Graphite Tile Performance on New DIII-D Lower Divertor

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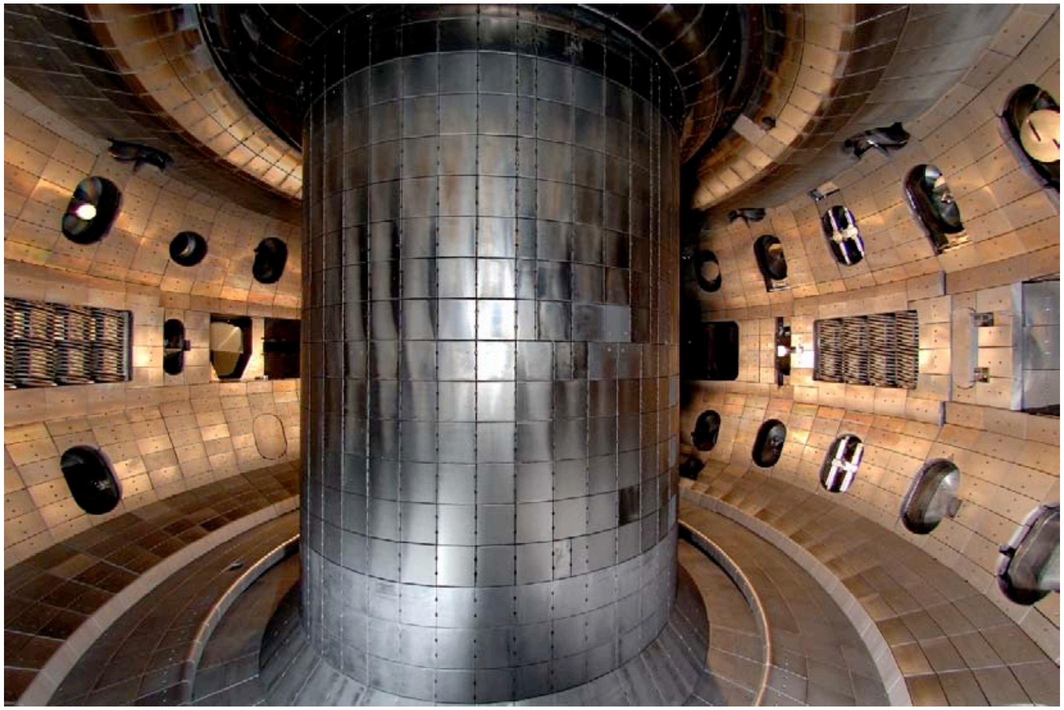
DIII-D is an Elongated Tokamak Operating at Reactor Relevant Parameters

- **Major Radius 1.67 m**
- **Minor Radius 0.67 m**
- **Elongation 2.6**
- **Maximum Toroidal Field 2.2 T**
- **Maximum Plasma Current 3.0 MA**
- **Current Flattop 5-10 s**
- **Central Ion Temperature 310,000,000 K**
- **Central Electron Temperature 175,000,000 K**



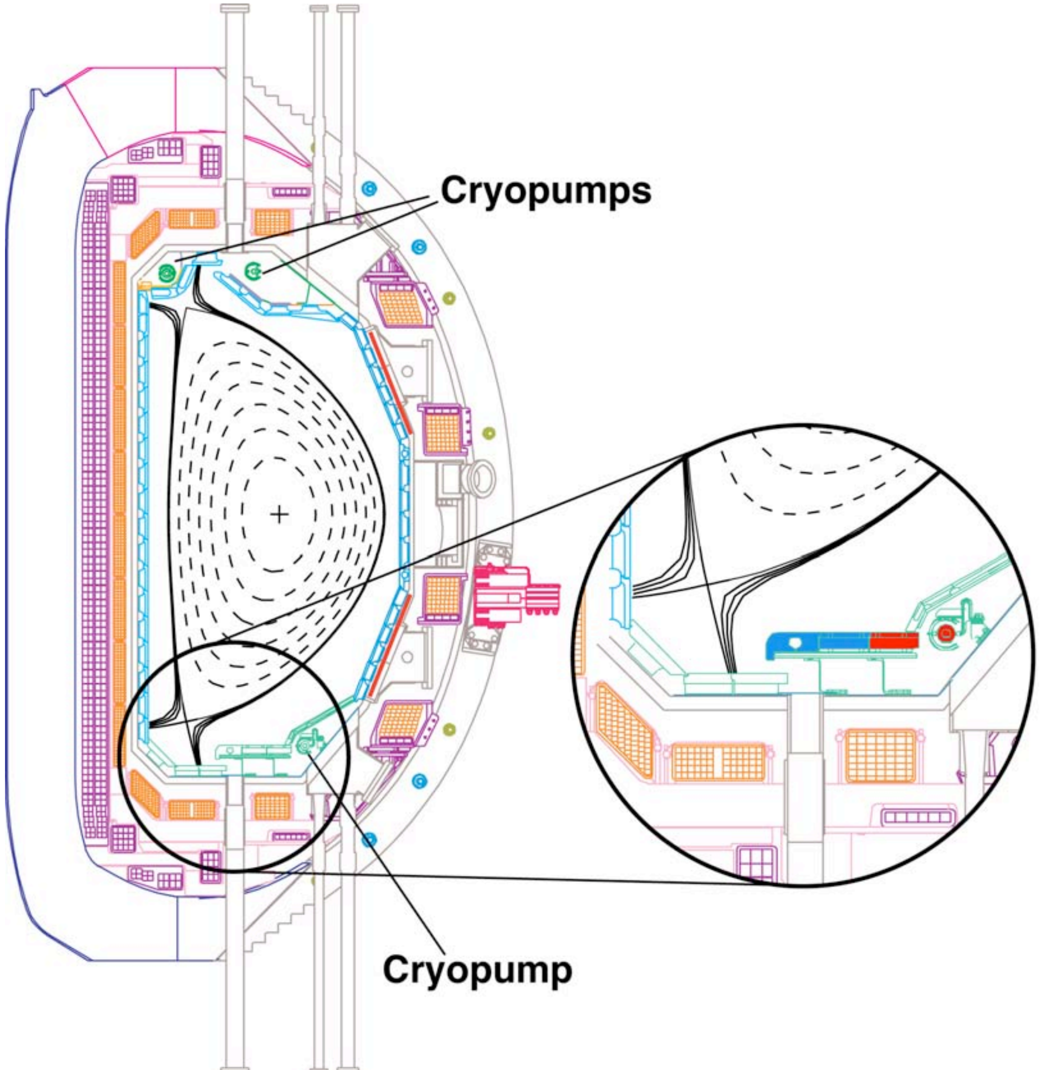
Presentation Outline

- Background/Overview
- Design Objectives
- Tile Alignment and Attachment
- Tile Thermal Analysis
- Operational Performance
- Conclusions

New Lower Divertor with Extended Shelf has been Installed for Pumping High Triangularity Double-Null Discharges

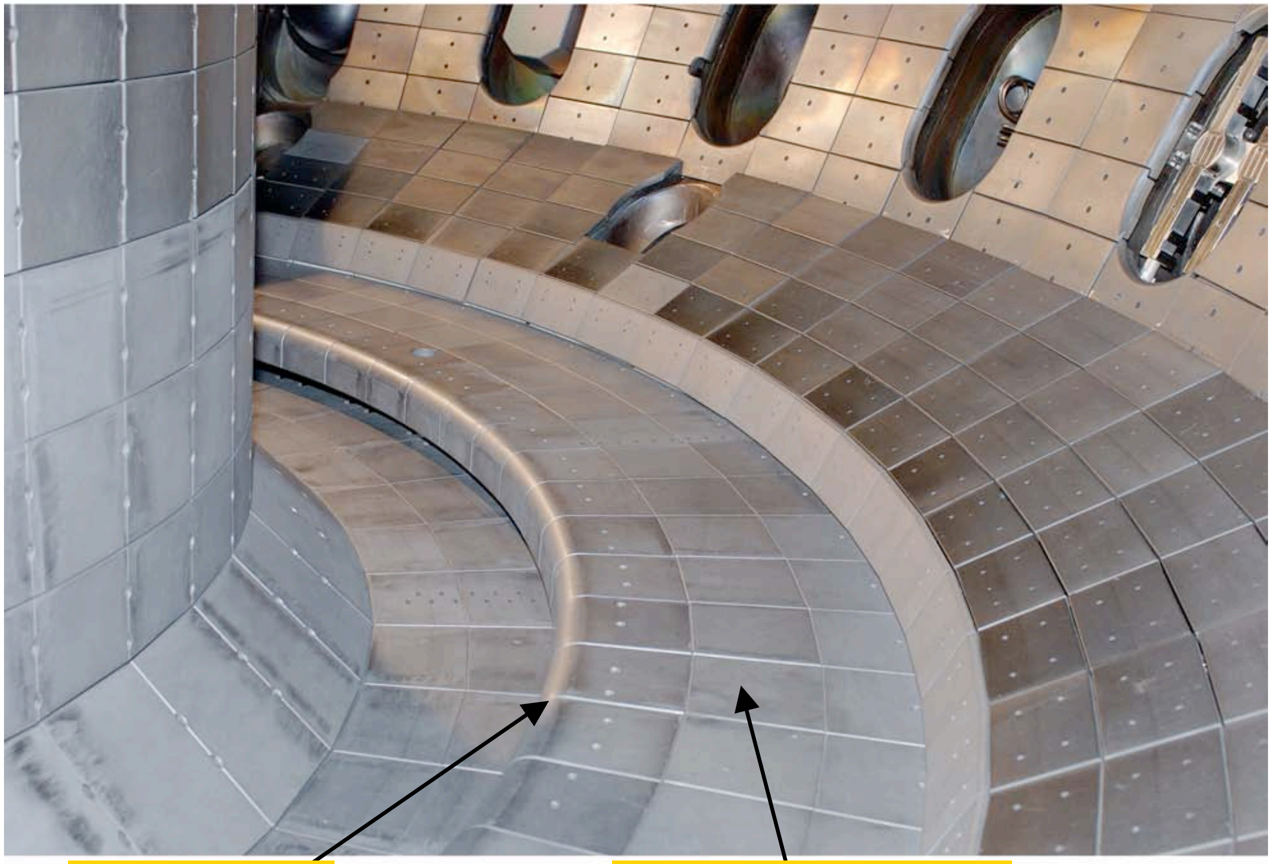
- **New lower divertor installed in 2006**
  - Stainless steel shelf covered by UCAR ATJ graphite tiles
  - Newly designed graphite tiles also cover the vessel floor

- **Outer strike point can be placed anywhere on the floor or divertor shelf tiles**
  - Some areas of lower heat flux established
  - Outer strike point provides majority of heat load to floor/shelf



DIII-D Lower Divertor Geometry

- **DESIGN FEATURES:**
  - 316 SS
  - Water cooled
  - Low gas leakage to main chamber



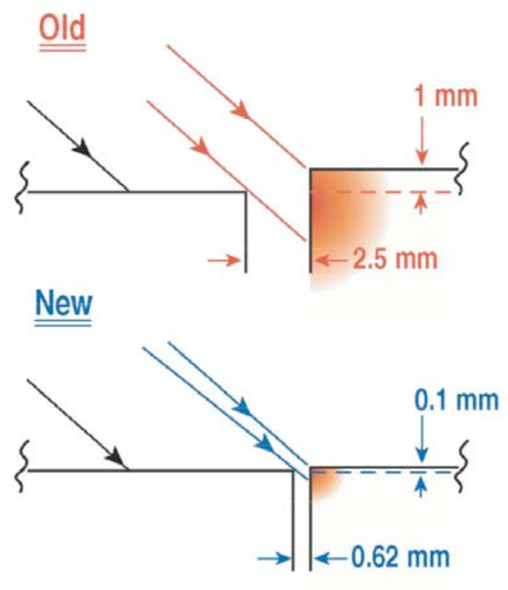
Two Main Design Objectives for the Graphite Tiles Covering the Divertor Shelf and Vessel Floor

- **Minimize the carbon introduced into the plasma by presenting more toroidally uniform surfaces and reducing exposed graphite edges**

- **Design tiles which can withstand anticipated high heat flux from high performance, high triangularity double-null divertor plasmas**

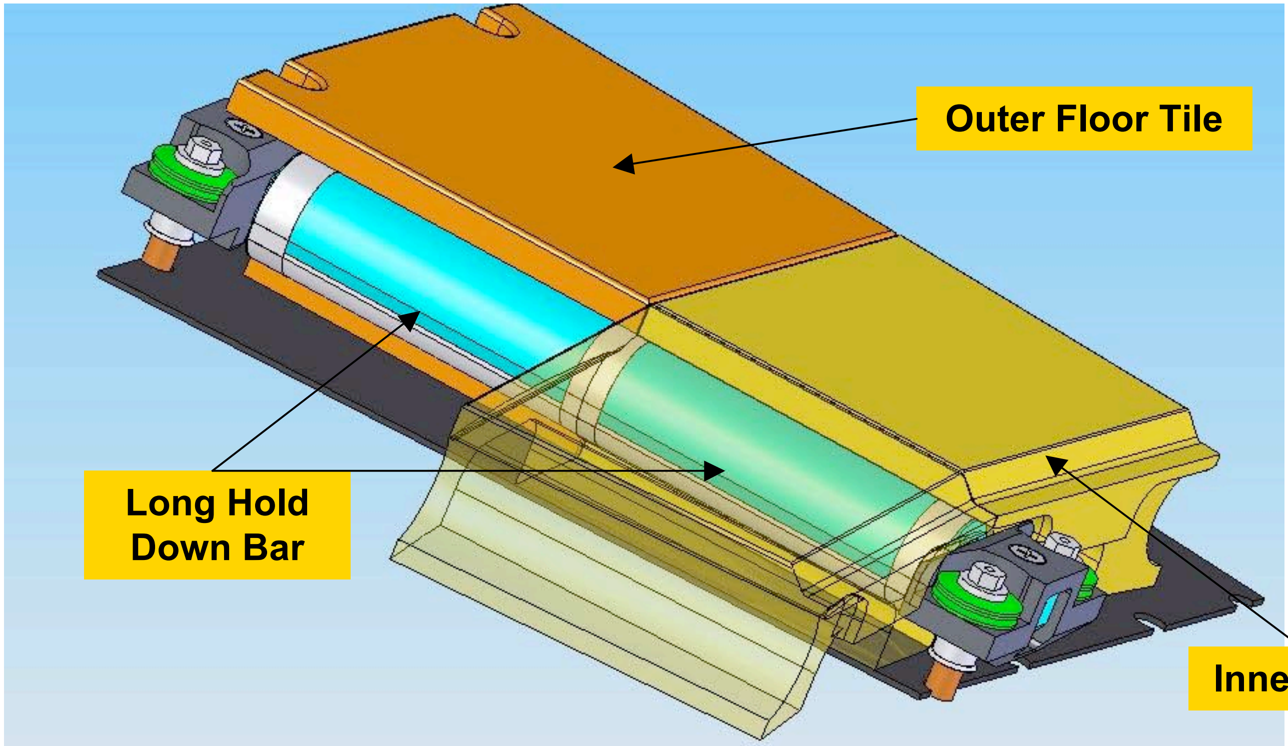
Design Specifications Developed to Meet Objective of Reduced Carbon Erosion

- **Tile to tile gaps not to exceed 0.4 mm, tile height alignment within 0.1 mm**
- **Tile alignment specifications were met. Contributing factors include:**
  - CNC positioned tile attachment locations on divertor shelf during machining of the shelf
  - Very smooth and flat divertor shelf surface
  - CNC machined graphite tiles are manufactured with tight tolerances and good repeatability
  - Use of SOLIDWORKS 3D modeling to fit assemblies and check clearances allowed for close fitting designs



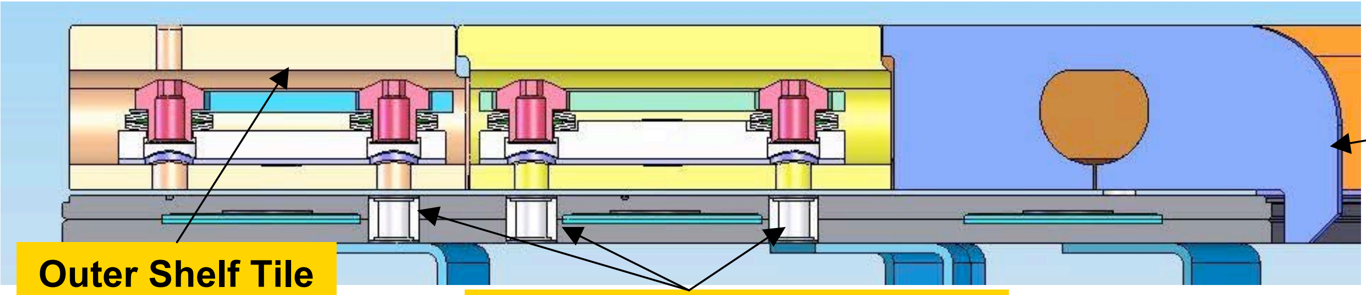
- **Exposed graphite edges are reduced through the use of new tile hold down techniques:**
  - Through-shelf hold down bolts on the divertor shelf tiles
  - Long radial edge hold down bars on the vessel floor tiles

New Tile Hold-Down Methods Reduce Holes in Tiles and Provide Exceptional Alignment



Grafoil gaskets are used under all tiles to:

- **Facilitate better thermal conductivity**
- **Reduce high localized stresses from uneven mounting surfaces**

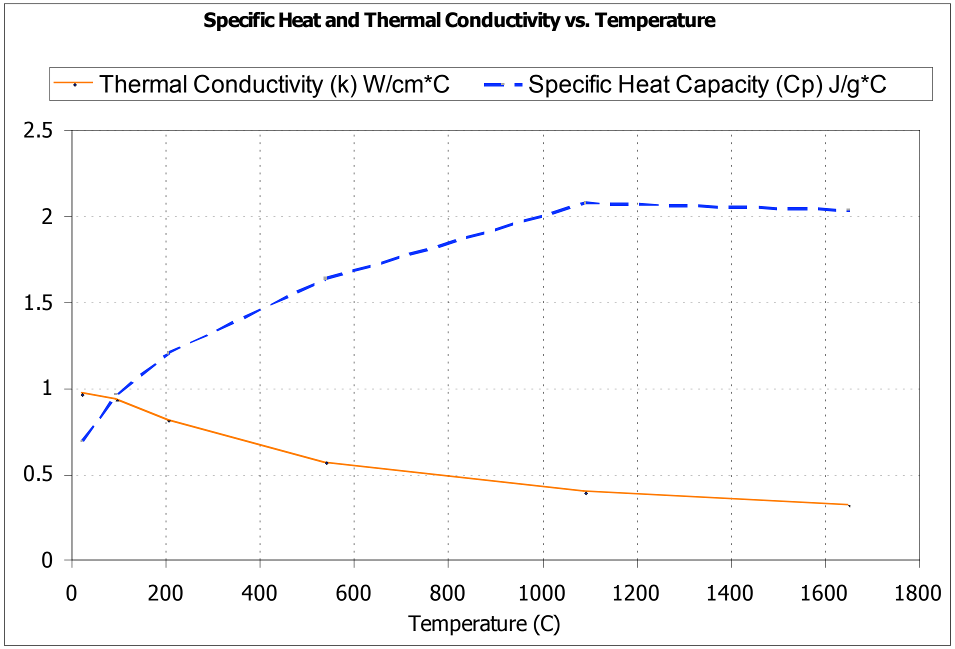


Floor tile attachment and shelf tile attachment, minimizing exposed graphite edges

DIII-D Vessel Floor and Lower Divertor Showing Very Good Toroidal Uniformity and Few Exposed Graphite Edges

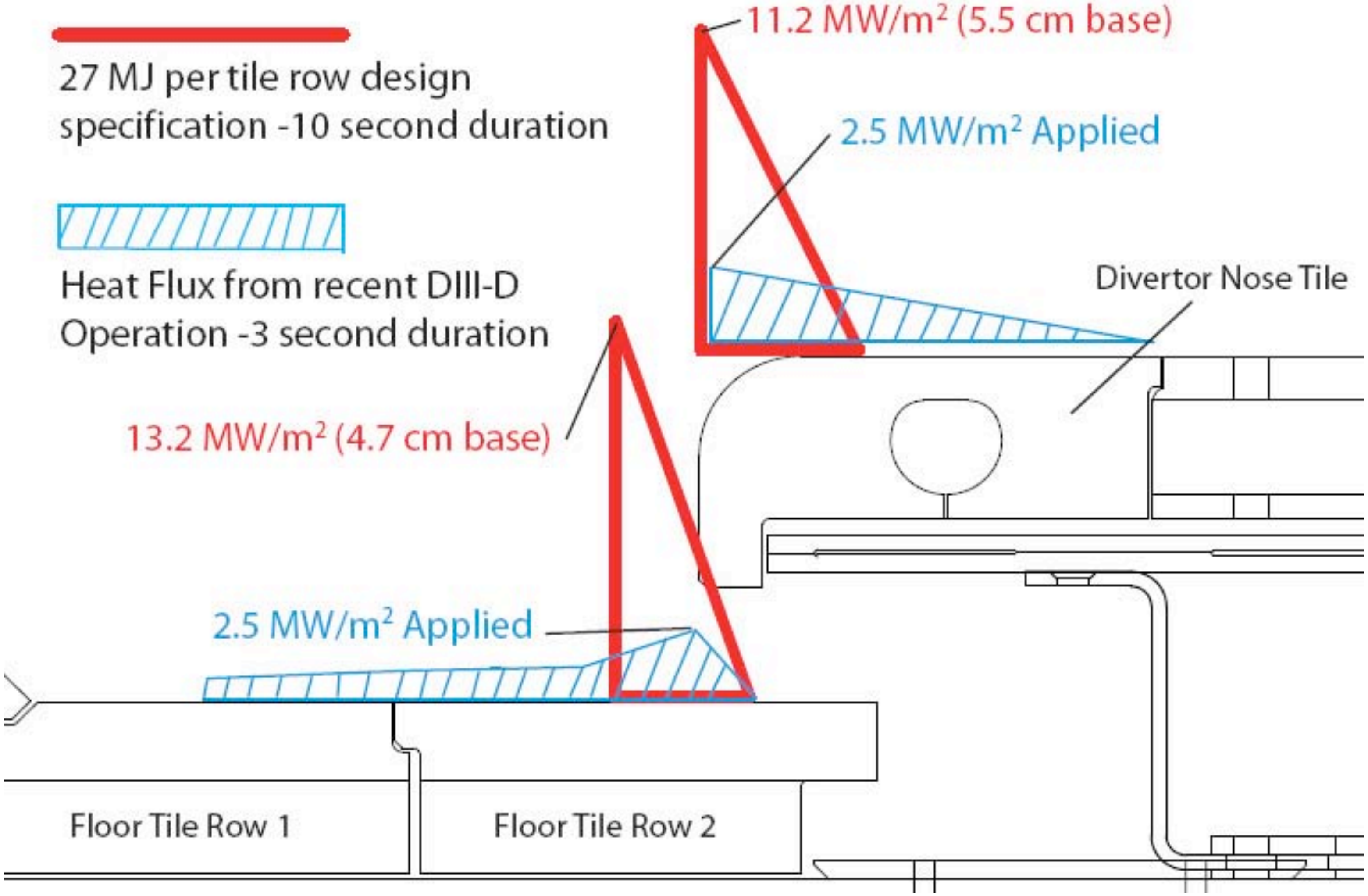
Tile Thermal Analysis Overview

- 10 second shot
- 14 minute cooldown period between shots
- COSMOSWORKS used
- Nonlinear physical properties of ATJ cause analysis to be nonlinear and not scalable



- **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.**

Tile Thermal Analysis: Design Specifications

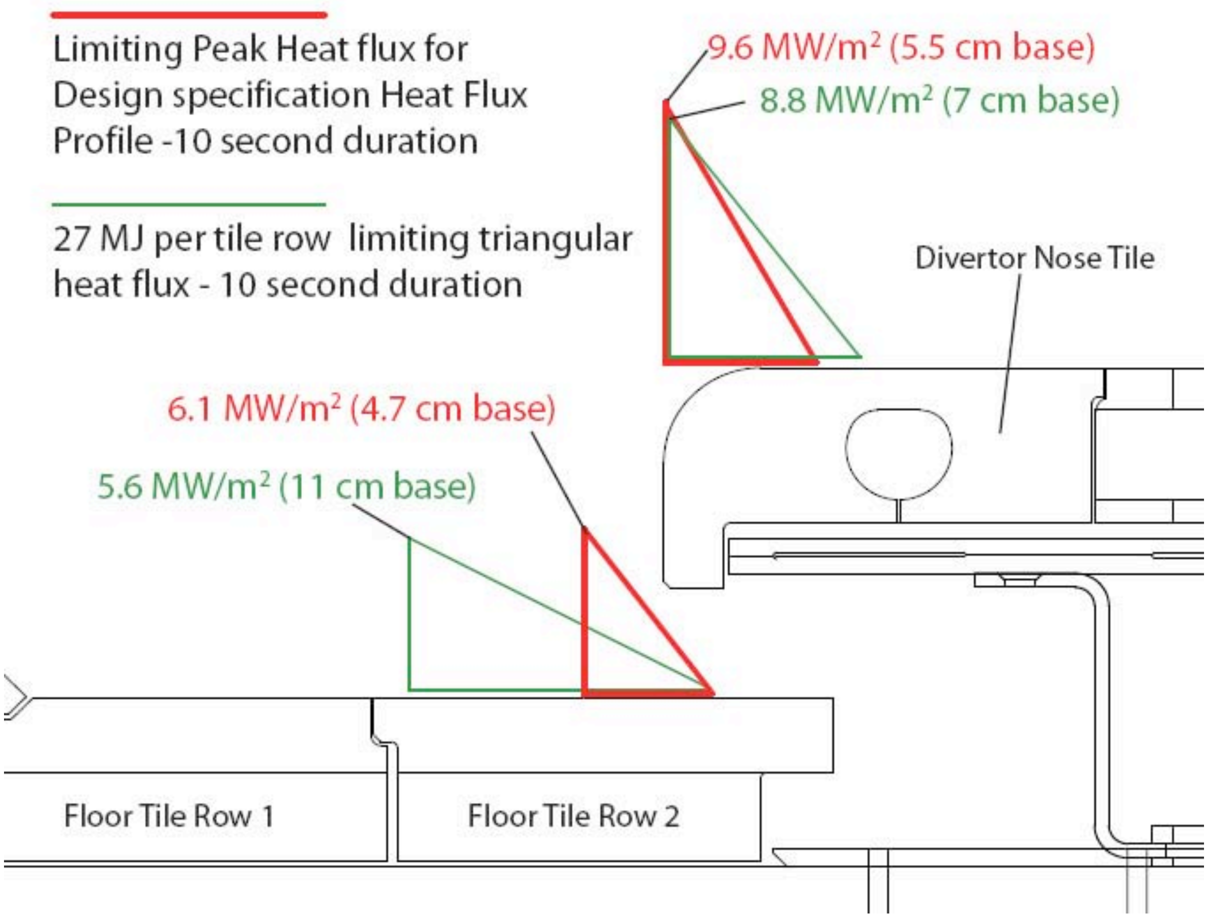


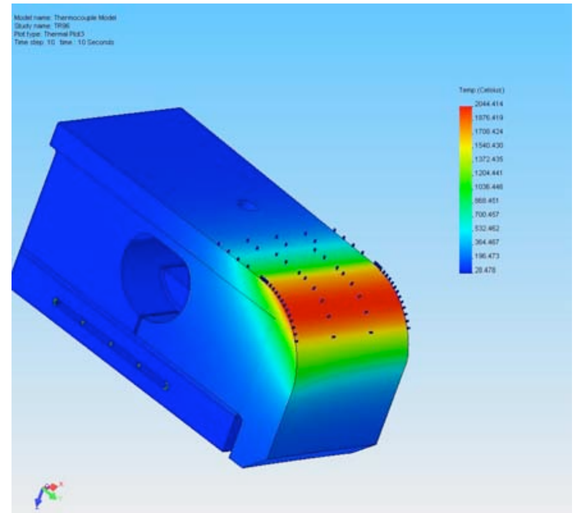
Tile Thermal Analysis (Continued)

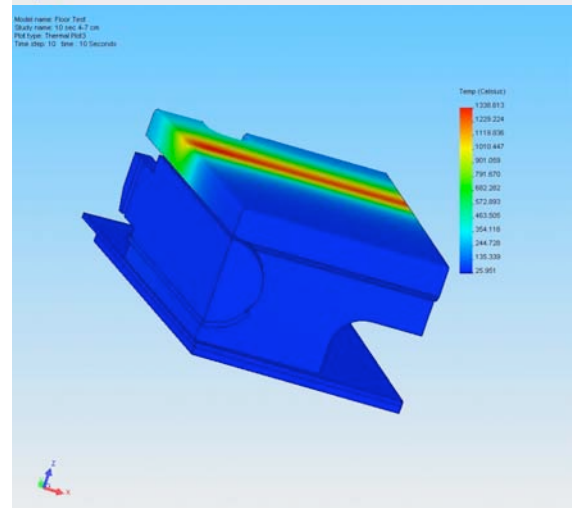
- **The stationary, narrow triangular heat flux profile specified in the original design specifications proved to be more than any of the ATJ tile designs could survive**
  - The graphite simply can not conduct the energy quickly enough to avoid creating large internal temperature gradients. These resulted in non-uniform thermal expansion and consequent thermally induced tensile stress

- **Two limiting heat flux cases were examined in which maximum allowable tensile stress was not exceeded:**
  - One case keeping the narrow design specification heat flux profile constant
  - One case keeping the design specification energy input of 27 MJ per toroidal row of tiles constant

Limiting Heat Flux Profiles (Analytically Derived)





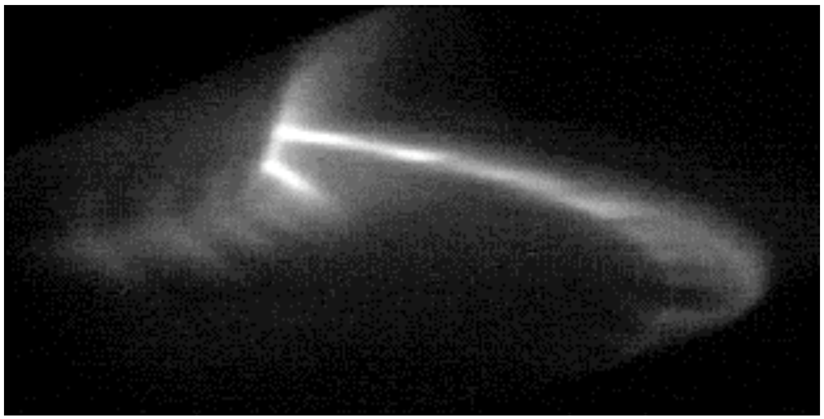


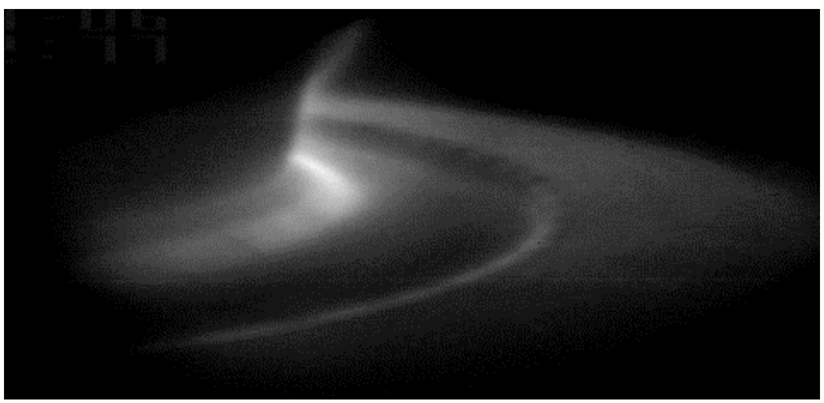
Operational Performance (No Tile Failure)

- **12 Week Operating Period Completed in 2006 after Divertor Installation – No tile performance problems**
- **Visible and infrared cameras are used to measure tile performance during operations**
  - The tangentially viewing visible camera has a wavelength filter centered at 4310A (carbon-deuteride, CD, part of the methane break-up chain). CD is a good indicator for toroidal uniformity of the carbon chemical sputtering source
- **Infrared camera validation of COSMOSWORKS model**
  - Tile surface temperature data from the IR camera was compared to COSMSOWORKS predicted tile surface temperatures and very close agreement was shown

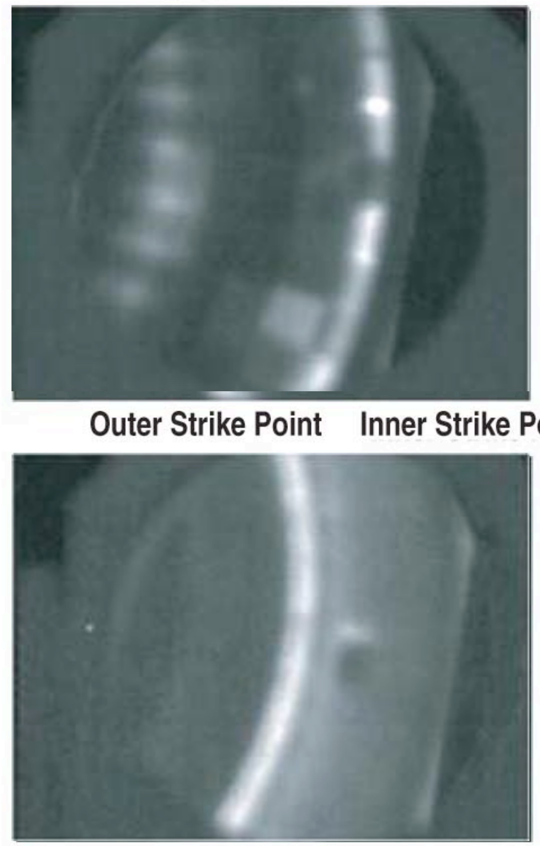
Operational Performance Comparison: New Divertor and Floor Tiles Provide Much Better Toroidal Symmetry

- **Visible Camera with CD Filter – Nearly Horizontal toroidal view**





Surface Temperature of Lower Divertor from IRTV



Conclusions

- **The design objective of minimizing carbon erosion was achieved through very good tile alignment and new tile mounting methods**

- **The design specification of 27 MJ input to a toroidal row of tiles was analytically shown to be achievable with small modification to the heat flux profile or sweeping of the strikepoint**
  - Operations have not yet produced the very narrow and powerful design specification heat fluxes. As operating scenarios produce more narrow and powerful heat flux profiles, the COSMOSWORKS model can be used to predict tile behavior and graphite tiles can be replaced with more robust/thermally conductive material, if necessary
  - Off-line high heat flux testing of tiles may indicate that tile can survive higher loads than the design limit of 60% of ultimate tensile stress