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ABSTRACT

The lower divertor of the DIII-D tokamak has been modified to provide improved density control of the tokamak plasma during operation in a high triangularity double-null configuration. Union Carbide ATJ grade graphite tiles covering the new lower divertor and vessel floor were designed to have better tile-to-tile alignment and to withstand higher heat flux than existing tiles.

Gaps between tiles were successfully reduced and tile top surface alignment was greatly improved from previous tile designs. Small tile gaps along with good vertical edge alignment greatly reduce the number and size of thin edges visible to the plasma, thus minimizing possible carbon introduction into the plasma. Close tile-to-tile alignment was the result of the very flat divertor plate surface, carefully controlled tile positioning, well-machined graphite tiles, and hand filing.

Tiles were specified to survive 27 MJ of energy deposited per toroidal row during a 10 s shot period. When this energy was applied over the narrow triangular heat flux profiles originally specified, modeling shows that the tiles exceed maximum allowable tensile stress. Modeling does show that the tiles are able to absorb the 27 MJ per row without exceeding stress limits in cases where the heat flux profile is less focused than the original design specification.

This paper will compare tile design analysis with operational experience obtained during the first 12-week operations campaign with the new divertor.

1. BACKGROUND

DIII-D has been using Union Carbide ATJ grade graphite tiles for the past 16 years. ATJ (also known as TS-1792) is an isomolded graphite. ATJ has proven to be very reliable in the DIII-D environment. Roughly 95% of the vessel plasma facing surfaces are covered by ATJ graphite tiles. No ATJ tiles have ever failed due to thermal cycling or thermally induced stresses. Tile performance is evaluated through the use of infrared and visible cameras in addition to visual tile inspection.

The lower divertor shelf was recently replaced (Fig. 1) [1] to allow improved density control in a double-null, high triangularity plasma. The new divertor structure consists of a horizontal SS shelf that extends the pumping aperture radially inward to the outer strikepoint for these triangular discharges. The divertor shelf is covered by 216 graphite tiles in three toroidal rows. In addition to these new tiles on the divertor shelf, two new toroidal rows of tiles covering the vessel floor are also installed.



Fig. 1. DIII-D vessel with new lower divertor. A cryopump is located under the outer baffle plate.

The design goals for the new divertor shelf and vessel floor tiles are to withstand high heat fluxes and to present much smaller tile-to-tile gaps and tile height mismatches than previous vessel tiles. Tile mechanical failure and carbon introduction into the plasma are the two key issues driving these goals.

2. DESIGN SPECIFICATIONS

The target heat flux profile is a very narrow triangular profile (5.5 cm wide on the divertor shelf and 4.7 cm wide on the vessel floor, see Fig. 2). This narrow heat flux is based on expectations for future Advanced Tokamak performance. Ten second heating pulses are followed by 14 minute cool-down periods. The design plasma delivers 27 MJ of energy to one row of lower divertor shelf or vessel floor tiles during the course of a 10 s shot. This 27 MJ rating is based on the assumption that there is a 60:40 power split between the outer and inner strikepoints and that the radiated power fraction is 25%. This means that 60 MJ of input energy is required for a shot that delivers 27 MJ to one row of tiles.

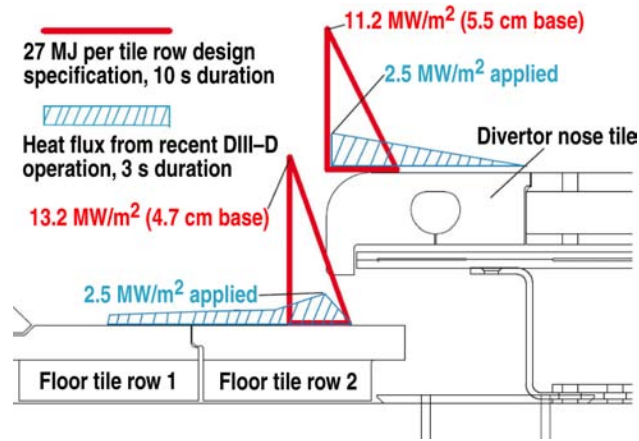


Fig. 2. Design and operational heat flux profiles.

In addition to the heat flux design requirement, acceptable tile spacing and alignment is also specified. Previous tiles on the vessel floor and old lower divertor had up to 2.5 mm tile-to-tile gaps and 1.0 mm tile height differences. The design specification for the new divertor shelf and vessel floor tiles is to have tiles gaps of 0.4 mm or less and tile edge height alignment within 0.1 mm.

3. TILE ALIGNMENT AND ATTACHMENT

In DIII-D, tiles have typically been held in place with nut bars that can be accessed through holes on the tile surface. These nut bars are attached to studs welded to the vessel and clamp the tiles either on their sides or through the tile centers. Grafoil gaskets are used under all tiles (and between hold down bars and tiles) to ensure good thermal conductivity and to minimize any high localized stresses resulting from uneven mounting surfaces. In order to achieve the above-mentioned tile alignment, tile attachment was re-engineered on the vessel floor and divertor shelf. The new lower divertor shelf and floor tiles were designed using SOLIDWORKS CAD software. This software allows for very good 3-D modeling and virtual assembly construction. The use of computer numerically controlled (CNC) machines during tile manufacture allowed for very good tile repeatability and dimensional accuracy. Once all tiles were in place on the divertor shelf and vessel floor, they were inspected and filed to achieve superior tile edge fit.

On the divertor shelf, the tile hold down clamps are installed through holes in the tile centers and these are attached through a combination of studs welded to the shelf and holes in the shelf which allow for through bolts to secure the tiles from underneath the shelf (Fig. 3). The use of through shelf bolts allowed for the middle row divertor shelf tiles to have no exposed bolt access holes and, therefore, fewer sharp edges. Through bolt holes were machined during divertor shelf fabrication and divertor tile stud locations were machine marked as well. This created a very precise and well controlled positioning of the tile hold down locations. The manufacture of a very flat and smooth divertor shelf for the tiles to sit on allowed for the divertor shelf tiles to have good edge alignment, despite independent clamping of each tile.

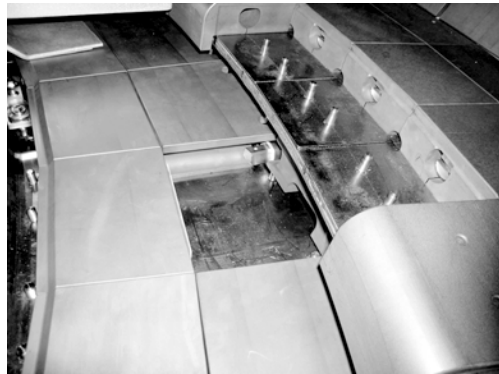


Fig. 3. Installation of divertor shelf tiles and vessel floor tiles.

The new vessel floor tiles use one long hold down bar oriented radially to simultaneously clamp the side edge of two (inner and outer) floor tiles (Fig. 3). The long hold-down bars are attached to the vessel floor at the innermost and outermost radial points, which alleviates the need for any through tile bolt access holes. This arrangement allowed for very good tile-to-

tile edge alignment despite irregularities in the surface of the vessel floor and also for very close radial tile positioning (Fig. 4).

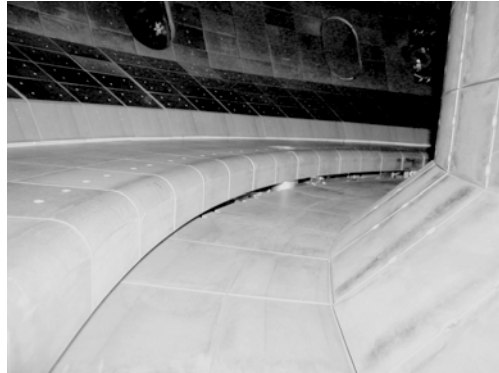


Fig. 4. Divertor shelf tiles and vessel floor tiles.

4. ANALYSIS

During the design phase of the divertor shelf tiles and vessel floor tiles, COSMOSWORKS (finite element analysis code) was used to test design validity. The outer floor tile and the divertor shelf inner-most tile were determined to be the two most vulnerable tiles based on proposed strike point location and were, therefore, examined in the greatest detail.

4.A. GENERAL

The stationary, narrow triangular heat flux profile specified in the original design specifications proved to be more than any of the ATJ tile designs either on the vessel floor or the divertor shelf could survive. The graphite simply could not conduct the energy quickly enough to avoid creating large internal temperature gradients. These resulted in non-uniform thermal expansion and consequent thermally induced tensile stress. Maximum allowable tensile stress was chosen to be 60% of ultimate tensile stress giving a value of 16.8 MPa. Compressive stress limits are much higher than the tensile limits and are never approached. Using the narrow triangular heat fluxes, maximum MW/m^2 limits were calculated for the tiles as well as peak heat fluxes for 27 MJ of energy to be safely absorbed by one tile row.

4.A.1. MATERIAL PROPERTIES OF ATJ GRAPHITE

The physical properties of ATJ graphite change non-linearly with increasing temperature (Fig. 5). The graph below shows how thermal conductivity and specific heat capacity vary with temperature. These properties have somewhat offsetting effects as far as increasing the ATJ temperature, but their non-linear nature makes their behavior difficult to predict in a simple model.

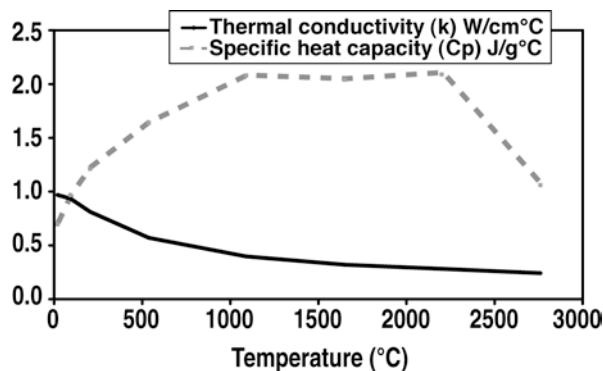


Fig. 5. Physical properties of ATJ graphite.

4.B. DIVERTOR SHELF

There are 72 tiles per row on the divertor shelf. The inner most tile on the divertor shelf was analyzed to be the most susceptible to failure due to its geometry and location. While the

design specification called for a 5.5 cm base triangular heat flux with a 11.2 MW/m^2 peak, analysis indicated that the tile can only withstand 9.6 MW/m^2 peak over a 5.5 cm base triangular heat flux (Fig. 6). The 9.6 MW/m^2 peak triangular heat flux causes the tile to reach approx 2000°C and to reach the maximum allowable stress at the edges of the tile under the peak heat flux. In order to withstand 27 MJ per row of tiles, the heat flux profile base had to be widened to 7 cm, and the peak heat flux decreased to 8.8 MW/m^2 . Subjected to a uniform heat flux, the row of tiles could survive substantially more than 27 MJ.

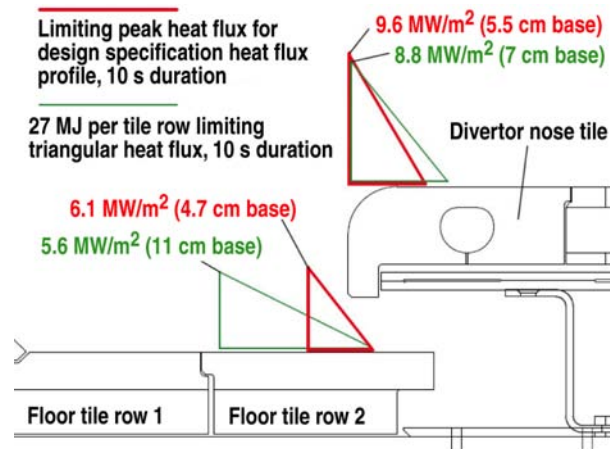


Fig. 6. Tensile stress limiting heat flux profiles for 27 MJ per tile row and for maximum heat flux for design specification heat profile.

4.C. VESSEL FLOOR TILES

There are 48 tiles per row on the vessel floor. The outer floor tile row was determined to be the most vulnerable of the two vessel floor tile rows due to its larger tiles and radial location. The narrow design heat flux band of 4.7 cm caused the outer row tiles to reach the tensile stress limit at a peak heat flux of 6.1 MW/m^2 . The tiles reached a maximum surface temperature of 1300°C at this point. The design specification called for 13.2 MW/m^2 peak heat flux over the 4.7 cm triangular base. As with the divertor shelf tiles, the peak stress on the vessel floor tile occurred on the tile edge right under the peak heat flux. In order to survive 27 MJ per tile row, the peak heat flux was reduced to 5.6 MW/m^2 and spread over an 11 cm base.

5. OPERATIONAL PERFORMANCE

Twelve weeks of DIII-D plasma operation have been performed since the new lower divertor and vessel floor tiles were installed. During that time 922 shots have had the outer strike point on the divertor shelf. Actual heat flux (as measured by an infrared camera) on the vessel floor and lower divertor shelf have been much less focused than the design specification (Fig. 7). In the initial operation since the new divertor installation, actual discharges have produced much broader (approximately 15 cm base) and less peaked heat fluxes ($\sim 2.5 \text{ MW/m}^2$ maximum) (Fig. 2). It is anticipated that lower density operation in the Advanced Tokamak discharges in DIII-D might produce narrower heat flux profiles.

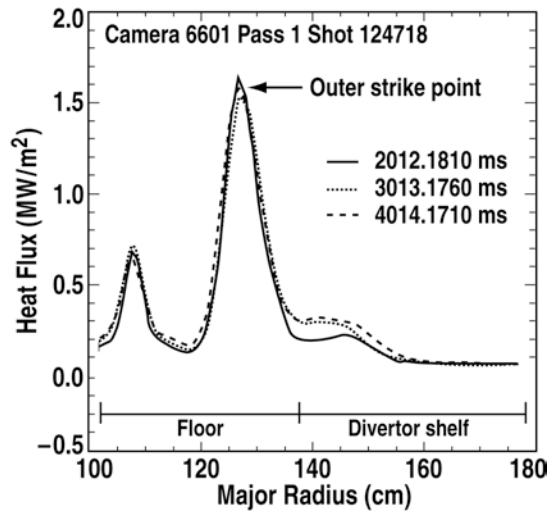


Fig. 7. Actual operational heat flux data stable strike point over 4 s.

In addition to plasma operations, DIII-D undergoes 350°C vessel bakes to develop the desired vacuum conditions. Numerous vessel bakes have also taken place since the installation of the new lower divertor. Vessel baking causes the tiles to reach over 350°C as measured by tile thermocouples. Vessel baking has not caused any tile failure as the uniform heating of the tiles does not induce significant thermal gradients and, therefore, thermally induced stresses are low. Tiles which contact at room temperature do not show signs of edge failure resulting from increased contact resulting from thermal expansion during a vessel bake.

5.A. VISIBLE CAMERA

One means of monitoring tile performance is via a tangentially viewing visible camera with a wavelength filter centered at 4310\AA (carbon-deuteride, CD, part of the methane break-up chain). CD is a good indicator for toroidal uniformity of the carbon chemical sputtering

source. The two contrasting images (Figs. 8 and 9) show the effect that the smaller tile gaps and fewer tile edges have on reducing the CD sputtering. The CD images clearly show a qualitative improvement in tile uniformity and alignment.

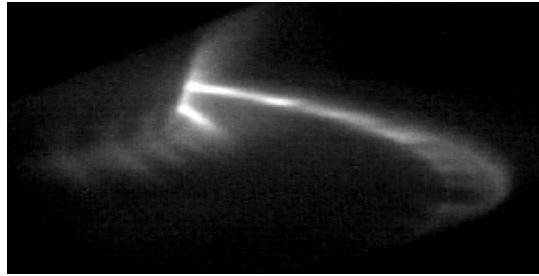


Fig. 8. CD filter view of vessel floor area prior to upgrade.

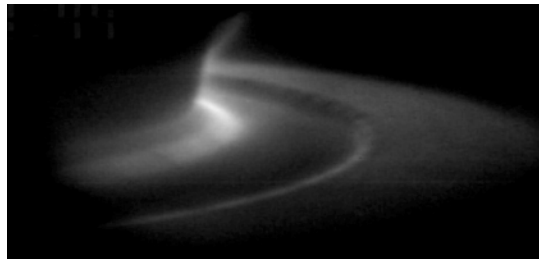


Fig. 9. CD filter view of vessel floor area after divertor upgrade.

In addition to the vessel floor and divertor shelf, the angled tile on the lower portion of the centerpost was also redesigned to reduce tiles gaps and improve tile alignment. These tiles were contoured to match the centerpost radius. This effort was successful as can be seen by the reduced peaking between tiles.

5.B. INFRARED CAMERA

The infrared camera (IRTV) images of the vessel floor with the old lower divertor and of the vessel floor with the new lower divertor show a marked difference in toroidal tile symmetry (Figs. 10 and 11).

5.C. TILE THERMOCOUPLES

Thermocouples are installed in two new vessel floor tiles (one inner row, one outer row), in one divertor shelf inner row tile and one divertor shelf middle row tile. These thermocouples are approximately 1 cm from the tile top surface. These thermocouples are useful in tracking tile bulk temperatures (as seen during a bake), but are less valuable during the plasma discharge. Due to the mobility of the strike point, and the fixed single position of a thermocouple in a tile, many different heat flux profiles (and surface temperature levels) will produce similar thermocouple location temperatures. An array of thermocouples in a single tile would help generate a clearer picture of the tile surface heat flux, but would still

produce only an estimated recreation of operational conditions. Thermocouples can show general tile temperature and alert operators to large problems, but are not able to fully predict peak tile surface temperature or conditions which would induce unacceptable stresses.

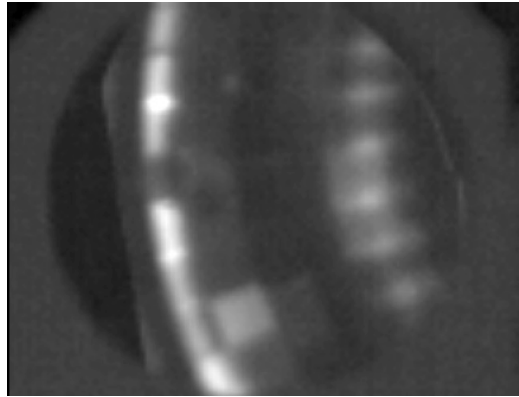


Fig. 10. Old lower divertor and vessel floor.



Fig. 11. New lower divertor and vessel floor.

5.D. VALIDATION OF TILE MODELING

In an effort to validate the COSMOSWORKS modeling of the new divertor shelf and vessel floor tiles, operational IRTV heat flux and tile surface temperature data were used. Heat flux information (profile, intensity and duration) derived from IRTV measurements was input into the COSMOSWORKS model as input heat flux. COSMOSWORKS then generated tile surface temperatures and these were compared with the IRTV recorded tile surface temperatures. COSMOSWORKS model and IRTV surface temperatures agreed within 2%.

This close agreement between measured (IRTV) and calculated (COSMOSWORKS) tile temperatures gives good confidence in the use of COSMOSWORKS modeling for future tile design validation and current tile behavior prediction.

IRTV data is calibrated during vessel bakes due to known steady temperature conditions. To further validate IRTV heat flux data, it has been compared to heat removal by the divertor shelf cooling water. Divertor shelf cooling water temperature measured on the inlet and outlet and the flow rate is known. These factors have allowed for IRTV heat flux on the divertor shelf to be compared to heat removed by divertor shelf water, and the two energy values are in close agreement.

6. CONCLUSIONS

While the original heat flux design specification for the lower divertor and vessel floor tiles could not be met through the use of ATJ graphite, only modest reductions in peak heat flux and increases in the width of the heat profile were required to remain below the max allowable stress for ATJ. The goal of improving toroidal tile symmetry was achieved.

The design flux heat profile is very focused and operations to date have not produced such a profile. It is possible that future high performance discharges operating at lower plasma density and higher injected power may approach these design heat flux profiles. The use of the IRTV to monitor heat flux profiles in conjunction with the COSMOSWORKS model will allow for operational guidelines to be put in place and tile safety to be maintained as the higher heat fluxes are approached.

REFERENCES

- [1] P. M. Anderson, Q. Hu, C. J. Murphy, E. E. Reis, Y. Song, and D. Yao, “Design, Fabrication and Installation of the Lower Divertor for DIII-D,” *24th Symp. on Fusion Technology*, Warsaw, Poland, September 11–15, 2006, to be published in *Fusion Engineering and Design*.

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