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Structural Assessments of the K-DEMO Blanket Modules

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Structural Assessments of the K-DEMO Blanket Modules

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The Korean fusion demonstration reactor (K-DEMO) is in the early stages of conceptual design. Ceramic breeder blanket modules are being investigated. These have had extensive nuclear and thermal evaluations. Structural assessments are in process. This paper presents stress analyses performed at PPPL in support of the blanket design. Disruption loading, including the effects of ferromagnetic structural materials is evaluated. An approximate, but representative model of the blanket is used to evaluate a full set of normal thermal , pressure, and static magnetic loads. Disruption and faulted pressure loads are assessed as well. In one structural concept being considered for K-DEMO a semi-permanent shield is employed that also serves as support for the blanket modules. Inner and outer support shells are planned. The inboard blanket support structure and the outboard blanket structure are toroidally electrically continuous and are structurally connected. The inboard modules are keyed into the toroidally continuous support structure which reacts disruption loads from the blankets and from its own internal eddy currents and static magnetic loads. The support shells serve as nuclear and electromagnetic shields for the vessel . This arrangement is a part of a vertical maintenance concept, that removes the inboard blanket module components with a radial and vertical traverse and leaves much of the massive shielding and support structure in place. Normal and disruption blanket loads need to be quantified to show that these loads can be carried by the proposed structure, and to qualify the internals of the blanket modules. . The K-DEMO disruption analysis employs a simple modeling of the plasma by adjusting current densities in regions of the cross section defined for the plasma. Static magnetic loads for both normal operation and disruption have been added by an approximate method developed using a representative blanket and an ITER disruption simulation. Thermal loads are added based on surface and volumetric heating from NFRI.

1. Introduction

The Korean fusion demonstration reactor (K-DEMO) is in the early stages of conceptual design. Ceramic breeder blanket modules are being investigated. These have had extensive nuclear and thermal evaluations. Structural assessments are in process.

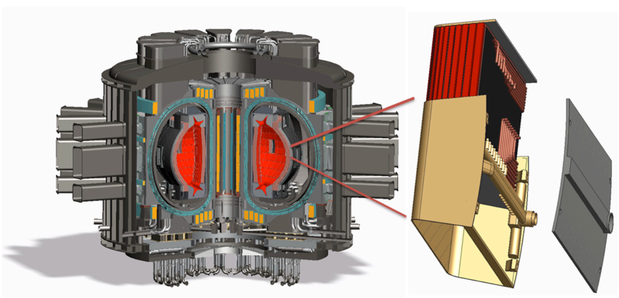

Figure 1

This paper presents stress analyses performed at PPPL in support of the blanket design. Thermal and disruption loading, including the effects of ferromagnetic structural materials is evaluated. An approximate, but representative model of the blanket is used to evaluate a full set of normal thermal , pressure, and static magnetic loads. Disruption and faulted pressure loads are assessed as well. In one structural concept being considered for K-DEMO a semi-permanent shield is employed that also serves as support for the blanket modules. Inner and outer support shells are planned. The inboard blanket support structure and the outboard blanket structure are toroidally electrically continuous and are structurally connected. The inboard modules are keyed into the toroidally continuous support structure which reacts disruption loads from the blankets and from their own internal eddy currents and static magnetic loads. The support shells serve as nuclear and electromagnetic shields for the vessel . This arrangement is a part of a vertical maintenance concept, that removes the inboard blanket module components with a radial and vertical traverse and leaves much of the massive shielding and support structure in place. Normal and Disruption blanket loads need to be quantified to show that these loads can be carried by the proposed structure, and to qualify the internals of the blanket modules. The KDEMO disruption analysis employs a simple modeling of the plasma by adjusting current densities in regions of the cross section defined for the plasma. Vertical translations can be modeled with decreases in current density in plasma regions at the mid plane while increasing current densities in a lower volume. The quench is modeled as a decay of the plasma current. Static magnetic loads for both normal operation and disruption have been added by an approximate method developed using a representative blanket and an ITER disruption simulation.

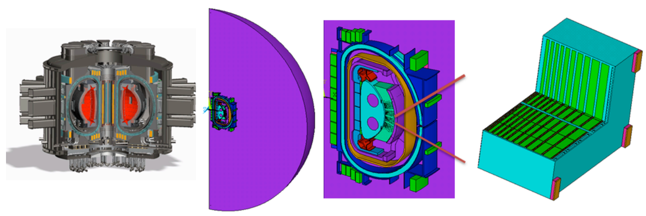

Figure 2

In figure 2, the CAD model is at left, Two plots of the disruption mode are in the center, and the blanket

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sub model is plotted at right. Not shown is the modeling of a representative blanket in an ITER disruption model that is used to calculate static magnetic loads of the RAFM Steel. Details of the blankets are developed from published descriptions of the KDEMO ceramic breeder concept[1]. Disruption eddy current loading is quantified by imposing time dependent vector potential gradients from the simplified global disruption model on a more detailed representation of the blanket structure. Static magnetic loading from the ferromagnetic properties of the RAFM steel are is added using a simplified method described below. The intention of this analysis is to develop tractable models of the blankets to investigate basic sizing and feasibility of the inboard and outboard blankets and their support mechanisms.

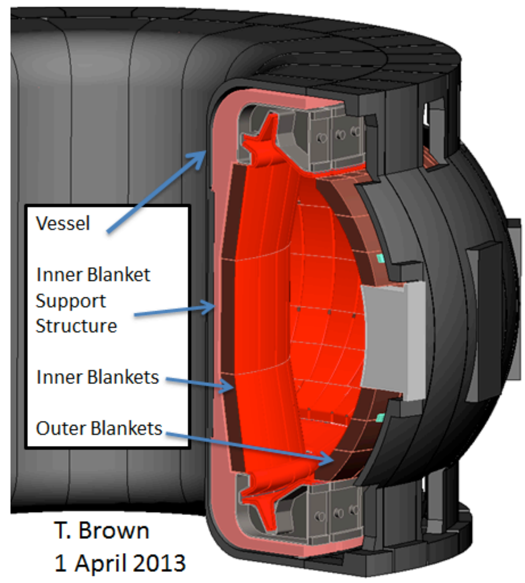


Fig. 3. Internal Vacuum Components of K-DEMO

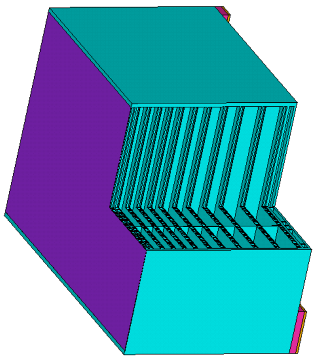


Fig. 2. KDEMO Blanket Model with Breeding Material Removed.

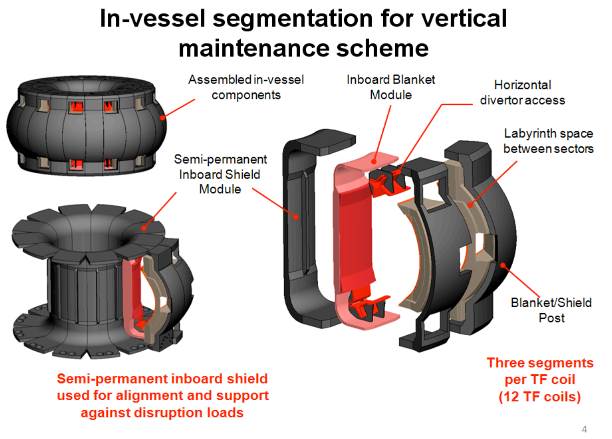


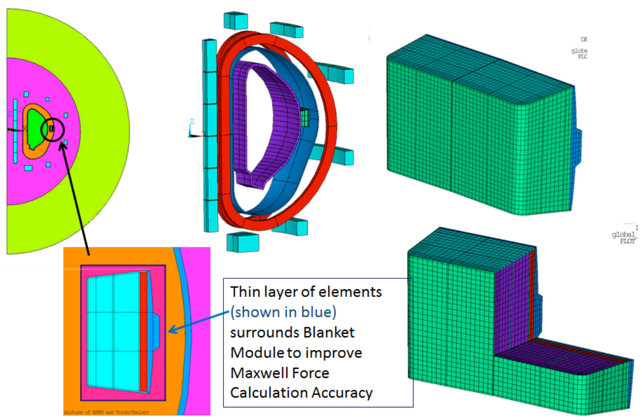
Fig. 4. Components inside the vessel – Blanket Support Shells and Blankets.

2. Disruption Simulations Including Effects of RAFM Steel

The disruption model used to evaluate the effect of using ferromagnetic materials in the structure of the blankets is based on an ITER analysis model. This is available from the PPPL port plug and diagnostic work. The Equatorial Port Plug (EPP) is replaced by a simplified version of a blanket structure composed of Reduced Activation Ferritic/Martensitic steel.

The blanket model and reactor model shown in figure 5 Are not intended to represent the details of the KDEMO blanket, rather the blanket design is arbitrarily chosen to allow a study of the relative magnitudes of the effects of including ferromagnetic materials. The model includes:

- The ITER Double Wall VV
- OH/PF and TF Coils with static fields
- Plasma Currents represented as equivalent surface currents as developed by the IO
- Linear Plasma decay in 36 ms from an initial total current of 15 MA
- Poloidal and Toroidal fields analyzed together



. Fig. 5. Blanket Module Ferromagnetic Magnetics Model.

Earlier Transient Analyses of Plasma Disruptions relied on ANSYS Solid97 elements which use a Magnetic Vector Potential (Ax, Ay, AZ) and Scalar Voltage Potential (Volt). However, known errors exist when used with nonlinear materials since fields are not continuous across boundaries. Methods exists to cope with this but can be difficult to implement. It requires double node-ing at air-iron interface and adding constraints to force continuity of normal flux but allow discontinuity in parallel flux. Procedures to do this have been developed by Han Zhang at PPPL, but the procedure applied to the complicated "cellular" geometry of the blanket module, remains onerous. The following analyses employ the Edge Flux Formulation in ANSYS Solid 236 element which avoids above problems. Care must be used in modeling cyclic symmetry. Since the degree of freedom is the integral of A.dl over the edge and assigned to the mid side nodes, the constraint equations must reflect direction of the edge which is governed by the node number of the corners – positive is from low number to high number

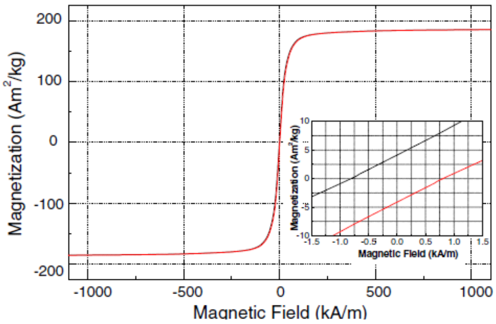


Fig. 6. Components inside the vessel – Blanket Support Shells and Blankets.

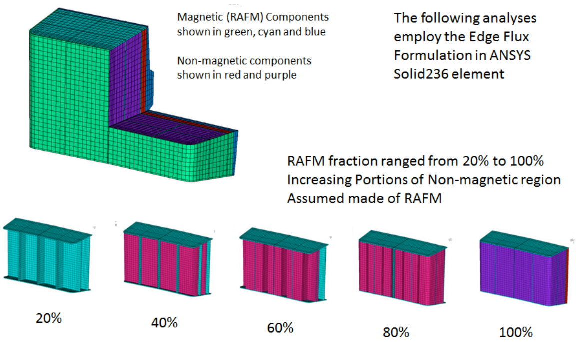


Fig. 7. RAFM Fraction Varied to show Impact on Forces Including the Distribution and Fraction of RAFM

Forces and Moments scale fairly linearly with RAFM fraction.

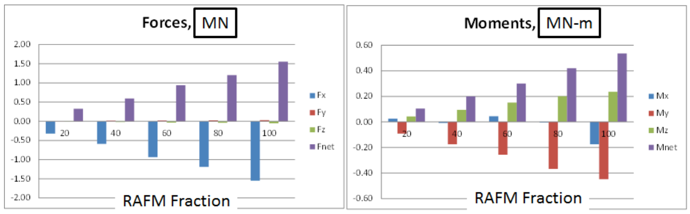


Fig. 8. Force and Moment Comparison

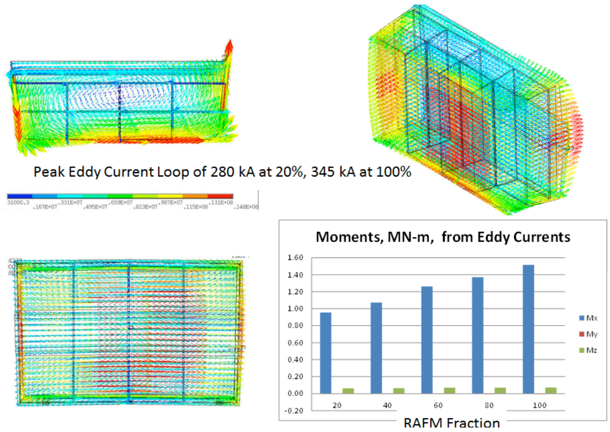


Fig. 9. Eddy Currents and Lorentz Forces are also impacted by RAFM Fraction

The presence of the magnetic material and its higher permeability increases the local field in the blankets and also increases the local change in field vs. time due to the disruption. The higher dB/dt induces more eddy currents which also cross with the higher local fields to produce higher loads. A blanket design goal is to minimize the structural material and maximize the breeding material. Typical of the blankets considered at PPPL is a RAFM fraction of ~20 %. The saturation fields of the magnetic material also needs to be considered. For inboard blankets in a high field tokamak, the saturation field of ~2T of the RAFM steel is significantly smaller than the main TF field component. For conceptual design of KDEMO, the static magnetic loading and the disruption eddy current loading will be considered separable with the provision that only including the induced eddy currents from a model with mu's of 1.0 may underestimate the disruption loading by amounts related to the magnetic steel fraction and the ratio of the saturation field to the TF field.

If you need to estimate the magnetic force on a RAFM module from the TF you can get reasonably close (ie ballpark) with the following expression:

Fr, MN = -1.75*Btf*Rtf/rad^2*Vol

where Rtf is the radius in meters of the reference toroidal field Btf in Tesla

rad is the radius in meters of the center of the RAFM module and

Vol is the volume in cubic meters of RAFM material in the module

The expression assumes a saturation field of 2.2 T in the RAFM.

The force will differ when the PF field is included. A uniform vertical field will not add to this but a field gradient will. So far the TF has dominated.

The radial static magnetic loads were applied to the blanket structural model using the equation above. In this procedure the volume of the RAFM steel in the model is computed with a APDL script and the total load on the blanket is divided up equally among the nodes in the RAFM steel portion of the model. The peak stress of 55 MPa occurs near the support points. In figure 10, the contours have been adjusted to more clearly show the stress levels in the rest of the blanket structure. The stresses due to the static magnetic loading on the outboard blankets are small relative to thermal and the eddy current stresses, and this provides some justification for using the approximate method of quantifying the static magnetic loads.

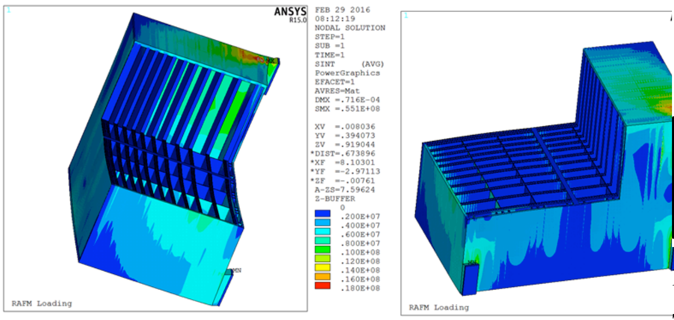


Fig. 10. Stress due to RAFM Loading on Outer Blanket

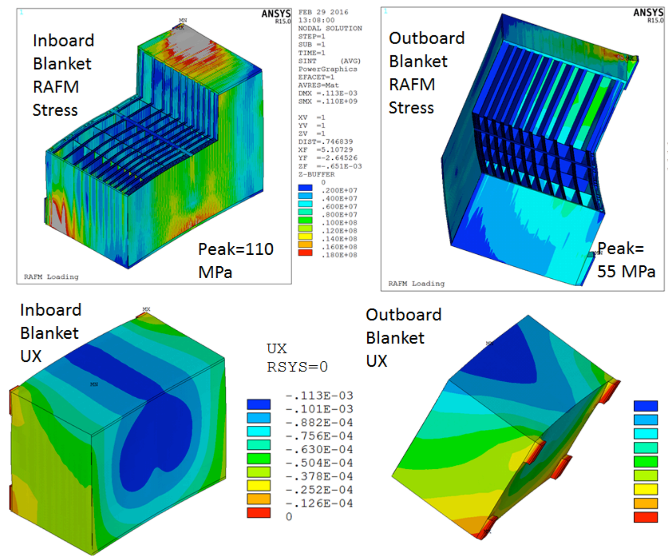


Fig. 11. Comparison of Inboard and Outboard Blanket Stress and Displacements Due to Static Magnetic Loads

In Figure 11, a comparison of the inboard and outboard blanket stresses and displacements due to static magnetic loads is shown. The finite element model is actually the same. The outboard blanket model was turned around and re-positioned. The TF field gradient produces a static magnetic load that is directed towards the center of the tokamak for both the inboard and outboard blanket modules. The inner blanket sees higher loads and stresses. In both cases, the stresses are modest compared with thermal and disruption stresses, but they will be a contributor to the normal operating stress.

Disruption Simulation Using Imposed Vector Potential Boundary Conditions

To facilitate loading of a blanket module with disruption loads, a sub structuring procedure is used which imposes a vector potential boundary condition based on the local B's and Bdots. This is usually is a conservative approach because it can underestimate the inductive flux exclusion by the conducting structures.

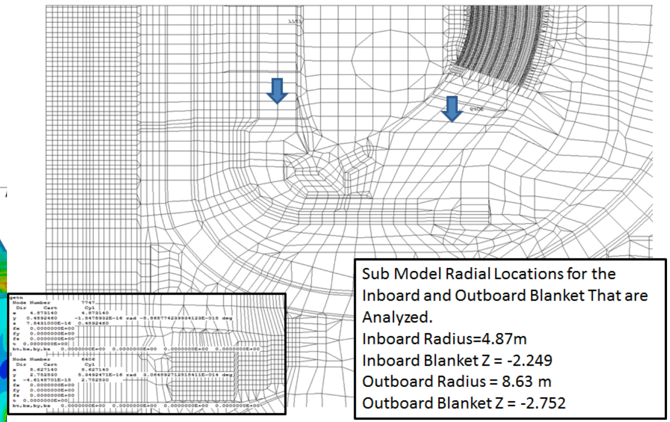


Fig. 12. Blanket Coordinates Dimensions Used in the Analysis

The blanket sub models are positioned at locations where the fields and changes in field with respect to time are expected to produce the most significant loading. An inner blanket module position and an outer blanket module position are analyzed. These are shown in Figure

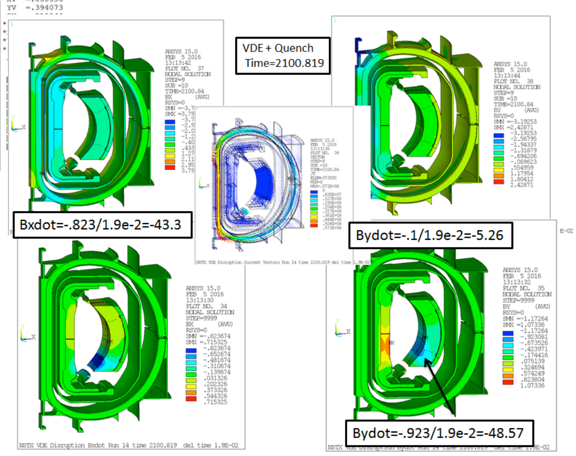


Fig. 13. Estimates of the B's and Bdots for the blankets :in K-DEMO

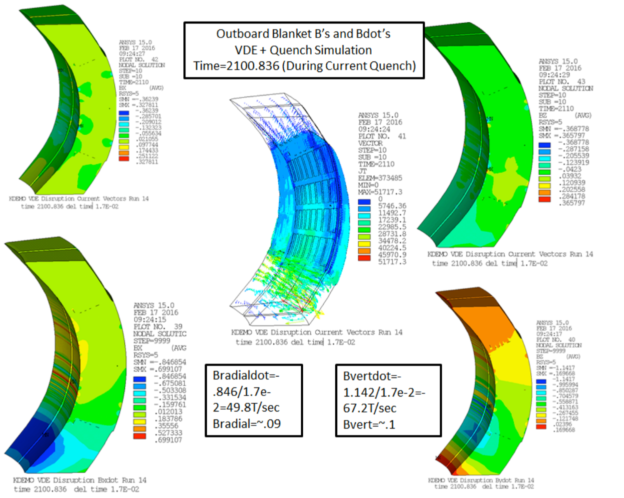


Fig. 14. Estimates of the B's and Bdots for the blankets :in K-DEMO

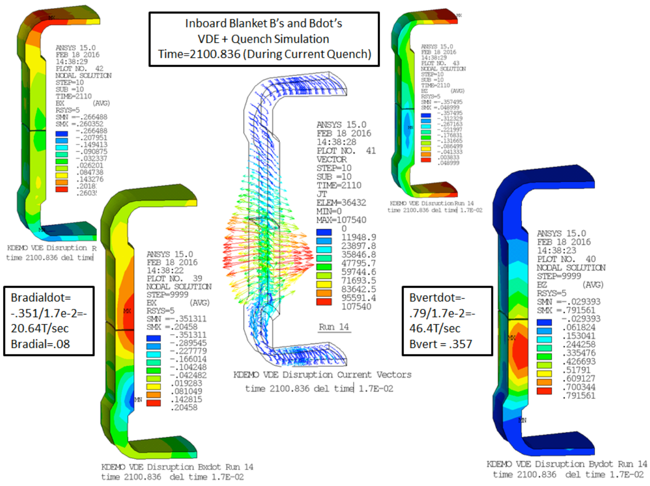


Fig. 15. Estimates of the B's and Bdots for the Inboard blankets :in K-DEMO

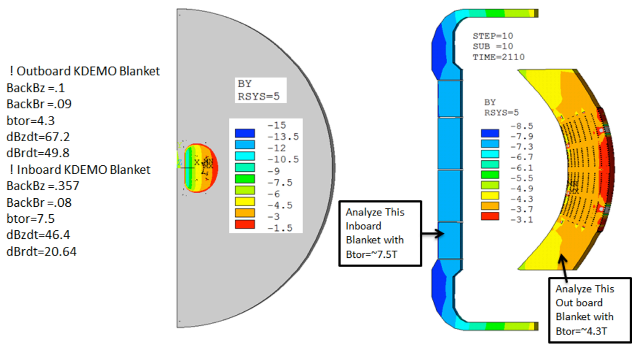


Fig. 16. Toroidal Fields at the Blanket Sub Model Locations

B's and Bdots for Generation of the Vector Potential Boundary Condition

Inboard	Outboard
BackBz =.357	BackBz =.1
BackBr =.08	BackBr =.09
btor=7.5	btor=4.3
dBzdt=46.4	dBzdt=67.2
dBrdt=20.64	dBrdt=49.8

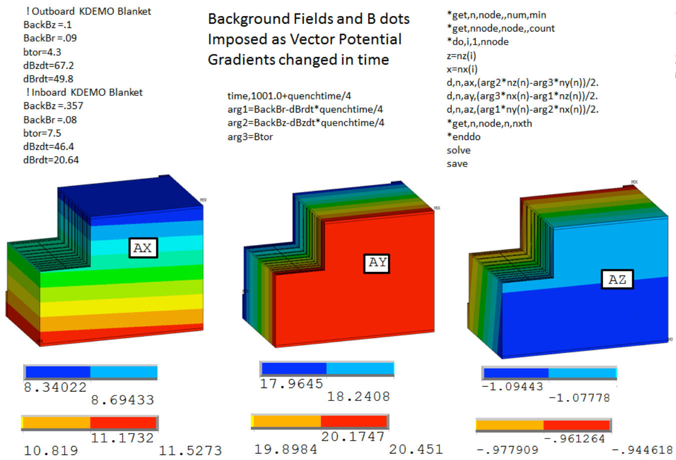


Fig. 17. Disruption Simulation By Imposing Vector Potential Boundary Conditions

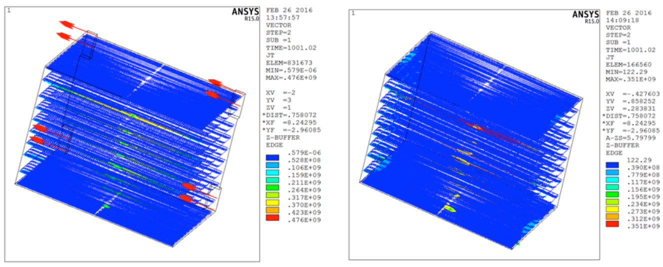


Fig. 18. Outboard Blanket Disruption Eddy Currents

In Figure 5-17, the mess density makes it difficult to see the eddy currents appropriately. The loops are not as evident. From the structural response, the torques look reasonable implying loops crossing the TF and poloidal fields.

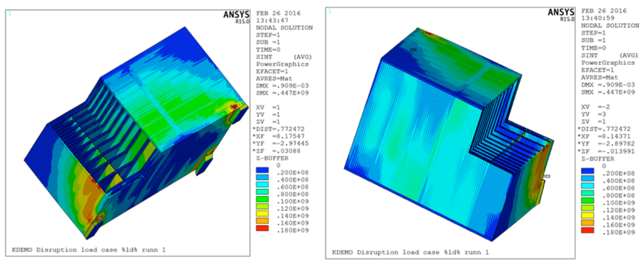
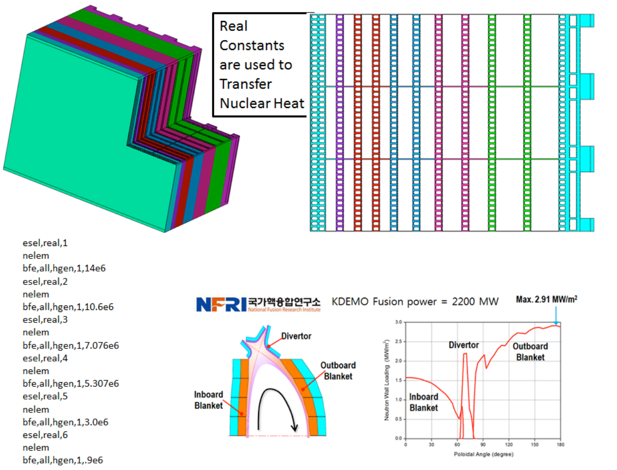


Fig. 19. Outboard Blanket Disruption Eddy Currents Stresses

2.6 5.3. Thermal Analysis

Nuclear heat and radiation on the plasma facing surface of the blanket are the source of power input to the blanket. In steady state the coolant flows extract the input power. In the simulations used to quantify the temperature distribution for the structural assessments, the temperature of the elements modeling the water in the coolant channels is "clamped" at the values derived from separate thermal hydraulic analyses. Nuclear heat and plasma surface heat fluxes are input to the model and a steady state heat conduction analysis is done. This provides a reasonable temperature distribution through the detailed structural features that might not have been modeled in detail in the thermal hydraulics model. Rigorous methods of mapping nuclear heating from the nuclear analyses to the thermal hydraulic analyses are used in PPPL. This is done when Attila or MCNP analyses of a model similar to the CFX flow model are available. In the case of K-Demo, PPPL has not developed nuclear or thermal hydraulic models of the blankets, and instead, PPPL is relying on published NFRI published results for nuclear heat and the coolant temperatures. To apply the nuclear heat to the thermal model, the model is regionalized by assigning real constants to the elements and using this designation to apply the appropriate heat generation rate in the ANSYS model. These details are shown in figure 5-19.



K-DEMO Outboard Mid-plane Blanket module - Nuclear Heating Data			
			2016. Sep. 13
Material	Nuclear Heating [W/m3]	Layer Thickness [cm]	mulated thickness of Layers
Tungsten	4.12E+07	0.5	0.5
Vanadium	1.13E+07	0.1	0.6
First Wall RAFM+H2O	1.51E+07	1.5	2.1
1st RAFM+H2O	1.51E+07	1.5	3.6
1st Mixture (Be12Ti + Li4SiO4)	1.53E+07	2.3	5.9
2nd RAFM+H2O	1.37E+07	1.5	7.4
2nd Mixture (Be12Ti + Li4SiO4)	1.35E+07	2.3	9.7
3rd RAFM+H2O	1.20E+07	1.5	11.2
3rd Mixture (Be12Ti + Li4SiO4)	1.14E+07	2.5	13.7
4th RAFM+H2O	1.00E+07	1.5	15.2
4th Mixture (Be12Ti + Li4SiO4)	9.13E+06	2.9	18.1
5th RAFM+H2O	7.98E+06	1.5	19.6
5th Mixture (Be12Ti + Li4SiO4)	6.88E+06	3.6	23.2
6th RAFM+H2O	5.93E+06	1.5	24.7
6th Mixture (Be12Ti + Li4SiO4)	5.23E+06	3.8	28.5
7th RAFM+H2O	4.46E+06	1.5	30
7th Mixture (Be12Ti + Li4SiO4)	3.54E+06	5.2	35.2
8th RAFM+H2O	3.16E+06	1.5	36.7
8th Mixture (Be12Ti + Li4SiO4)	2.22E+06	6.6	43.3
9th RAFM+H2O	1.93E+06	1.5	44.8
9th Mixture (Be12Ti + Li4SiO4)	1.36E+06	8	52.8
10th RAFM+H2O	1.14E+06	1.5	54.3
10st Mixture (Be12Ti + Li4SiO4)	6.14E+05	10	64.3
11st RAFM+H2O	4.49E+05	1.5	65.8
Mixture	Li4SiO4 : Be12Ti = 15 : 85		
RAFM + H2O	RAFM : H2O = 6 : 4		

Fig. 20. Neutron Wall Loading and Input of the Nuclear Heat into the Model

Similarly, the surface heat flux is taken from published NFRI analyses and applied to the surface of the blanket module in the thermal/structural analysis.

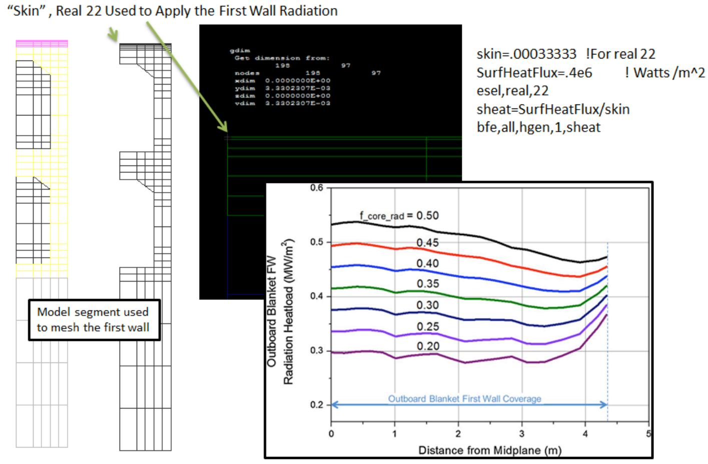


Fig. 21. Surface Heat Flux (Photons), and Input of the Surface Heat Flux into the Model

Figures 22, and 23_ show the temperature distribution for the outer blanket with prescribed heat fluxes from the NFRI nuclear analysis and surface radiation of .4 MW/m^2 on the Tungsten first wall. . Water in the cooling channels is held at a uniform temperature derived from NFRI analyses. A heat conduction analysis is performed which then gives a temperature distribution in the steel structure that is input to the thermal stress analysis.

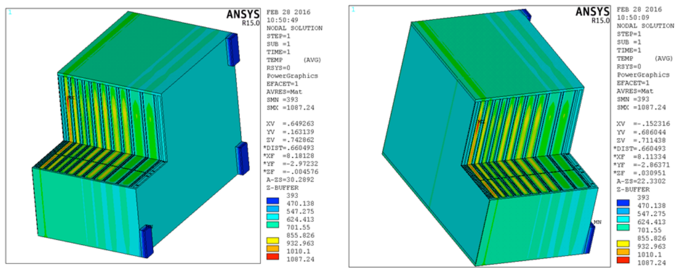


Fig. 22. K-DEMO Outboard Blanket Thermal Results – Including Breeding Material

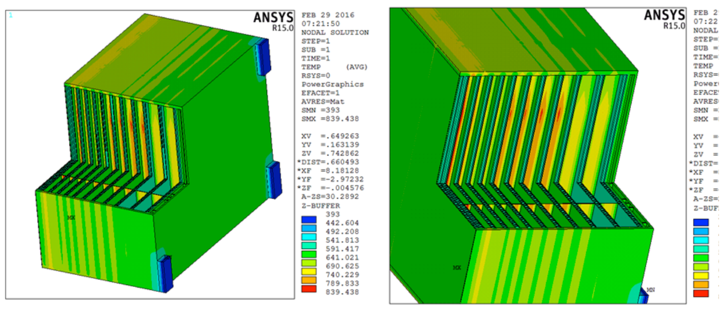


Fig. 23. K-DEMO Blanket RAFM Steel Temperatures

The temperature in the blanket structure is up to 839K or 566 C.

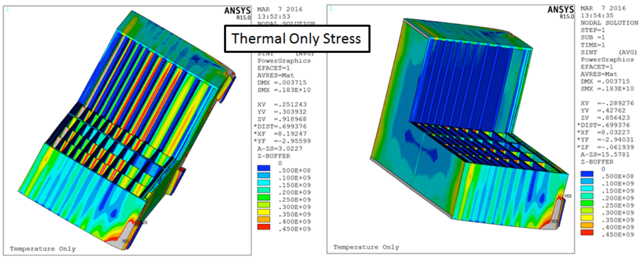


Fig. 24. K-DEMO Blanket RAFM Steel Thermal Stress

Thermal stresses are the most significant of those investigated to date. One significant component not shown in the RAFM steel stress plots is the stress in the Tungsten plasma facing cladding the coefficient of expansion and modulus of the Tungsten is significantly different than the structural steel and with the first wall temperature gradient, the tungsten stress is very large. In Figure 5-23, the Tungsten layer is shown removed. The largest thermal stress occurs at the attachment points and in the ribs bridging across the breeding chambers. These will need cooling.

In Figure 25, normal stresses are evaluated. The 3*Sm stress is ~550 MPa. Pressure stresses have not been included at this time because of the difficulty of properly applying pressure on all the cooling channels and maintaining proper cancellation of net loads. The fluid pressure on the small coolant channels should not add significantly to the normal load. Faulted loads, in which the breeding chambers might be pressurized will impose a significant stress on the blanket structure.

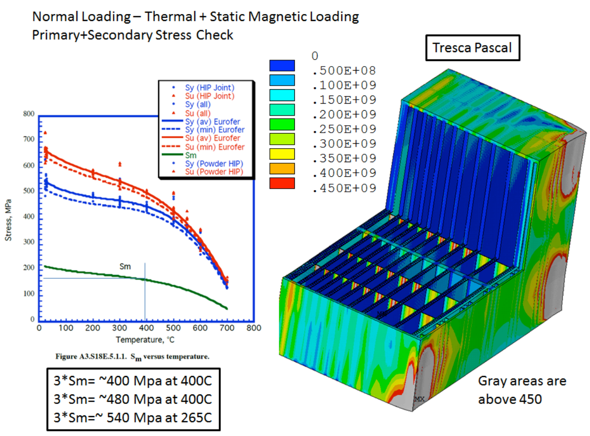


Fig. 25. Normal Operating Stress Allowables (Left) Normal +Disruption Blanket Stress Levels (Right)

In Figure ___, the primary +secondary stress exceeds the 3*Sm allowable at the corners where the supports are. These areas will need reinforcement. There are also some areas in the ribs that support the breeding chambers that are above the allowables. These ribs will need active cooling to remove the thermal stress and improve the allowable.. The difference between the normal stress and the normal+disruption stress is hard to discern in the plots. The disruption stress in Figure 5-18 is 180 MPa at the attachment points. When the thermal stresses are improved with more cooling channels – especially in the ribs bridging across the breeding chambers – the thermal stresses will go down and disruption stresses will appear more significant.

In these stress evaluations, the primary membrane stress has not been considered. Because of the complexity of the structure, it is difficult to separate out the primary stress. One allowed approach is limit analysis in which a large displacement elastic-plastic analysis is performed with loading that goes above the nominal load1ng. If the structural simulation can take twice the load without collapse (or numerical instability or non-convergence) then an adequate margin against the primary loading is demonstrated. This was attempted for the K-DEMO blanket, but the thermal loading is failing to converge. A more gradual application of the temperature loading is probably needed but this will have to be the subject of future work.

7.0 Conclusions

A full set of normal thermal, pressure, and static magnetic loads were evaluated. Disruption and faulted pressure loads are assessed as well. Individual structural stress components are within reasonably qualifiable levels. There remains some work needed to qualify combined loading for a proper stress decomposition – Normal, Upset, Faulted, Primary and secondary stresses. Significant nuclear effects on materials have not been considered. Some non-linear analyses can be performed. Elastic-plastic stress strain modeling and creep simulations can be a part of future work

This paper addresses the structural adequacy of the KDEMO blanket module as of November 2015. The design point provided as of November 2015 has been found to be within present structural design practice based on analysis performed to date. Disruption loads, Thermal Loads, Static Magnetic loads, Pressure loads, and Deadweight have been assessed. Elastic stresses, plastic stresses and creep behavior have been investigated.

As a pragmatic compromise, the effects of RAFM steel on the disruption fields and currents are considered secondary, and the eddy current analysis is assumed minimally effected by the field changes due to the ferromagnetic properties or RAFM steel. The static and disruption eddy current magnetic analyses are considered separable.

There is more to be quantified including all of the material degradation due to radiation effects, but initial sizing is appropriate for this point in the project.

Acknowledgments

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