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Stress Analysis of the KDEMO Vacuum Vessel

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ABSTRACT

Components that make up the central column of a tokamak have a strong impact on the overall sizing of the reactor. In most of the next generation tokamaks being considered at PPPL, the vessel is separate from the blanket support structures. A substantial structure is provided as nuclear and electromagnetic shielding to protect the inner legs of the TF and the vessel pressure boundary. The KDEMO reactor uses a version of this concept.

This paper addresses the structural adequacy of the K-DEMO vacuum vessel design as of November 2015. The vessel surrounds the internal vacuum components of the reactor and its primary purpose is only to provide the vacuum boundary for the rest of the internals. Static vacuum pressure stresses, stresses due to static magnetic loads, and approximate disruption stresses have been evaluated

Keywords: KDEMO; Stress analysis; Disruption.

I. INTRODUCTION[1]

Components that make up the central column of a tokamak have a strong impact on the overall sizing of the reactor. In most of the next generation tokamaks being considered at PPPL, the vessel is separate from the blanket support structures. A substantial structure is provided that shields the inner legs of the TF and the vessel pressure boundary. Shielding is both nuclear and electromagnetic. The KDEMO reactor uses a version of this concept (Figure 1). To check the vessel sizing and space allocation, an approximate approach has been used to quantify both the disruption eddy current loading and static magnetic loading (If a conventional 316 vessel proves unacceptable in terms of activation, waste and nuclear damage). Since the vessel pressure boundary is separated from the blankets, divertor and other internal components, halo current loading will be

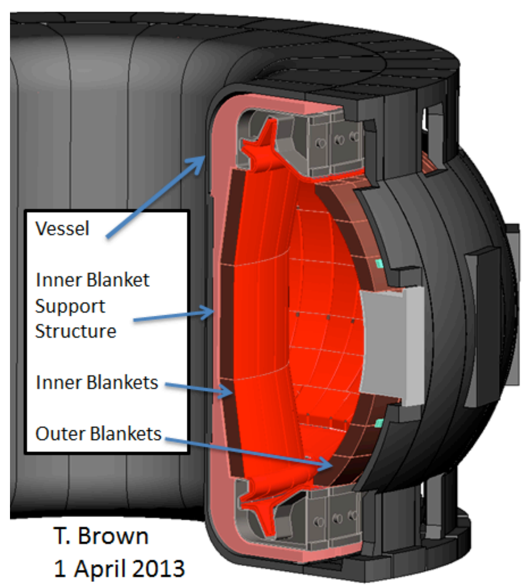


Figure 1. Internal Vacuum Components of K-DEMO.

minimal. Significant electromagnetic loads occur on the blanket support structures. The vessel structure can be relatively "thin". In this case 10.8 cm. Pressure, thermal and possibly ferrite magnetic loads are considered in the normal stress analysis of the vessel. Disruption loads are estimated by imposition of vector potential boundary conditions from a more detailed disruption simulation of the reactor. This allows simplified modeling of the vessel in the global disruption simulation and detailed modeling of ports, reinforcements in the vessel stress model.

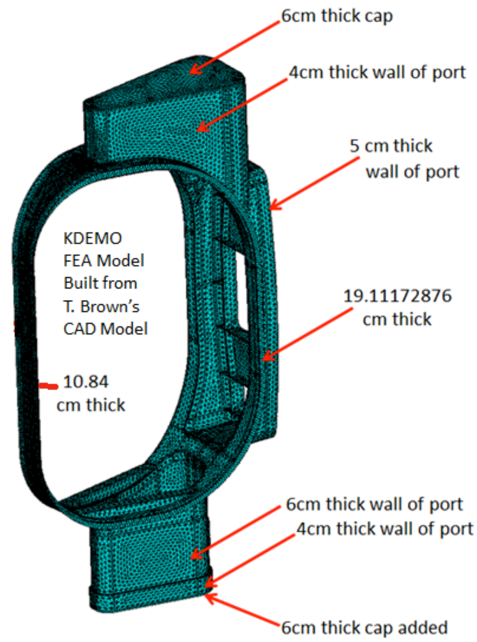


Figure 2: K-DEMO Vacuum Vessel Mesh.

II. Pressure Loading

The vessel model segment is shown in figure 2. Upon vacuum pressure, the deformation and stress are shown in figure 3.

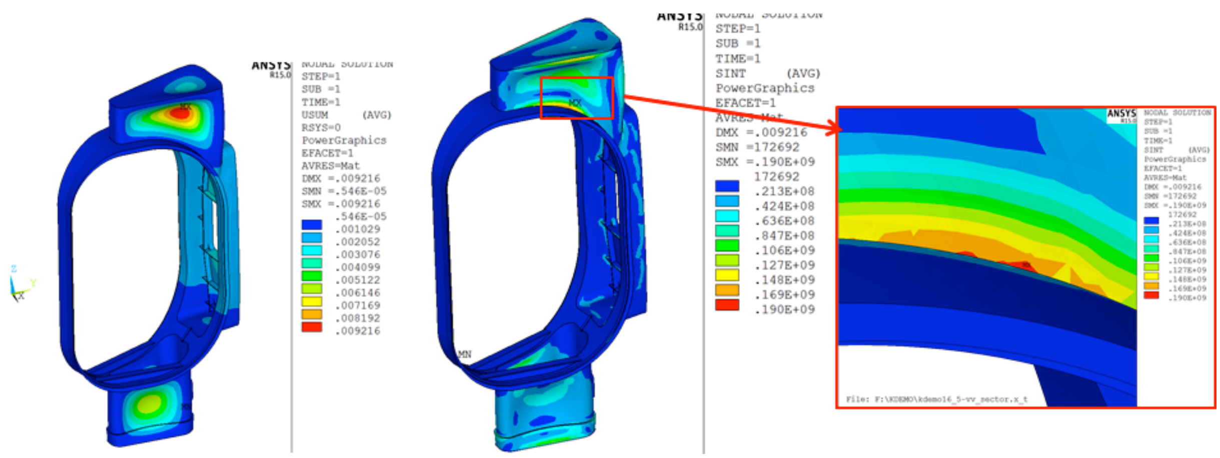


Figure 3: Displacements and Stresses upon vacuum pressure.

III. RAFM Loading

The vessel will potentially be made from low activation steel such as the reduced activation ferritic martensitic (RAFM) steels. There may be a low temperature issue in their use, but if a magnetic steel is used there will be centering forces on the vessel sectors due to the 1/r toroidal field gradient.

The vessel stresses in figure 4 are locally comparable to the pressure loading – the peak is 209 MPa, but the bulk of the loading is below this. If magnetic steel is used for the vessel the static magnetic loads need to be included. The estimate of the RAFM loading comes from the blanket module analyses being developed at PPPL.

The RAFM loading is only approximated by the volumetric inventory of the RAFM steel. In the macro in figure 5, individual element loads are computed from the element volume and applied to one of the corner nodes. The load plot shows the correct centering load vectors which are irregular magnitudes because they are a result of the element mesh size variation.

Because of the centering nature of the loading, Buckling or plastic collapse is a possible failure mechanism. In order to address this, the vessel model with the RAFM loading was loaded incrementally using a large displacement solution and elastic-plastic material data shown in figure 6. This demonstrated a substantial margin against collapse for just the RAFM static magnetic loads.

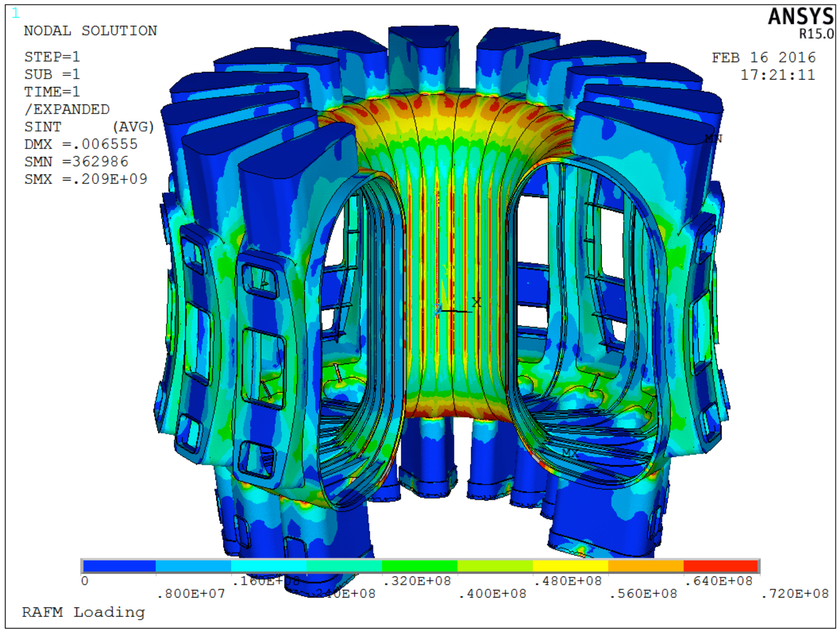
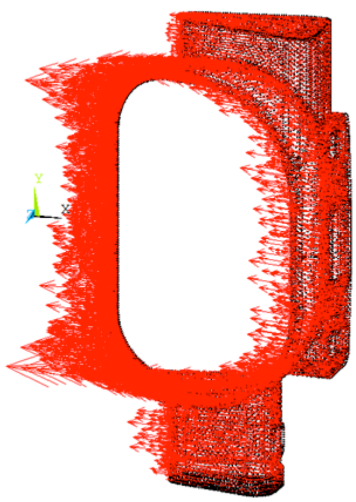


Figure 4: Stress Resulting from the Static Magnetic Properties of RAFM Steel.



```
/title, RAFM Loading
Btf=7
Rtf=7
ESEL,mat,1
*GET,numberOfElements,ELEM,,COUNT
elementNumber = 0
totalVolume = 0
*DO,i,1,numberOfElements,1
elementNumber = ELNEXT(elementNumber)
*GET,volume,ELEM,elementNumber,VOLU
*get,n1elem,elem,elementnumber,node,1
rad=nx(n1elem)
fcum,add
FrTot = (-1.75*Btf*Rtf/rad**2*Volume)*1e6
f,n1elem,fx,FrTot
*ENDDO

nall $eall
solve $ save
```

Figure 5: Loads Resulting from the Static Magnetic Properties of RAFM Steel.

With only the static magnetic loads applied, this result is only qualitative. Pressure, deadweight and thermal loads need to be added. And the electromagnetic and other effects of equipment mounted on the vessel need to be considered, but the magnitude of the RAFM stresses and the margin against buckling and the character of the buckling, which is plastic collapse of a very thin weld section, indicate that the RAFM loads are not a major load on the vessel (Figure 7).

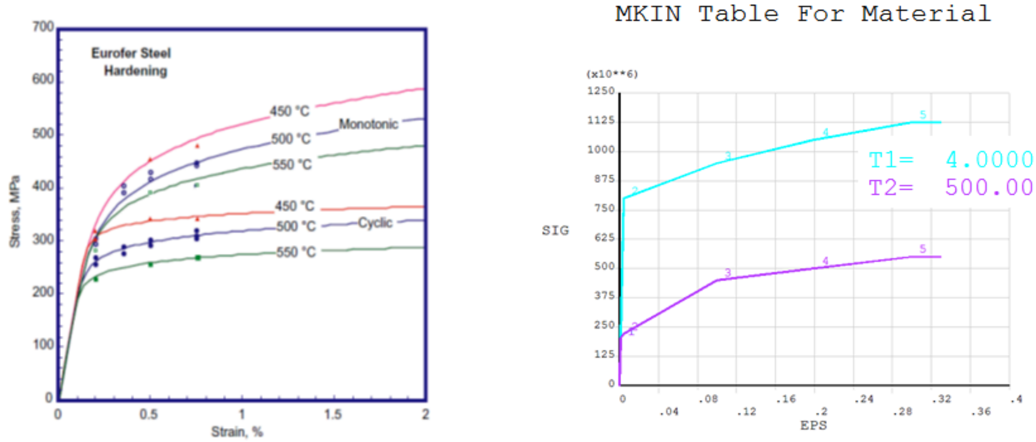


Figure 6: Stress Strain Curves Used for the Vessel If It is Made from one of the RAFM Steels.

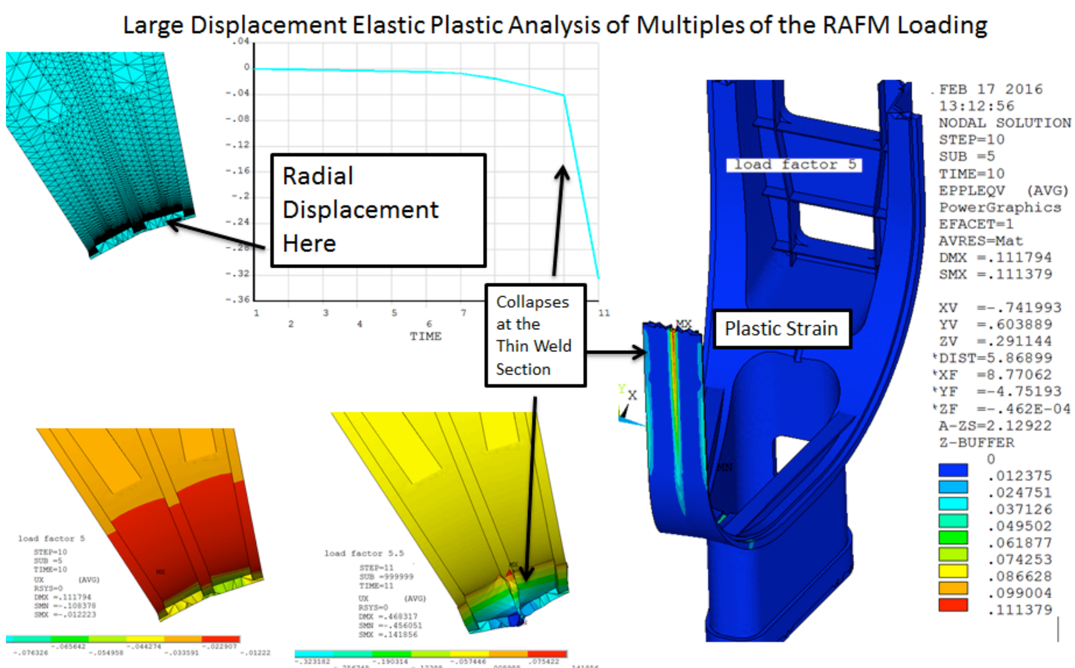


Figure 7: Large Displacement Elastic-Plastic Analysis of the RAFM Loading.

IV. Disruption Loading

The configuration of K-DEMO is evolving and the global disruption analysis is based on an early approximation of the machine cross section. To allow a meaningful assessment of vessel stresses, an approximate sub-structuring procedure will be used. The transient solution of the VDE disruption is used as a source of B's and Bdots to impose on the detailed vessel model. Vector potential boundary conditions are imposed in a transient electromagnetic model.

The K-DEMO disruption analysis used for the vessel assessment is a VDE with drift and current quench based on ITER disruption parameters. At this time only the VDE has been simulated. This was chosen because it potentially applied large net loads on the structures and local loads on the blankets. The assumed disruption specifications taken from ITER data are 0.8 sec for the drift and 36 millisec for the quench.

The modeling of the vessel (Figure 8) in this simulation of the VDE is very simple but it provides a basis for quantifying the B's and Bdots experienced by the vessel during the disruption. These could be mapped to the detailed model of the vessel via imposed vector potential boundary conditions. This has been done for NSTX U and for the C-Mod advanced divertor project, but requires some effort to build the data tables for the full region of the vessel and all the time steps. A simplification is to impose the vertical B dot as enveloped for the vessel and also impose the appropriate vector potential distribution to get the toroidal field. The procedure maps the background vertical field, and the background toroidal field with currents in the vessel driven by the change in vertical field. This is a gross approximation, and will only be warranted if the stresses are modest. Figure 9 shows the background fields and time derivatives of the fields at a time point midway through the quench.

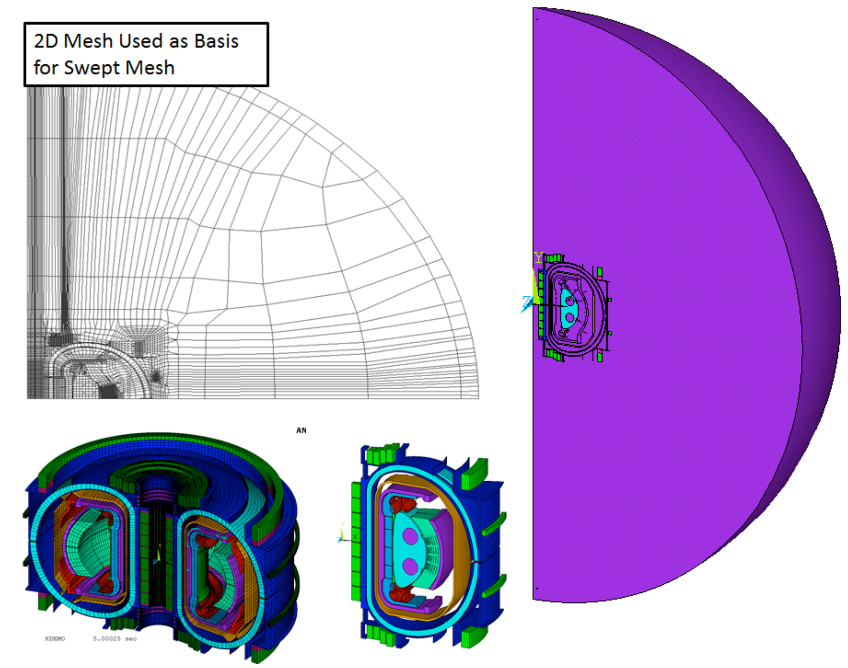


Figure **Error! No text of specified style in document.**-1. K-DEMO Disruption Model.

The background fields and time derivatives of the fields on the vessel are also extracted. These are input to a transient analysis of the detailed vessel model with incremental changes in the vertical field that are spaced in time to obtain the required Bdot. The limitation of the analysis to the toroidal and vertical field and the change in vertical field with time is partially a consequence of wanting to utilize cylindrical coordinates to ultimately allow use of cyclic symmetry coupling in the structural model. This allows a complex model of the vessel to address only one of 16 sectors.

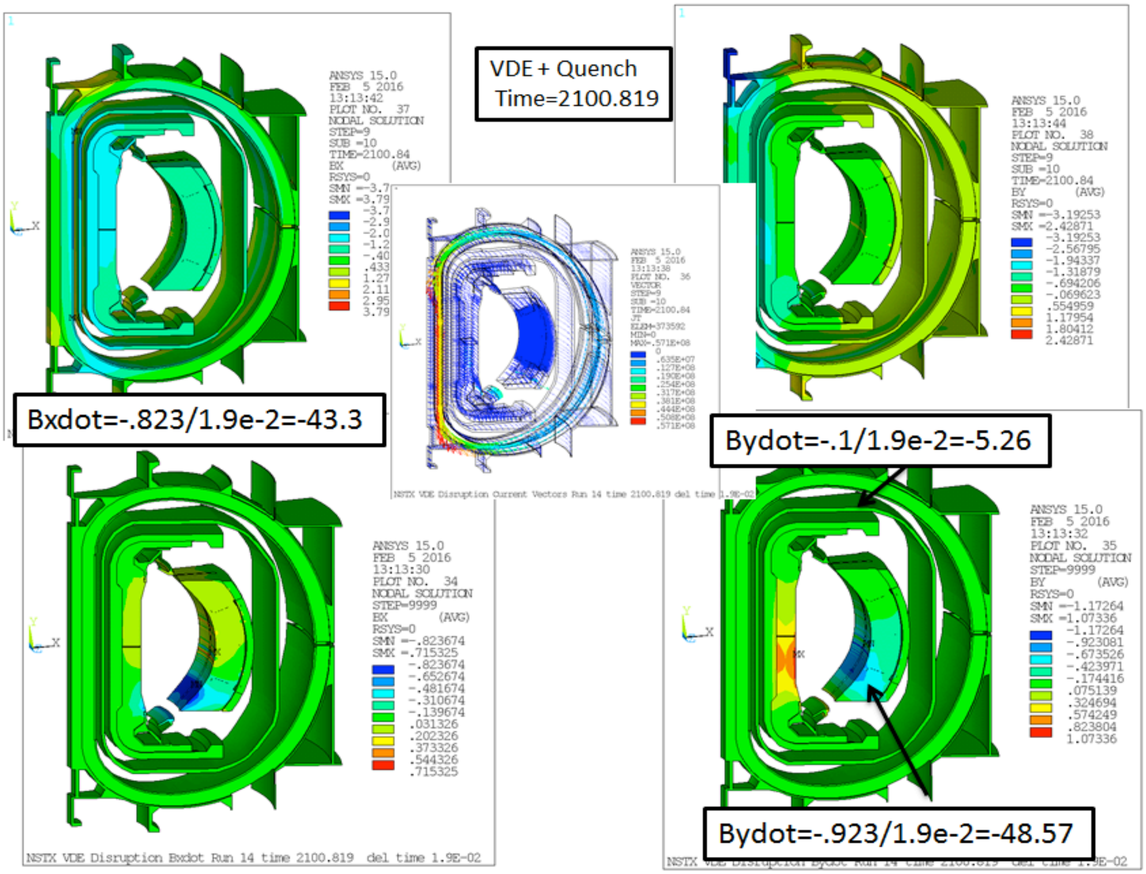


Figure 9: K-DEMO Background Fields and Bdots.

The electromagnetic transient produces Lorentz loads in cylindrical coordinates available to be read into the identical structural mesh with nodes which have rotated degrees of freedom. These degrees of freedom may then be coupled across the cyclic symmetry surfaces.

In figure 10, the complexity of the current densities is evident. The simplified model used in the global simulation of the VDE is shown in figure 11 that produces simpler current densities, but this model does not capture the complexity of the actual vessel.

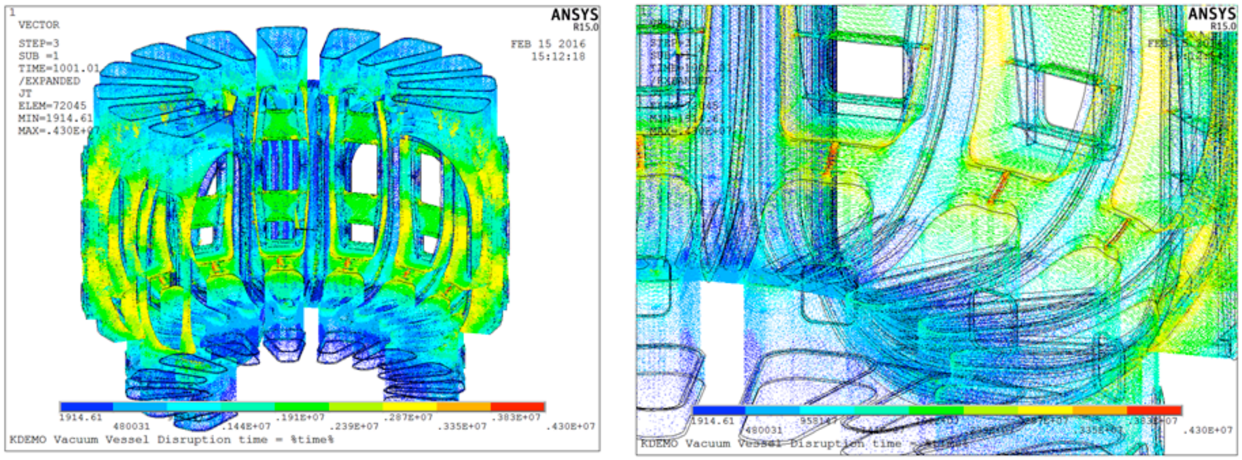


Figure 10: The resulting Current Densities.

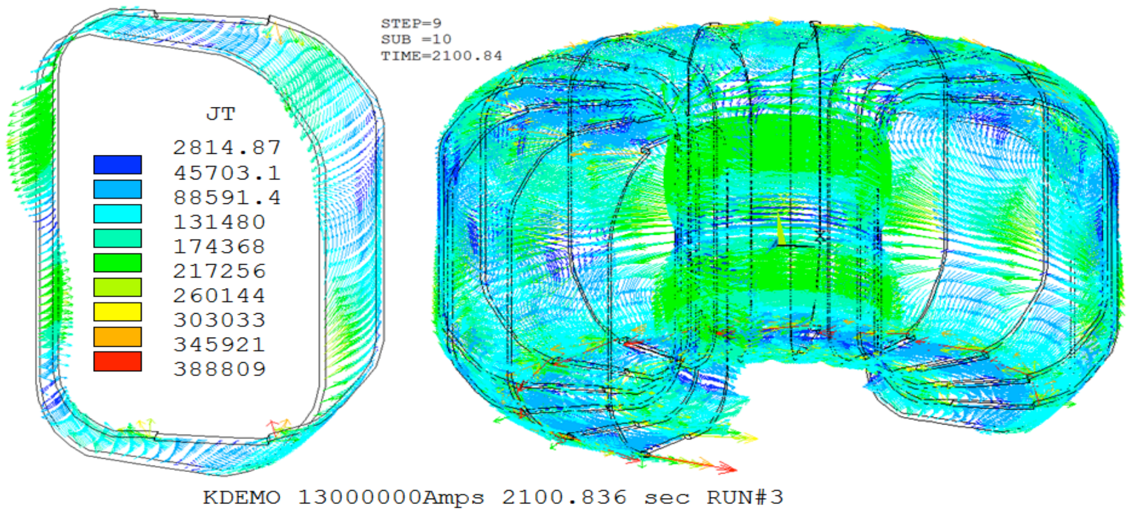


Figure 11: Vessel Current Densities from the Global VDE Disruption Model.

In Figure 12, the stress during the drift phase is on the left and the stresses during the quench are on the right. In this simpler model of the vessel section, the inboard shell is 13 cm and the outboard shell is 19 cm. These are similar to the 10cm and 19 cm of the CAD model shown in figure 2. The simpler model lacks the stiffening effects of the ports. The vessel stresses in this model peak around a cut-out and the support (at bottom) but are around 100 MPa away from these points (Figure 13). In the more detailed model with multiple stiffeners, the stresses in similar regions are around 40 MPa.

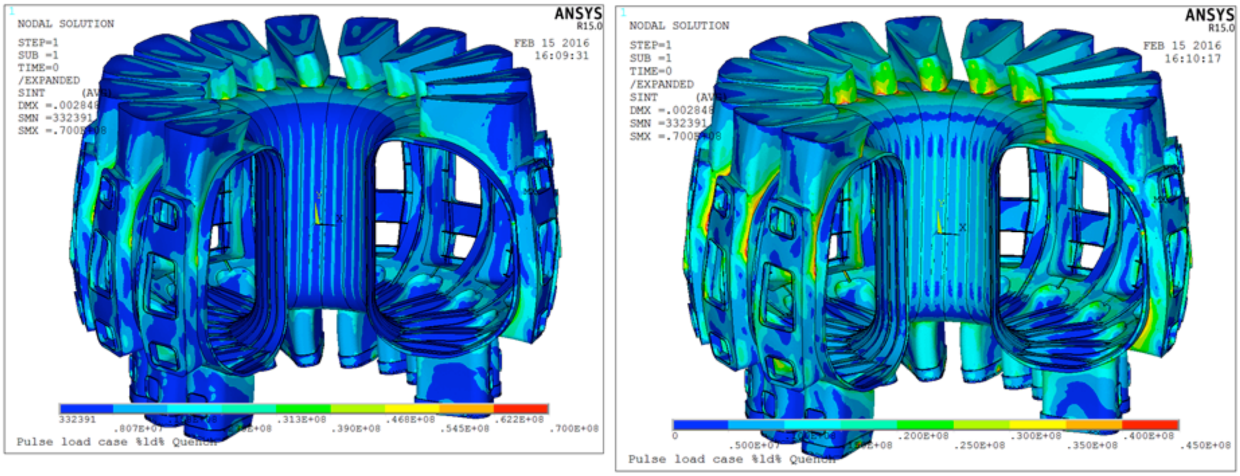


Figure 12: K-DEMO Vessel Disruption Stress Results.

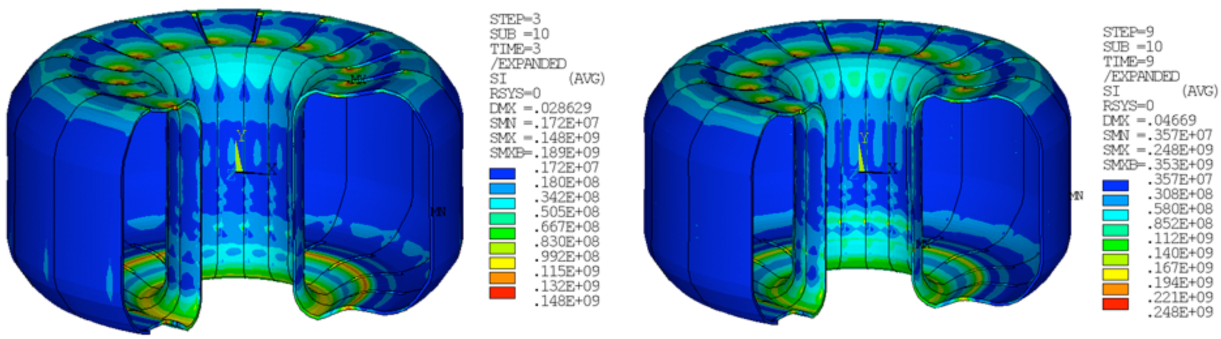


Figure 13: Vessel Disruption Stresses From the Global VDE Disruption Simulation.

V. CONCLUSIONS AND DISCUSSIONS

This paper addresses the structural adequacy of the K-DEMO vacuum vessel design as of November 2015. The vessel surrounds the internal vacuum components of the reactor and its primary purpose is only to provide the vacuum boundary for the rest of the internals. The vessel is not used as a support for the blankets as in ITER. Static vacuum pressure stresses, stresses due to static magnetic loads, and approximate disruption stresses have been evaluated. Pressure stresses peak at 190 MPa and are at the intersection of the vertical port and vessel shell. These could be improved with a transition in thickness between the duct vertical wall and vessel shell. Adding stiffeners or adding thickness to the 4 cm thick wall would improve stresses as well. The static magnetic loads comparable stresses to the pressure stresses. Disruption stresses are smaller than pressure stresses. This is a consequence of the small transient vertical field that develops in the vessel during the disruption, and is probably a consequence of the shielding effects of the blankets and semi-permanent blanket support shell. The design point provided as of November 2015 has been found to be within present structural design practice, but the analyses contain a number of simplifications that would be inappropriate for anything but conceptual design.

ACKNOWLEDGMENTS

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