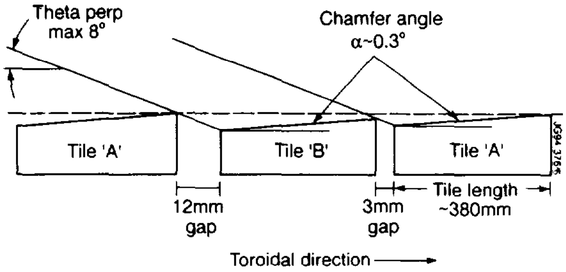

Figure 7. Schematic tile design

Transforming this into toroidal co-ordinates means that α changes across the tile but, for manufacturing reasons, α was held constant across each tile face to give a conical surface profile for a 1-2% reduction in power handling capability at the lowest field line angles.

4.5 Tile manufacture

Prototypes have been produced both for neutral beam testing and for determining the build-up of tolerances. Machining of the front and rear faces will be done by a conical cutter with the tiles supported in vacuum chucks at the same orientation that exists on the divertor.

REFERENCES

1. P. Noll, P. Barabaschi, G. Sannazzaro, C. Sborchia, "Electromagnetic forces during JET Divertor operation, unpublished.