# Princeton Plasma Physics Laboratory

**PPPL-5174**

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February 2015

PRINCETON PLASMA PHYSICS LABORATORY

**Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.**

# ANALYSIS OF ITER UPPER PORT DIAGNOSTIC FIRST WALLS

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*The Diagnostic First Walls (DFWs) were designed to handle the plasma nuclear and radiant heating along with electro-magnetic loading induced from plasma disruptions. The DFWs also provide custom viewing apertures for the diagnostics within. Consequently, the DFWs contain numerous complex water cooling channels and are designed per ITER SDC-IC criteria for design by analysis.*

*This paper presents the analyses of the Upper Port DFWs proceeding to a final design review. The finite element analyses (FEAs) performed includes neutronics, radiative heating, coupled fluid dynamics and heat transfer, and static and transient structural analysis using the combined multi-physics load conditions. Static structural FEAs performed account for the dynamic amplification effects of the transient load. A detailed bolt analysis was also performed per the ITER SDC-IC bolt evaluation criteria based on reaction loads obtained from the mechanical simulations.*

## I. INTRODUCTION

In ITER the Diagnostic Port Plugs (DPPs) provide a common platform for a variety of diagnostics. The port plug structure, including internal Diagnostic Shield Modules (DSMs) contributes to the nuclear shielding of the port. Both components contain circulated water to allow cooling during operation and heating during bake-out. The DSMs also mechanically support the forward diagnostic components and the Diagnostic First-Walls (DFWs). The stainless steel DFWs weigh up to 2 metric tons, and are large irregular shaped components bolted to the front of the DSMs. The DFW's are designed to withstand severe plasma radiant and nuclear heating. The DFWs also provide custom viewing apertures for the diagnostics within. Consequently, the DFWs contain numerous complex water cooling channels. Refer to figure 1 for a cross section image of ITER with the diagnostic port plug locations. Figure 2 shows the Upper Diagnostic Port Plug main components and figure 3 shows examples of UDFWs for two port locations.

## II. ANALYSIS PROTOCOL

### II.A. Background

The analysis began with the neutronics and EM studies of the frozen configurations prior to the DFW PDR activities. Concurrently, plasma facing surfaces, aperture side walls, and edges, were analyzed for surface heat loads. The coolant circuit was designed based upon these results, and earlier PDR design, evaluation and parametric studies. ANSYS CFX was used to develop the flow, velocity and pressure drop. Modifications to the

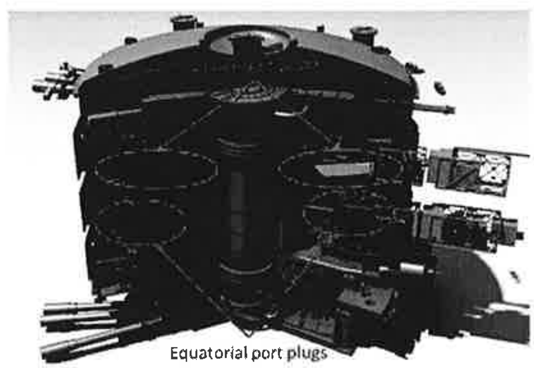


Fig. 1. ITER Cross-sectional View with Diagnostic Port Plugs.

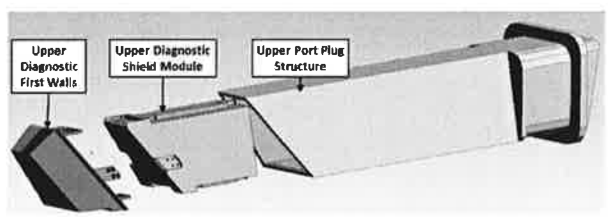


Fig. 2. Upper Diagnostic Port Plug Main Components.

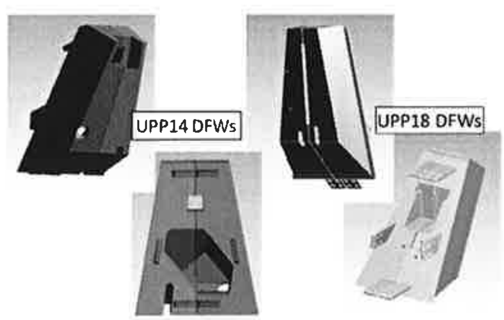


Fig. 3. Upper Port 14 and 18 DFWs with Apertures.

coolant circuit were implemented as needed. Volumetric & surface heating were applied to each DFW model. Results determined whether design iterations were necessary. For the combined mechanical analysis, Lorentz forces + thermal loads, a DSM coolant circuit was developed at the DFW-DSM interface. These models were used in CFX analyses to produce temperature distributions at the bolted connections.

### II.B. Analysis Method and Protocol

The analyses were performed based on the SDC-IC requirements and physical phenomenon: static or transient; nuclear, thermal-hydraulic, electro-magnetic or mechanical conditions; elastic vs nonlinear analysis, and M-type vs C-type failure criteria. Pressure loading is minor as compared to the effects of the thermal or EM loading. Thermal stress dominates the plasma side first wall (FW) design. Lorentz force induced stress dominates the connection tab design. As such, the analysis reported follows this reality.

Two separate simulation methods were used for the DFW assessment: method 1 – FEAs with detailed FW cooling circuits used for pressure and thermal loading. This evaluation accounted for fatigue and required a non-linear analysis. Method 2 – FEAs without detailed FW cooling, but high fidelity pinned & bolted frictional connections. Combined multi-physics FEA included dead weight, Lorentz forces, thermal gradients, and seismic accelerations, and is the most severe loading condition for the DFW-DSM connection. Refer to figure 4 for the UDFW design and analysis protocol along with the software used.

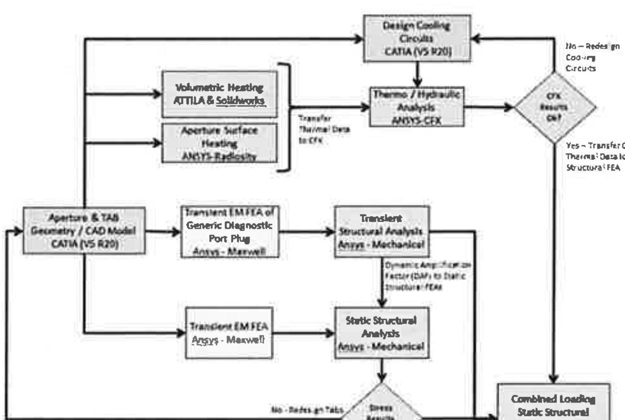


Fig. 4. UDFW Design and Analysis Protocol.

Computer Aided Design (CAD) models for UPP 14 and UPP18 were received from the ITER-IO. These models, which contained the DFW's with custom diagnostic viewing apertures, were de-featured for use in the FEA software. Generic DFW models, with no apertures, were created based on the ITER-IO models.

### III. NEUTRONICS ANALYSIS AND RESULTS

Neutronics simulations were performed using ATTILA which solves the Boltzmann transport equation by discretization in space, angle, and energy. The project standard 500 MW 14 MeV neutron source is used. The ATTILA neutronics volumetric heating analysis was done for two upper ports, UPP 14 and UPP 18. Each port was placed in a simplified ITER model that focused specifically on the upper port in question. Figure 5 shows the global model for nuclear analysis along with DPA results. Note, the maximum DPA for the UDFW is approximately 2.0 dpa.

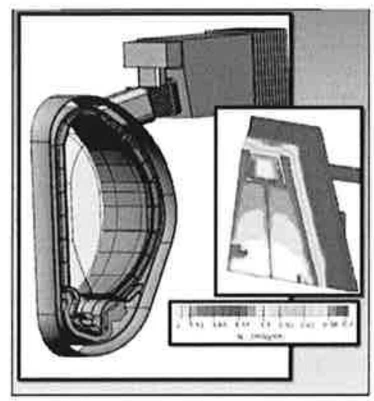

Fig. 5. Neutronics Model & UDFW DPA Results

### IV. RADIOSITY FEA AND RESULTS

The non-penetrating "radiation" heat flux on the DFWs was computed using the ANSYS radiosity solution approach. ANSYS Radiosity uses view-factoring among surfaces to determine the amount of heat flux emitted and striking a surface. Newton-Raphson procedure was employed in ANSYS Radiosity solver.

Each DFW has a unique aperture and cavity surfaces. Based on the plasma radiated thermal flux of 0.35 MW/m², the incident heat flux of each plasma facing surface was derived from the surface elemental results. The global coordinates of the center of each surface element and corresponding heat flux constitutes a input data file, which was used for the subsequent ANSYS CFX wall boundary. Refer to figure 6 for surface heating results.

### V. CFX FEA AND RESULTS

The DFWs possess flowing liquid coolant. Thus thermal and hydraulic analysis of the DFW was performed. The analysis method uses conjugated heat transfer in which heat transfer was resolved in both solid and liquid regions. Simultaneously, fluid dynamics analysis was performed on the liquid region. This approach includes interfaces between the solid and liquid regions of the system. The conjugated heat transfer analysis was performed using ANSYS CFX software

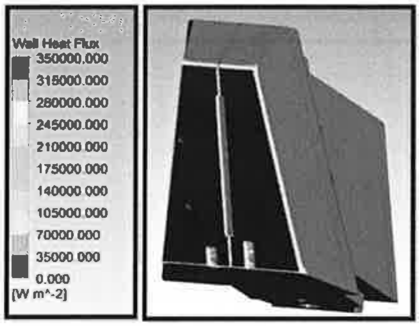


Fig. 6. Radiosity FEA Results.

At the solid-liquid interfaces, conservation of the heat flux was assumed together with the non-slip wall boundary conditions for the liquid. Turbulent flow is mostly occurring in the DFW cooling system. As such, non-slip wall boundary conditions take the form of wall functions. The assumed turbulent flow was resolved using Reynolds averaged Navier-Stokes equations with Shear Stress Transport turbulence model proposed by Menter.

The following boundary conditions and loads were imposed for the fluid flow and heat transfer calculations:

- Outlet water pressure: 2.65 MPa,
- Inlet water temperature of 70 °C.
- Inlet flow rate at 1.5 kg/s
- Turbulence intensity of 3.7%
- Inlet turbulent viscosity ratio of 1000,
- Non slip boundary conditions channel walls.
- Heat flux conservation solid-liquid interface.
- Volumetric heat flux on liquid as a heat source.

The following boundary conditions and loads were imposed for heat transfer calculations:

- Heat flux 0.35MW/$m^2$ on DFW plasma face.
- Surface heat flux distributions: sidewalls& apertures
- Rear DFW walls assumed adiabatic.
- DFW-DSM interfaces constant temperature 300 $^0$C.
- Heat flux conservation on the solid-liquid interface.
- Volumetric heat flux on DFW body as heat source.

Refer to figure 7 for the CFX FEA results.

## VI. ELECTRO-MAGNETIC FEA AND RESULTS

The EM simulations were performed using the Ansys Maxwell Software. Eddy current analysis was used to evaluate plasma disruption and displacement event induced current profiles. The analysis was intended to develop the eddy currents and obtain forces and moments on various structures during major plasma events. Eddy currents and resultant EM forces are greatly influenced by the presence of other structures including the Vacuum Vessel, DSMs, Blanket Shield Modules, and Port Extension, which are all included in the simulation. Refer to figure 8 for the Maxwell FEM. The highest loading condition for UPP is VDE_UP_LIN36 – Upward VDE with 36ms Linear Decay. This event was used for the UPP EM analysis. Refer to figure 9 for the EM FEA results.

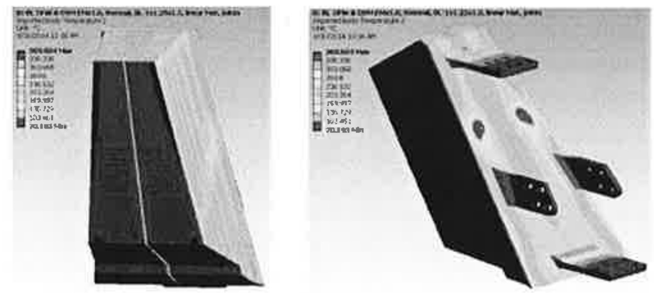

Fig. 7. UDFW CFX Results.

## VII. MECHANICAL FEA AND RESULTS

The purposed of the mechanical analysis is to validate the final design of the UDFWs during normal and abnormal events against SDC-IC requirements. The design by analysis validation includes evaluation of:

1) DFW tabs, pins and bolts at the connection;
2) DFW deflection from EM & thermal events;
3) FW thermal fatigue during normal operation;
4) Fluid pressure stress for ESPN considerations.

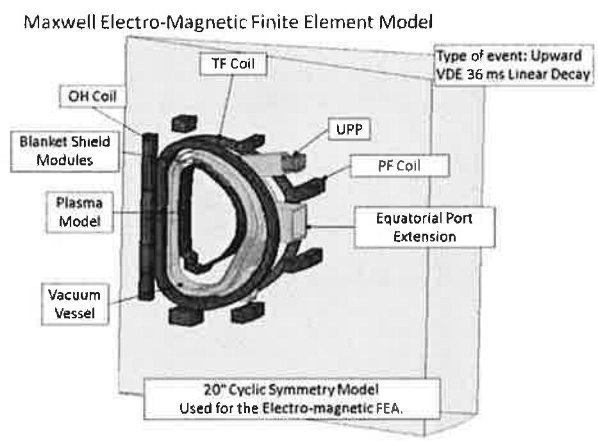


Fig. 8. EM FEA Model.

### VIII.A. Detailed First Wall FEA and Results

Cyclic thermal strain is the dominate failure mechanism for the FW. To assess this, non-linear elastic-plastic FEAs were performed for 3 detailed FW models: (1) a parametric study, (2) EDFW FW model, and (3) UDFW FW model. Refer to figure 10 for these models.

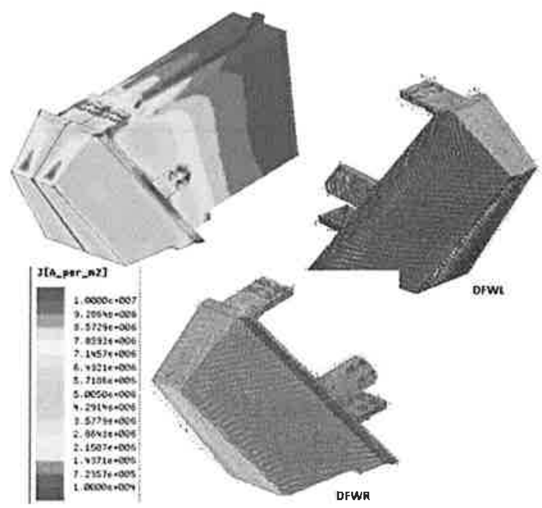


Fig. 9. EM FEA Results: Current Density and Vector Plots.

Figure 11 shows results from the UDFW cyclic thermal strain FEA. Results from the three studies led to similar conclusions of the FW fatigue life. The strain range for a majority of the UDFW FW is < 0.3%, which satisfies the SDC-IC requirements at 30k cycles of life. However, many localized regions experience strain ranges > 0.6%. For these regions only 4,000 cycles can be achieved. Yet, adjustments to cooling channel geometry: size of radii, channel shape/location etc. can reduce the strain range and provide greater fatigue life.

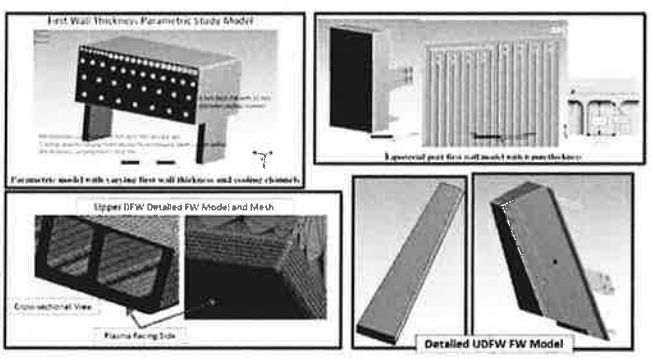


Fig. 10. Detailed First Wall Models.

### VIII.B Detailed Tab Connection FEA and Results

Numerous simulations have been performed to assess the various load cases prescribed in UDFW Load Specification. Primary load simulations were performed to assess M-type damage. Stresses developed from primary loads were linearized to obtain membrane, and membrane + bending stresses used for the assessment. The most severe loading condition results from the combined loadings of: dead weight, Lorentz forces, thermal gradients, and seismic accelerations. These results were used for both M and C type damage assessment. C-Type damage assessment required a multi-physics elastic FEA to evaluate progressive deformation – ratcheting. Furthermore, fatigue life was assessed by summing the cumulating damage with the usage fraction method. Figure 12 shows results for M-type damage assessment of primary loading. Figure 13 shows the fatigue life assessment.

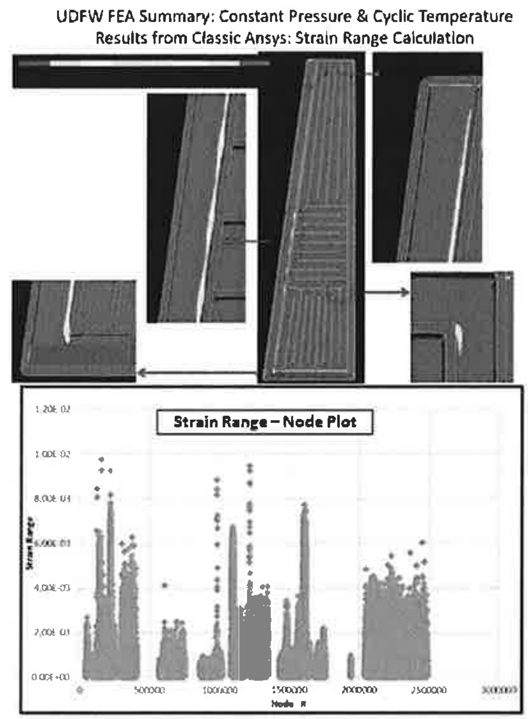


Fig. 11. FW Strain Range Results

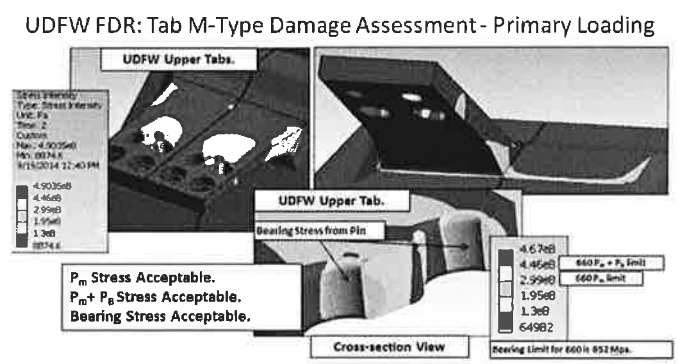


Fig. 12. M-Type Damage Assessment of the Tabs.

### VIII.C. Pin Analysis & Results

Elastic FEA was performed using the most severe primary and secondary loading conditions and the results compared to the SDC-IC criteria. Pin stress was linearized for the primary load case. Due to the material properties, low neutron fluence and relatively low temperature, several M-type damage modes were eliminated. Combined loading was used for evaluating progressive deformation and fatigue life. Refer to figure 14 for the pin geometry, mesh, stress intensity and linearize stress results. The pin design satisfies the SDC-IC requirements for M and C-type damage.

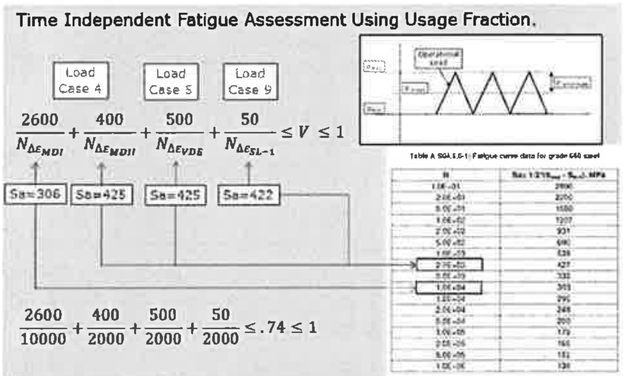


Fig. 13. Fatigue Assessment of the Tab.


Fig. 14. In718 Pin Stress Results.

### VIII.D. Bolt Analysis & Results

The detailed tab FEA included bolts. The bolt models were de-featured, no threads. The correct size, length and material properties of the bolts were used. The bolts are Inconel 718. Frictional contact is used at the DFW–DSM interface, and underneath the bolt heads. FEAs included frictional coefficients of 0.15-0.5. The bolts are "bonded" to the DSM and assumed not to contact the tab at the bolt shoulder or threads. Bolt mesh is sized to properly develop the bolt preload and reaction forces, refer to figure 15. Bolt preloads simulated were 68KN-110 KN. Upon FEA convergence, the reactions underneath the bolt heads are obtained. The reactions are used in an Excel spreadsheet for calculating the required SDC-IC parameters and determining design safety factors, refer to figure 16.

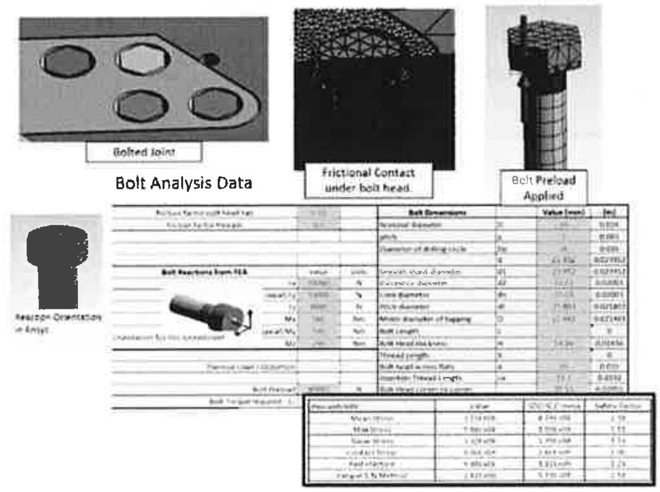


Fig. 16. Bolt Analysis Spreadsheet & Results.

## II. CONCLUSIONS

The UDFW final design has been validated in accordance with the SDC-IC criteria for design by analysis. Specifically, the FW thermal strain range and fatigue life have been determined. For the most severe loading, the DFW connection: tabs and pins satisfy requirements for both M-type and C-Type damage criteria. The analytical calculations for bolt assessment show the bolts are acceptable.

This work is supported by US DOE Contract No. DE-AC02-09CH11466.

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