THERMOMECHANICAL ANALYSIS OF THE REVISED U.S. ITER DCLL TEST BLANKET MODULE

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The US Fusion Nuclear Science and Technology program selected the Dual Coolant Lead Lithium (DCLL) concept as the primary Test Blanket Module (TBM) for testing in ITER. The DCLL blanket concept has the potential to be a high-performance DEMO blanket design with a projected thermal efficiency of >40%. Reduced activation ferritic/martensitic (RAF/M) steel is the structural material, helium is used to cool the first wall and blanket structure, and the self-cooled Pb-17Li breeder is circulated for power conversion and tritium extraction.

The DCLL TBM has undergone major design changes since 2005. We present here the most recent thermo-mechanical analysis of the newly revised DCLL TBM. The analysis described here is aiming to verify the thermo-mechanical response of the DCLL TBM under relevant normal operating conditions as well as during a loss of coolant accident (LOCA).

A full 3-dimensional solid model of the entire DCLL TBM structure was developed, which included FW, top and bottom lids, internal supporting ribs, manifolds, plena, and flexible frame-attachment supports. A coupled thermo-mechanical analysis was performed for both normal- and off-normal operating conditions. Thermal loads included surface heat load, volumetric heating, as well as detailed position- and location dependent heat transfer along all coolant channels. Structural loads incorporated helium coolant pressure loads, self-weight, as well as the weight of the PbLi. Maximum structure temperatures of nearly 560 ^{o}C along with a maximum resultant net displacement of more than 10 mm were mapped for normal operating conditions and a number of stress concentration locations were identified. The ITER SDC-IC-1300 criteria were applied to the LOCA analysis results. It is shown that the DCLL TBM exhibits admissible behavior regarding the ITER Design Criteria and that the most recent design modifications did not compromise the structural integrity.

I. INTRODUCTION

The Dual Coolant Lead Lithium (DCLL) Test Blanket Module (TBM) concept chosen by the US Fusion Nuclear Science and Technology program for testing in ITER is the subject of the thermo-mechanical analysis presented in this paper[1, 2]. The TBM structure consists of reduced activation ferritic/martensitic (RAF/M) steel, with helium (He) used to cool the first wall and blanket, and self-cooled Pb-17Li breeder circulated for power conversion and tritium extraction. A mid-plane section view of the DCLL TBM assembly is shown in Figure 1. The goal of this analysis is to conduct the first Structural Evaluation Plan (S.E.P.) using the ITER Structural Design Criteria for In-Vessel Components (SDC-IC).

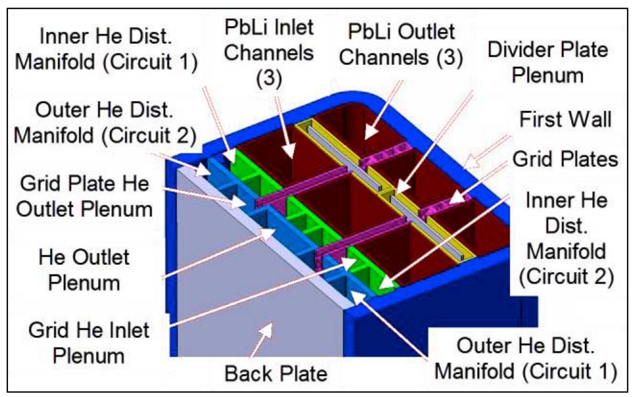

Fig. 1. DCLL TBM assembly mid-plane section view [note: print copy is b&w, but color online].

I.A. Thermo-mechanical Analysis Approach

The general approach used to perform this thermo-mechanical finite element analysis (FEA) is given here:

1) Pre-Process the TBM solid model.
2) Generate necessary data tables and ANSYS scripts.
3) Mesh model, and apply loads and boundary conditions (BCs).
4) Perform thermal analysis.
5) Perform structural analysis with and without thermal effects.
6) Apply SDC-IC rules to FEA results.

Solid modeling operations were performed using the SolidWorks CAD software by Dassault Systèmes. All analysis tasks were performed using ANSYS Mechanical APDL (ANSYS Classic) FEA software by ANSYS, Inc.

II. MODELING OPERATIONS

The original 3-dimensional DCLL TBM solid model is imported into SolidWorks while retaining all significant features including: the first wall, top and bottom lids, internal support ribs, manifolds, plena, and flexible frame-attachment supports. Minor cleaning operations are performed to remove component interferences and other small edges/features that could cause meshing problems.

To facilitate the application of loads and boundary conditions, solid bodies are modeled for the non-structural regions occupied by He and PbLi. The He region is created as 85 discreet solid bodies, and the PbLi region as a single body. Selected views of the TBM structural CAD model, and the PbLi regions are given in Figure 2. These regions are imported into ANSYS along with the structural bodies, and assist in the application of FEA loads and boundary conditions.

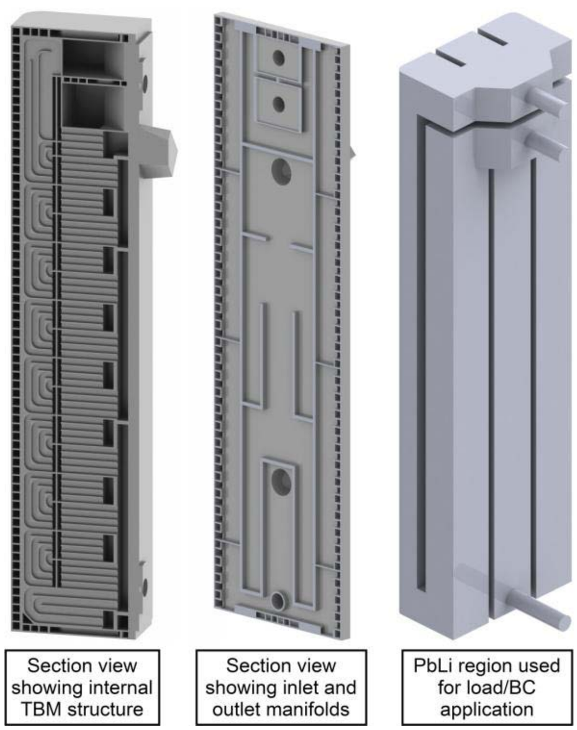

Fig. 2. Section views depicting the internal features of the TBM structural CAD model, and the PbLi region.

III. DATA TABLES AND LOADS ON COMPONENT GROUPS

Due to the complexity of the analysis, numerous data tables and ANSYS scripts are generated. Material property tables are made for F82H and Ti-6Al-4V using temperature dependent data. Tables I and II provide sample material property data used in this analysis.

TABLE I. Selected F82H Material Properties[3]

Temperature [°C]	Density [kg/m^3]	Young's Modulus [GPa]	Thermal Conductivity [W/m-K]	Thermal Exp. Coeff. α [^{o}C^{-1}]
20	7871.0	217.3	32.53	10.35×10^{-6}
100	7848.6	212.2	32.2	10.66×10^{-6}
200	7818.7	207.3	32.84	11.2×10^{-6}
300	7786.5	202.7	33.22	11.36×10^{-6}
400	7752.1	197.1	33.30	11.67×10^{-6}
500	7715.4	189.2	33.02	11.96×10^{-6}
600	7676.5	177.6	32.34	12.23×10^{-6}

TABLE II. Selected Ti-6Al-1V Material Properties[4]

Temperature [°C]	Density [kg/m^3]	Young's Modulus [GPa]	Thermal Conductivity [W/m-K]	Thermal Exp. Coeff. α [^{o}C^{-1}]
20	4430.0	111.23	7.17	8.60×10^{-6}
100	4430.0	103.49	7.63	8.81×10^{-6}
200	4430.0	98.02	8.50	9.07×10^{-6}
300	4430.0	92.96	9.61	9.30×10^{-6}
400	4430.0	77.85	10.84	9.50×10^{-6}
500	4430.0	65.77	12.10	9.70×10^{-6}
600	4430.0	34.51	13.27	9.90×10^{-6}

TABLE III. Thermal Boundary Conditions

Component Group Description	**Thermal BCs Applied to Component Groups**
TBM structure	Volumetric heating, and FW surface heat flux
Flexible supports	N/A
PbLi-facing surfaces	Heat flux from PbLi heat leakage into TBM structure
FW Helium (He) channels	Convection coefficient (h_{conv}) 6979 W/m^2-K with variable He bulk temperatures (T_{conv})
He-channels: inlet, manifold, 1st layer in	h_{conv} = 3586 W/m^2-K T_{conv} = 350 °C
He channels: 1st layer out, 2nd layer in	h_{conv} = 3586 W/m^2-K T_{conv} = 358.57 °C
etc…	etc…
He channels: 7th layer out, grid channels, outlet	h_{conv} = 3586 W/m^2-K T_{conv} = 410 °C

Data tables and scripts were created to apply spatially dependent loads and boundary conditions including:

- FW surface heat flux (q'' = 0.5 MW/m^2)
- Spatially dependent volumetric heating [q'''(x,y,z)]
- Helium pressure (8 MPa)
- PbLi pressure (2 MPa + gravitational effect)
- Structural fixtures (flexible joints)
- Structural gravitational loads (including PbLi).

Table III outlines the relationship between TBM subcomponent regions and their respective loads/BCs.

IV. THERMAL FINITE ELEMENT ANALYSIS

A static thermal analysis is performed to obtain the temperature distribution within the TBM structure. The TBM model is imported into ANSYS and meshed using ~2.82 million elements. A section view of the meshed model is shown in Figure 3. Thermal loads and BCs applied on the FEA model include the first wall surface heat flux, convective BCs, and volumetric heating.

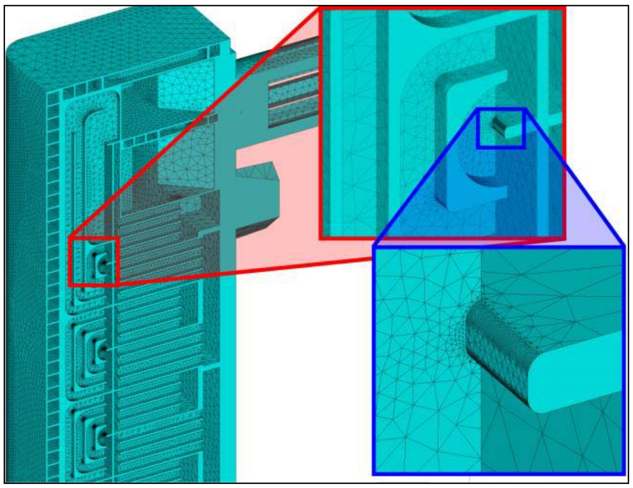

Fig. 3. Section view of meshed TBM model in ANSYS [note: print copy is b&w, but color online].

IV.A. First Wall Surface Heat Flux

The surface of the first wall receives a heat flux of 0.5 MW/m^2 in the radial direction (normal to its main, flat surface). The flat first wall surface receives the full magnitude of the heat flux, while the curved surfaces receive lower amounts of heat proportionally to the cosine of the angle of incidence. Figure 4 shows the location and values of the surface heat fluxes applied.

IV.B. Heat Convection Boundary Conditions

The internal geometry of the TBM contains numerous channels through which He and PbLi flow, effectively cooling the structure. For the thermal analysis, this contribution is modeled as heat convection boundary conditions using prescribed heat transfer coefficients and bulk temperatures which vary spatially based on knowledge of the cooling behavior of the flow.

Fluid heat convection (h_{conv}) values along the first wall He channel surfaces were estimated to be 6979 W/m^2-K, and 3586 W/m^2-K within all other He channel surfaces. The FW h_{conv} values were based on 0.5 mm tall ribs with periodic spacing inside a square duct.[5] Bulk temperatures start at 410 °C at the He inlet, and gradually cool to 350 °C at the outlet, with the majority of the temperature changes occurring along the first wall. The bulk temperature distribution within the He is shown in Figure 5.

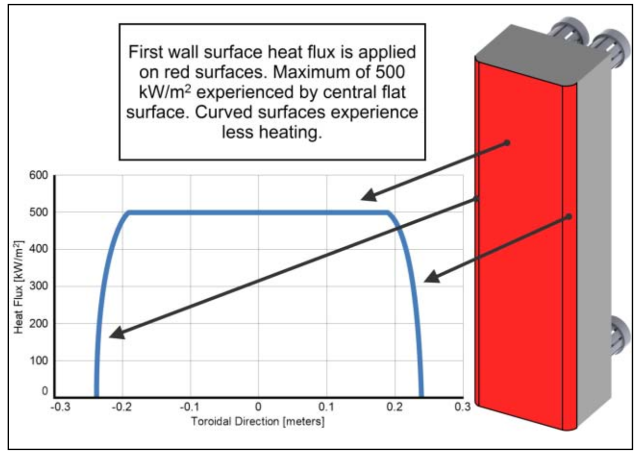

Fig. 4. First wall surface heat flux loads [note: print copy is b&w, but color online].

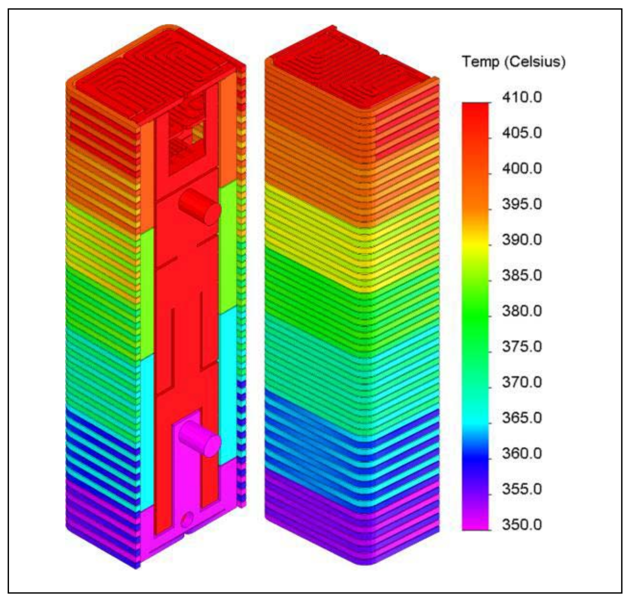

Fig. 5. Model of helium regions colored to represent the convective bulk temperatures applied. [note: print copy is b&w, but color online]

IV.C. Volumetric Heating

Spatially dependent volumetric heating, q'''(x,y,z), within the TBM structure/PbLi were calculated[6] and imported into ANSYS as data tables in order to accurately apply volumetric heating to all components as a function of x, y, and z as shown in Figure 6.

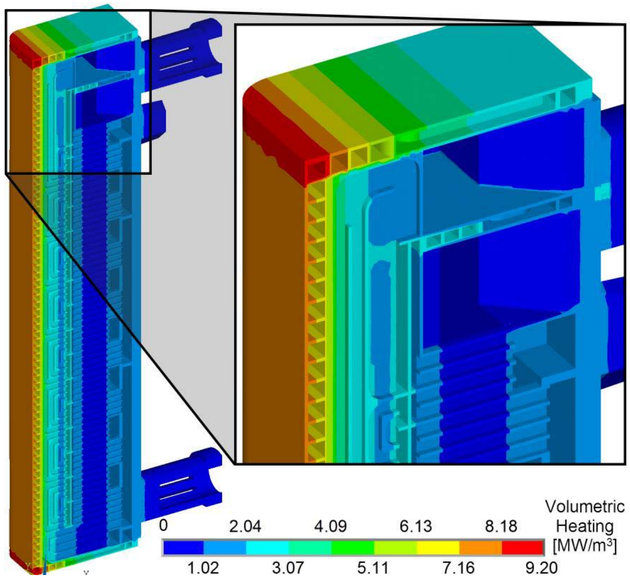

Fig. 6. Section view of TBM structure showing the spatial variance of the volumetric heating loads applied. [note: print copy is b&w, but color online]

IV.D. Thermal Analysis Results

The thermal analysis results yield maximum temperatures of 560-587 °C occurring near the upper lip of the first wall. Temperature distributions can be seen in Figure 7. Horizontal and vertical temperature variations on the first wall demonstrate the spatial dependence of the heat transfer effects that the He coolant channels provide. These temperature results are stored for use in the structural analysis.

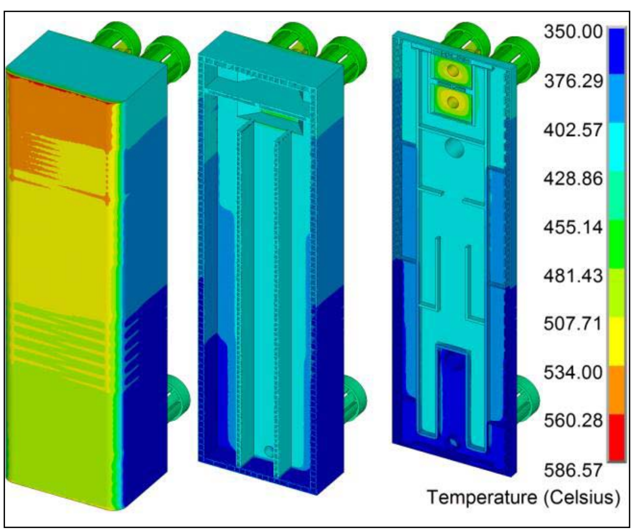

Fig. 7. Temperature results from the ANSYS thermal analysis at various section cuts. [note: print copy is b&w, but color online]

V. STRUCTURAL FINITE ELEMENT ANALYSIS

The mechanical response of the TBM is evaluated by performing a structural finite element analysis using the results from the thermal analysis, and all applicable structural loads.

- 8 MPa pressure loads are applied on He-facing surfaces.
- Pressure loads applied to PbLi-facing surfaces are equal to 2 MPa plus the hydrostatic pressure due to gravitational effects on the PbLi fluid.
- Fixed structural restraints are applied on the faces of the Ti-6Al-1V flexible supports as shown in Figure 8.
- Uniform gravity of 9.809 m/s^2 is applied on the entire structure.
- Temperature results from the thermal analysis are applied for thermal expansion, and accurate material property evaluation.

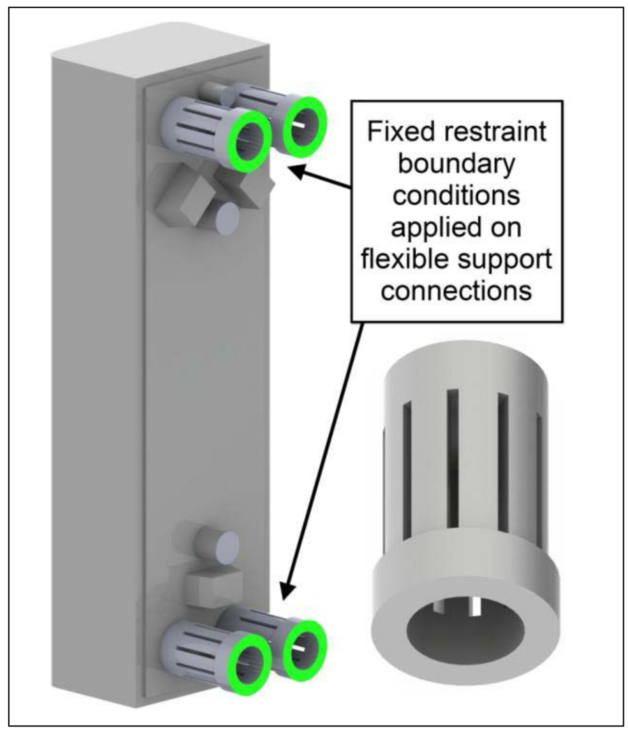

Fig. 8. Flexible support connections used to provide structural restraints. Inset is the flexible support itself.

V.A. Structural Analysis Results

Structural analysis results are shown in Figure 9. Maximum displacements of 5.224 mm are witnessed in the top and bottom first wall lips. Although the maximum calculated Von Mises Stresses are in the range of 2230 MPa, further investigation shows that these values are discontinuities caused by geometrical issues. The thermal Von Mises Stress in the majority of the TBM is around

250 MPa, with maximum stresses occurring at the flexible joints, and internally at a number of internal rib structures and sharp features.

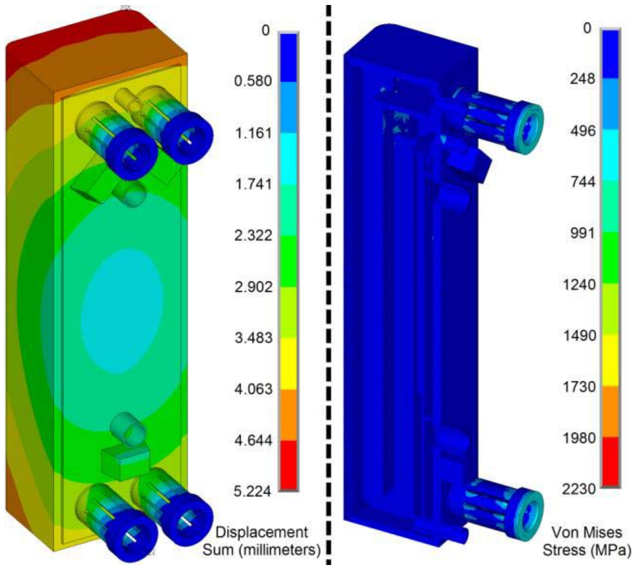

Fig. 9. Displacement sum (left) and Von Mises Stress (right) contour plots from the structural analysis results. [note: print copy is b&w, but color online]

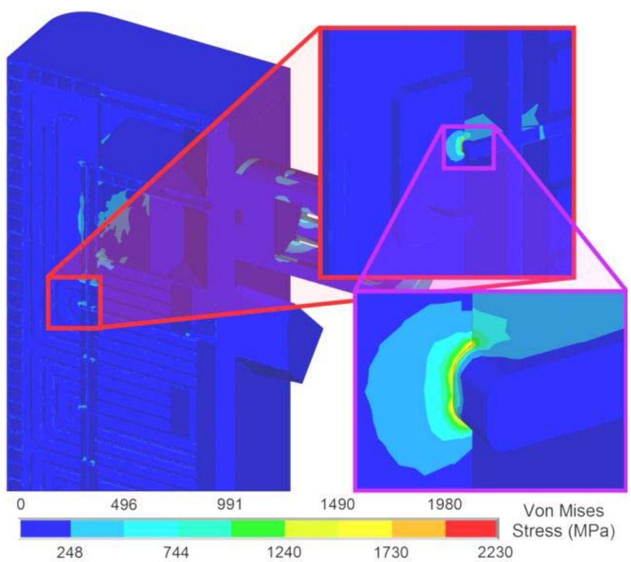

Fig. 10. Von Mises Stress concentration region. [note: print copy is b&w, but color online]

These stress concentration locations are analyzed by applying the SDC-IC rules. Both low-temperature and high-temperature design rules are implemented. Using these design rules to correctly interpret stress results, one location near the top of the first wall lid shows a factor of safety less than 1 (FoS = 0.71). The TBM S.E.P. shows the need to perform additional elastic-plastic analysis.

VI. CONCLUSIONS

The revised (2009) TBM CATIA model was "cleaned" and used to create a detailed solid model of the DCLL TBM, including flexible joints. Data tables for material properties, loads, and BCs were generated, and the TBM model was imported and meshed in ANSYS using ~2.82 million elements. Thermal analysis identified hotspots along the top TBM edge (560-587 °C), and provided the temperature distribution required for the structural analysis. The structural analysis identified stress concentrations which must be addressed in the next design iteration, mainly inside the flow dividers and support rib structures. SDC-IC (2004) rules were applied onto regions of high temperatures, and high stresses. This effort identified areas exhibiting a factor of safety less than 1. Future work would include:

- Performing transient analysis with the inclusion of disruption loads.
- Adding fillets and rounds to high stress areas.
- Coupling CFD-based temperatures and pressures with thermal and structural analysis.
- Performing an elastic-plastic thermo-structural analysis.

ACKNOWLEDGMENTS

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