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GENERAL ATOMICS

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*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R. China.

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ABSTRACT

The geometry of the DIII-D tokamak lower divertor was recently modified to improve tokamak plasma density control during operation in a high triangularity double-null configuration. The primary component of the lower divertor is a toroidally continuous flat cooling plate that was fabricated by the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). Three rows of graphite tiles are mechanically attached to the plate to shield it from plasma impingement. The plate is water-cooled for heat removal between shots and is heated to 350°C with hot air and inductive current during vessel baking. The divertor plate is supported 100 mm from the vacuum vessel floor to allow for cryopumping. The vacuum tight 90 deg. plate sectors were positioned and welded together inside the vessel forming a toroidally continuous ring. Plasma facing tile designs have evolved from previous installations. To limit erosion caused by plasma impingement on sharp edges, the through tile-face bolt holes were eliminated from graphite in areas of high heat flux. Upgraded floor tiles were installed to improve the target for the plasma strike point for outer leg pumping. Thermal analysis was done for the Union Carbide ATJ grade graphite divertor shelf and vessel floor tiles and results are presented.

1. INTRODUCTION

The new lower divertor of the DIII-D tokamak was designed for improved density control of a balanced double-null high triangularity tokamak plasma configuration. The new divertor replaced the smaller advanced divertor (AD) installed in 1990. Installation of the new lower divertor was completed in March 2006. In addition to the graphite tiles covering the new divertor shelf, tiles for the vessel floor and lower three rows of the center-post were redesigned for improved performance.

The physics specified requirements included a maximum heat flux of 13.2 MW/m^2 peak for 10 second shots followed by 600 second cool-down. Reduced tile gaps of 0.6 mm and tile edge height alignment of 0.1 mm were also specified. Tiles designated for high heat flux areas were not allowed to have bolt access holes. A maximum panel heat load of 54 MJ (27 MJ to any one tile row) per shot was specified. The divertor panels were designed for a halo current of 30% plasma current with 2:1 toroidal asymmetry. The physics requirements were based upon projected future operations.

Using the physics requirements as a foundation, complementary engineering requirements were developed. The engineering requirements specified a minimum water flow rate of 0.07 l/s (1.2 GPM) through each of six water channels to achieve desired cooling between shots. [Measured water flow through each channel was ≈0.35 l/s (6 GPM)]. Panel flatness was also specified to achieve the tight tile edge-to-edge alignment.

The previous lower advanced divertor or AD ring was built in 1990 and was successfully used until 2005. Between 1998 and 2000, two additional divertors [inner and outer upper radiative divertors (RD)] were installed in DIII-D. These divertors have many similarities but also have differences as shown in Table 1.

TABLE I
GENERAL ATOMICS DIII-D DIVERTOR HISTORY

	Thickness (mm)	Water Channel	Construction	Panel/Seal Weld	Vacuum Surface	Cooling Path/Section Length	Fabrication Issues
Inconel 625, flat ring AD outer floor (1990)	19	Machined and welded one side	Machined with welded cover plate	TIG/TIG	Machined	180°/90°	Conical distortion due to single side machining and welding. Weld porosity due to Inconel cleaning problems
Inconel 625, conical and flat ring outer RD ceiling (1996)	9.5	Chemical mill	Back-to-back welded	Spot/TIG	Mill finish	360°/120°	Vendor delivery issues. GA completed fabrication
Inconel 625, conical and flat ring inner RD ceiling (1999)	9.5	Chemical mill	Back-to-back welded	Overlap Spots/TIG	Mill finish	360°/120°	No major problems
316 Stainless steel, flat ring lower floor (2006)	15.2	Machined one side	Back-to-back welded	Spot/TIG	Electro-polished	180°/90°	Material flatness thick spot welds. Weld shrinkage

2. COOLING PANEL DESIGN

Initially, two prototype panels were designed and built to test and refine manufacturing methods. These prototype panels tested welded joints, flatness control and tile fastening methods. Lesson learned from these panels were instrumental in the successful fabrication of the four production divertor panels. The new divertor ring is comprised of four 90 deg. sectors or panels. Two sectors constitute one 180 deg. cooling circuit. Ninety degree sectors were determined to be the largest able to fit into the vessel through available openings. Each cooling panel sector consists of two stainless steel plates with water passages milled 1.3 mm deep on one side of each plate and then spot-welded together with the water passages facing each other. The 316 stainless steel was chosen over other available grades of stainless steel due to low magnetic permeability after welding and machining.

Through all machining and welding, plate and panel flatness were tightly controlled (Fig. 1), as a flat final product was necessary (within 2 mm over entire panel) for tile alignment. Through plate holes for bolting of tiles were required every 5 deg. [Fig. 1(b)], and these allowed additional clamping during plate and panel machining, enabling greater flatness control. (Production panel achieved flatness within 1.3 mm.) The panel plates are each 7.6 mm thick, for a 15.2 mm total panel thickness. This thickness was based primarily on material strength characteristics to withstand the maximum halo current forces. Each 90 deg. panel was spot welded together in approximately 200 places to provide sufficient strength to allow the plates to act as one stiff panel during disruptions and halo current events and to react the water pressure of 517 kPa (75 PSI). Due to the thickness of the material, no American Weld Society standards existed for the required spot welds. In order to determine spot welding machine settings, a weld schedule was developed and demonstrated on the prototype panels. Each spot weld nugget was approximately 10 mm diameter and showed high strength (~82.7 MPa shear). The large spot welds caused noticeable material deformation [Fig. 1(b)], but this was very localized.

While the spot welds provided sufficient plate-to-plate strength, panel vacuum sealing was also required between the cooling passages and the vacuum vessel. The panels were sealed with Tungsten inert gas welds around the perimeter of the panels. This welding was done in small steps on alternating sides to avoid panel deformation. In order to fasten tiles to the panels, Inconel studs were electric discharge welded to the inner and outer edges (in the low flux heat zones) and bolt sleeves were machined through and seal welded in the high heat flux areas to allow for through plate fastening [Fig. 1(c)]. Inconel studs were chosen over stainless steel studs to prevent galling problems that have developed in previous applications. The fully welded 90 deg. panels were baked to 400˚C prior to numerical controlled (NC) milling of weld stud locations and through holes for tile attachment and panel to panel joints.

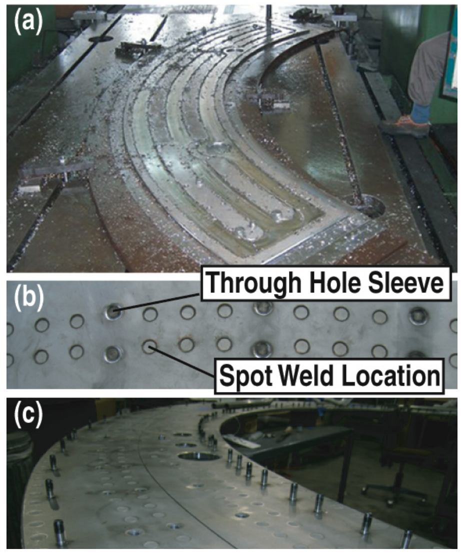

Fig. 1. (a) Machining of cooling channels, (b) spot weld and through hole locations on panel, (c) tile studs on divertor panel.

The DIII-D tokamak has 21 years of experience using “reverse” conflat flanges for passing water or gas lines into the vacuum vessel. This arrangement is shown in Fig. 2. The “reverse” conflat flange design uses two concentric copper seal rings to seal an outer annular flange to both the vessel port flange and the inner tube flange. Since the copper gaskets are not trapped in place by welds, this bolted arrangement allows for seal replacement without cutting or re-welding. For the new lower divertor, bent 25.4 mm diameter Inconel 625 tubing was welded to the cooling channel connections and welded to a “reverse” conflat to seal the vacuum to atmosphere. The bent lines provide radial flexibility for differential thermal expansion and eliminate the need for bellows. Outside the vessel, the two Inconel tubes are joined into a single inlet or outlet line using conflat flanges. These flanges operate at up to 400˚C during vessel baking.

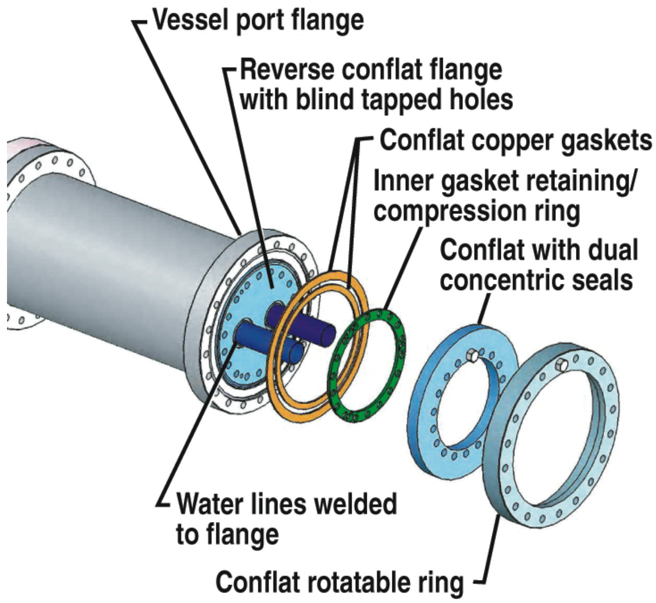

Fig. 2. Reverse Conflat arrangement.

3. PLASMA FACING TILE DESIGN

The divertor shelf is covered by three rows of Union Carbide ATJ graphite tiles. A new requirement was to have no fastener holes visible to the plasma in specific high heat flux zones as defined by the physics requirements. The annular zone containing the vertical diagnostic ports and the through-tile bolt access holes is not rated for maximum heat flux due to potential ablation at these holes. The innermost divertor shelf tile is held onto the panel by two studs welded to the panel. This tile required two through-tile bolt access holes that are located outside the high heat flux zones. The middle row divertor shelf tile is attached by two bolts from the underside of the panel. The outer row divertor shelf tile is secured to the panel through the use of one underside bolt and one welded stud. This tile arrangement requires access to the underside of the divertor shelf for installation and removal of either middle or outer row shelf tiles. Compliant carbon gaskets are placed between the tiles and the shelf to prevent high-localized graphite loads and stresses.

The new lower divertor shelf covers a 41 cm radial width leaving approximately 22 cm of the DIII-D vacuum vessel floor inboard of the shelf. This floor space is covered by graphite tiles that have no fastener holes or other sharp exposed edges. The floor tiles are attached to the vessel floor using long hold-down bars (Fig. 3). The long hold down system employs one large stainless steel bar which clamps the edges of two tiles radially and is fastened to the floor at the radial edges of the tiles. This design provides for very good tile edge-to-edge matching as it has a common clamp point. This design also allows for smooth surface tiles with no bolt holes. The combined stiffness of the stainless steel bar and the compliant gasket result in good thermal conductivity along the length of the tiles.

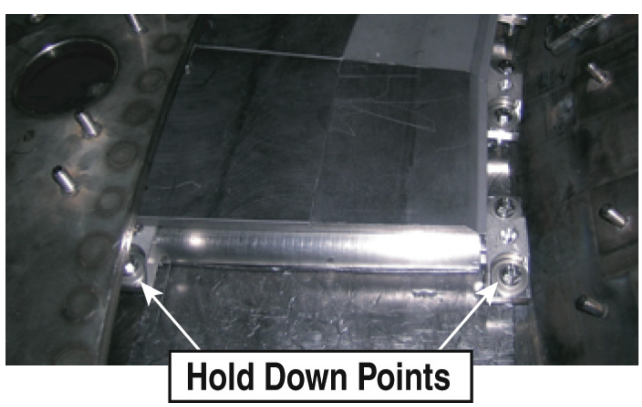

Fig. 3. New floor tile installation using long holddown bars.

The floor and divertor shelf tiles were designed for diagnostic requirements. On the divertor shelf, the middle and outermost tiles all have radial passages on both sides for cable routing, and the outermost tile has a rear toroidal passage for cable routing as well. The vessel floor tiles allow for radial cable routing under their center arches.

The diagnostics attached to the divertor shelf and interfacing with divertor shelf tiles include: Langmuir probes, Divertor Material Evaluation System (DiMES), Thompson laser, magnetic probes, flux loops and tile thermocouples. Vertical ports that are covered by the divertor shelf have special tiles allowing access to the plasma for various diagnostics including DiMES and the X-point probe Thomson laser. The vertical port openings in the tiles range from 20-80 mm diameter holes. Recycling of neutral particles from below the divertor plate in the main plasma region is restricted by port chimneys and particle seals between tiles. Diagnostics integrated into the vessel floor tiles include Langmuir probes, magnetic probes, and tile thermocouples.

Tile thermal analysis was performed using ANSYS and COSMOSWORKS models. Finite element analysis was required as ATJ material properties change nonlinearly and significantly with temperature from 0˚C to 2500˚C. The design heat flux specifications were a triangular distribution with a 11.2 MW/m^2 peak over 5.5 cm base on the divertor shelf and 13.2 MW/m^2 peak over a 4.7 cm base on the vessel floor for 10 seconds. Thermal analysis was done on divertor shelf tiles and the new floor tiles. The relatively poor thermal conductivity of ATJ graphite combined with the desired focused high heat flux, resulted in extremely high local temperatures on the tile surfaces. This temperature was known to be past the point of ATJ ablation and allowable stresses in the tiles were exceeded.

Based upon the tile damage predicted for the desired heat flux, analysis was done at reduced heat flux levels to identify operational limits. Heat flux was reduced until the combination of mechanical and thermal stresses was within the allowed limit of 60% of the ultimate tensile stress. Thermal stresses in the tile decreased much faster than linearly with decreasing tile temperature. Cases were evaluated for both 5 and 10 second shot lengths. Figure 4 shows the specified heat flux, the calculated maximum allowable heat flux, and an actual plasma shot. The tiles are cooled by the water flow in the divertor shelf and vessel floor. Figure 5 shows COSMOSWORKS analysis on the inner divertor shelf tile where the largest triangular heat flux does not exceed tile allowable stresses. The maximum tensile stress on the tile occurs where the temperature gradient is the largest. This stress can be reduced by strike-point sweeping over the tiles.

Transient thermal analysis based on repeated 10 second plasma shots followed by 600 second cooldown periods (10/600 cycle) was performed using COSMOSWORKS and tile temperatures were seen to ratchet up from an initial starting temperature to a new equilibrium value. The 10/600 cycle shot equilibrium temperature varied for different tiles, but were always below 120˚C prior to a shot.

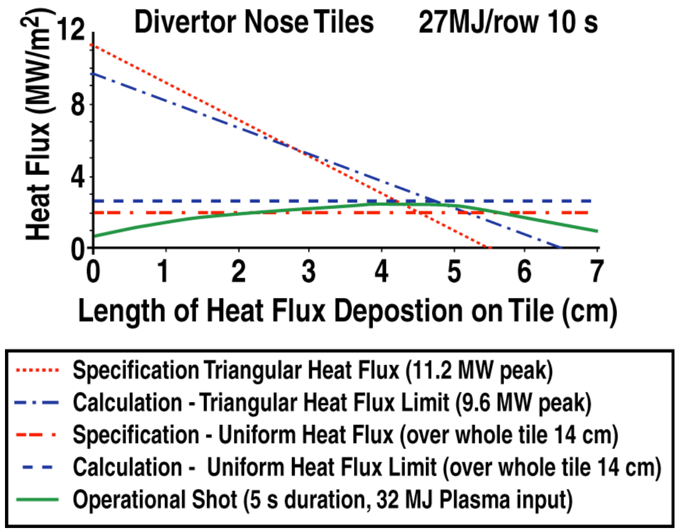

Fig. 4. Divertor nose tile heat flux limits, specification, and operational data.

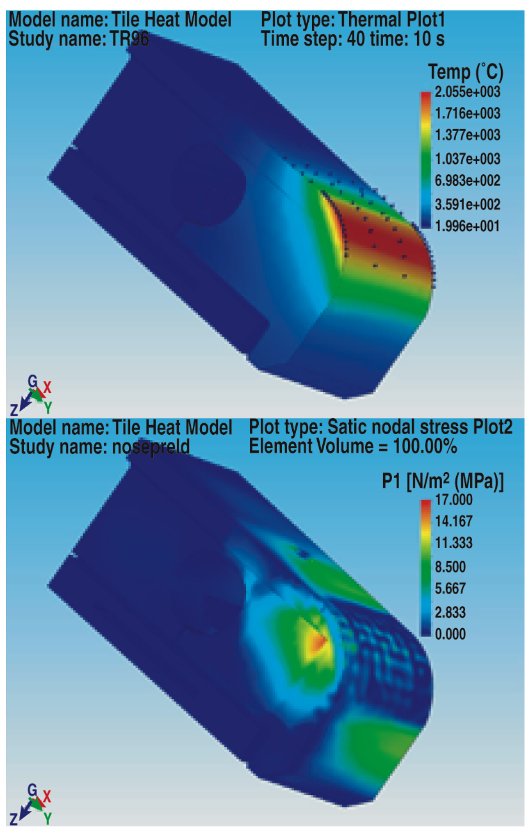

Fig. 5. COSMOSWORKS tile thermal analysis, COSMOSWORKS stress analysis.

4. INSTALLATION

The four 90-deg. panels were test fit in a large assembly area (Hi-Bay) and studs for tiles, support legs and diagnostics were electric discharge welded to them (Fig. 6). Stud locating, which had previously relied upon mylar templates, was improved through the use of small NC machine marks which were made during final panel machining. Upon completion of the stud welding and cleaning, the panels passed their final vacuum leak test. After leak testing, several ball transfers were temporarily attached to the plate to facilitate vessel entry.

The 90 kg (200 lb) panels were moved by overhead crane to the side of the vessel and loaded onto a large aluminum transfer plate, allowing the panels to roll on their ball transfers into the vessel. Once inside the vessel, the panels were supported by cables, flipped over and lowered onto support posts where the panels were assembled and welded into the ring configuration (Fig. 6).

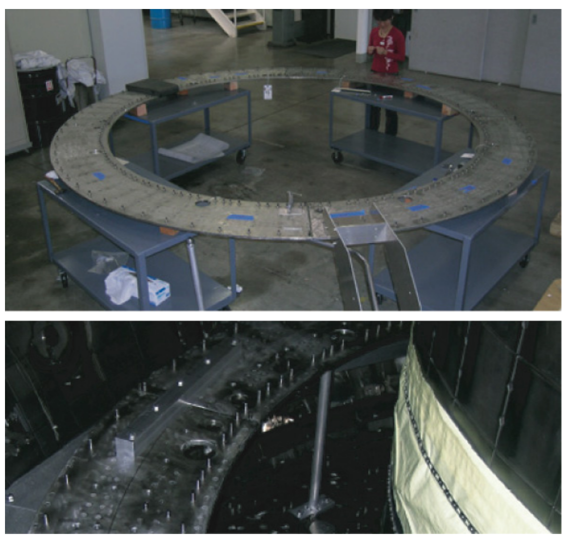

Fig. 6. Divertor ring in Hi-bay, divertor ring during vessel installation.

The divertor ring was then lowered into its final position and the water lines were welded in place with access through the top of the divertor panels. Once the divertor ring was lowered to its final position and attached to the vessel floor, graphite tiles were secured to the divertor. As seen in Fig. 7, the graphite tiles on the vessel floor were attached to the vacuum vessel with no exposed bolt access holes.

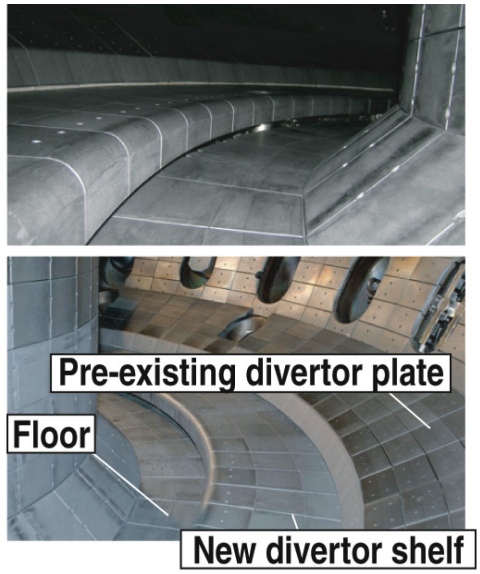

Fig. 7. Lower divertor installation complete, DIII-D with new lower divertor.

5. OPERATIONS

The new lower divertor has provided for pumped high triangularity double-null plasmas in DIII-D. The new center-post and 45 deg tiles have cylindrical and conical surfaces replacing flat tiles. Views from the Divertor Tangential Camera using an IR edge filter show more uniform heating of the tiles compared to the previous installation. To date, operations have produced tile surface temperatures on the order of 400˚C, and all tiles have cooled to within 10˚C of their starting temperature prior to the next plasma shot.

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