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Disruption Analysis of the Proposed K-DEMO Inner Blanket Support Structure

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The Korean fusion demonstration reactor (K-DEMO) is in the early stages of conceptual design. In one structural concept being considered for K-DEMO a semi-permanent inboard shield is employed that also serves as support for the inner blanket modules. The inboard blanket 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. 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. It is important to show the disruption loads can be carried by the proposed structure. The 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 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. Details of the blankets are developing. The intention of this analysis is to develop a tractable model to investigate basic sizing and feasibility of the inboard and outboard shield and blanket support concepts and not to rigorously simulate the disruption.

I. INTRODUCTION

(K-DEMO) or Korean fusion demonstration reactor is a large (Ro=6.8m), high field (Bo=7Tesla) steady-state fusion reactor study. The design employs high performance low temperature Nb3Sn conductor. Currently the preferred blanket concept is a solid breeder. In one structural concept being considered for KDEMO a semi-permanent inboard shield is employed that also serves as support for the inner blanket modules. 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. The inboard blanket structure and the outboard blanket structure are shown in figure 1 and are toroidally electrically continuous and are structurally connected. 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. It is important to show the disruption loads can be transferred across keys that connect the blanket and inboard shield structure but the key design must allow easy disconnect, hopefully by a simple passive engagement of the keys.

The analysis is 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 plasma regions at the mid plane while increasing current densities in a lower volume. The quench is just modeled as a decay of the plasma current. The intention of this analysis is to investigate basic sizing and feasibility of the inboard shield concept and not to rigorously simulate the disruption. Blanket modules are modeled with “smeared” properties. Blanket module modeling is only approximate. The analysis is carried out in ANSYS EMAG. The approach has been used for C-Mod antenna’s [2] and NSTX Passive plate analyses.

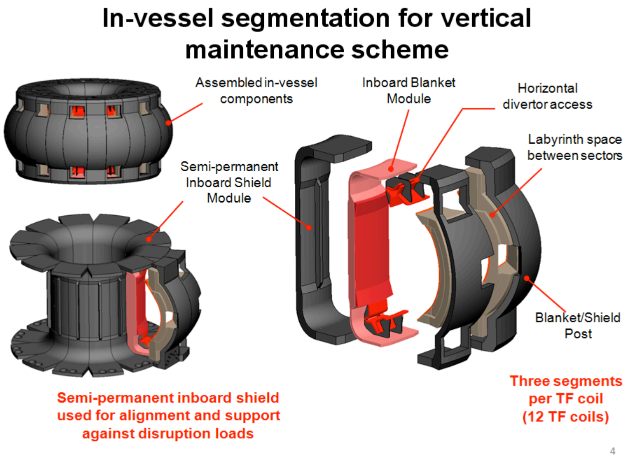


Fig.1. KDEMO Internal Structures

II. ELECTROMAGNETIC MODEL

A basic 2D Mesh, shown in figure 2 is reflected and swept to form a 3D 22.5 degree cyclic symmetry model. Openings and electrical breaks are created with select commands. This approach allows creation of a modest model that is representative of the major conducting elements and eases the necessity of meshing air.

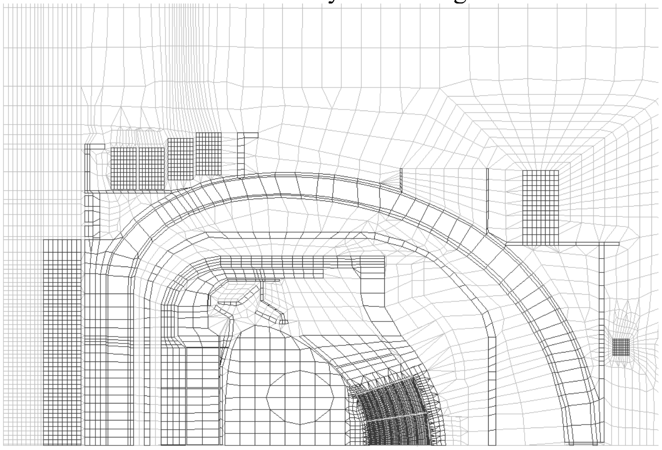


Fig. 2. Basic 2D Mesh

In figure 2, a finer mesh has been developed for the outboard blankets in an attempt to be able to develop preliminary stresses on the blanket internals. At this time the results presented are for simpler smeared property representations of the blankets.

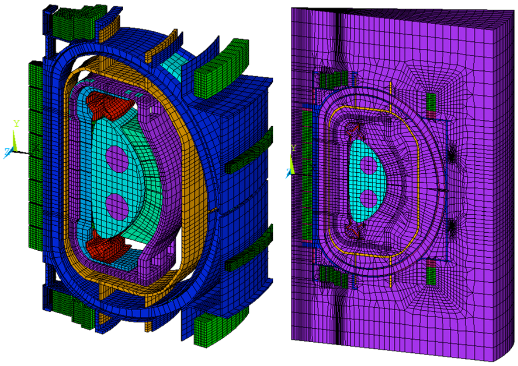


Fig. 3. Electromagnetic Model Shown with and without "Air" Elements

The "wedge" model has cyclic symmetry vector potential coupling applied across the symmetry surfaces.

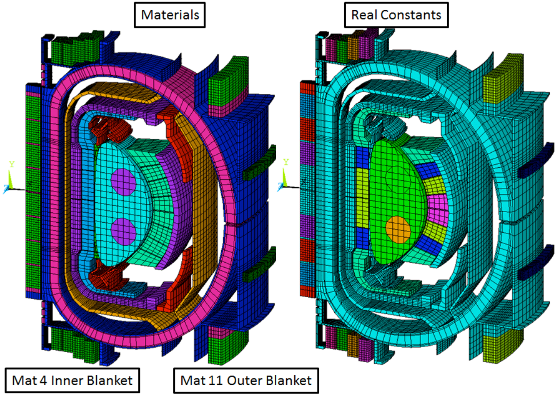
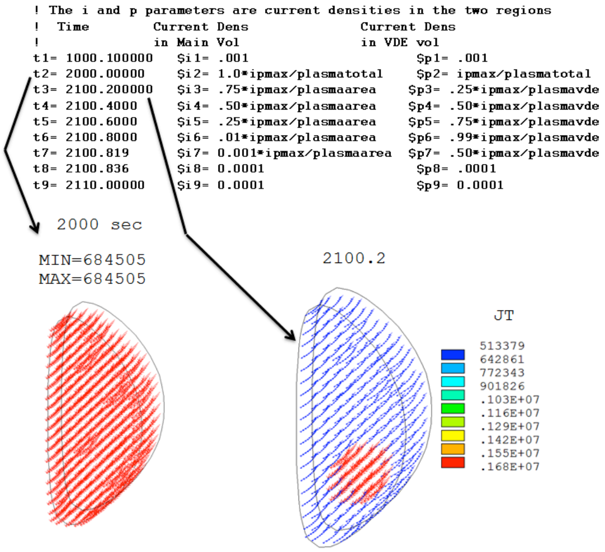


Fig. 4. Model Material s and Real Constants

Appropriate boundary constraints are applied to the outer, upper and lower "air" surfaces.

II.A. Plasma Currents During the Vertical Displacement Event (VDE) Disruption

At this time only the VDE has been simulated. This was chosen because it potentially applied large net loads on the structures. Figure 5 shows the ANSYS ADPL input for the plasma currents vs. time. The assumed disruption specifications have been taken from ITER data and are 0.8 sec for the drift and 36 millisec for the quench.



```
! The i and p parameters are current densities in the two regions
!  Time          Current Dens                Current Dens
!                in Main Vol                 in VDE vol
t1= 1000.100000   $i1= .001                        $p1= .001
t2= 2000.00000    $i2= 1.0*ipmax/plasmatotal       $p2= ipmax/plasmatotal
t3= 2100.200000   $i3= .75*ipmax/plasmaarea      $p3= .25*ipmax/plasmavde
t4= 2100.4000     $i4= .50*ipmax/plasmaarea      $p4= .50*ipmax/plasmavde
t5= 2100.6000     $i5= .25*ipmax/plasmaarea      $p5= .75*ipmax/plasmavde
t6= 2100.8000     $i6= .01*ipmax/plasmaarea      $p6= .99*ipmax/plasmavde
t7= 2100.819      $i7= 0.001*ipmax/plasmaarea    $p7= .50*ipmax/plasmavde
t8= 2100.836      $i8= 0.0001                      $p8= .0001
t9= 2110.00000    $i9= 0.0001                      $p9= 0.0001
```

Fig. 5. Plasma Current vs. Time

. Simulations of the plasma during a disruption for K-DEMO are not yet available, necessitating the ITER approximation.

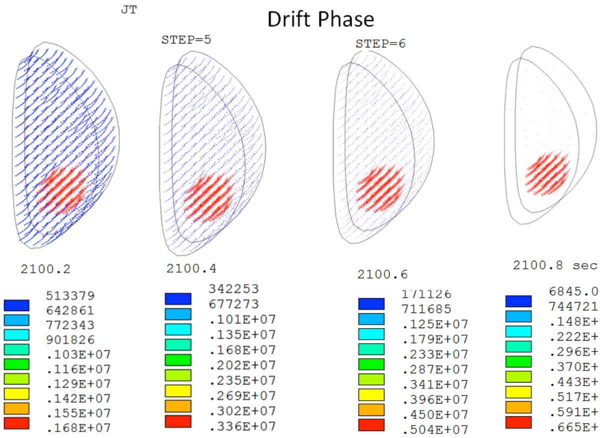


Fig. 6. Imposed Plasma Currents During Drift.

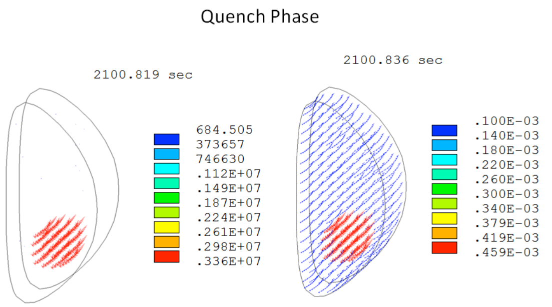
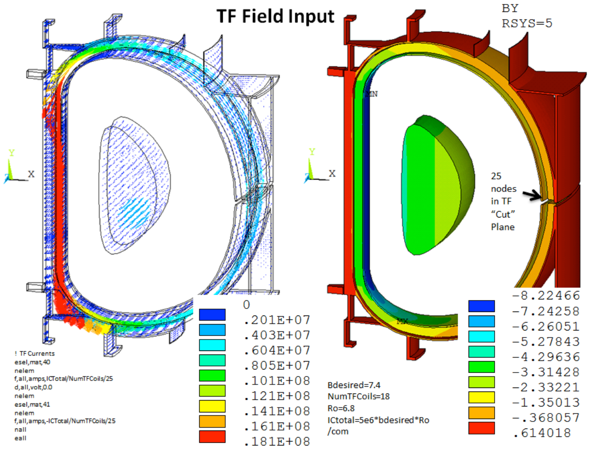


Fig. 7. Imposed Plasma Currents During Quench.

II.B. Input of the Background Poloidal and Toroidal Fields

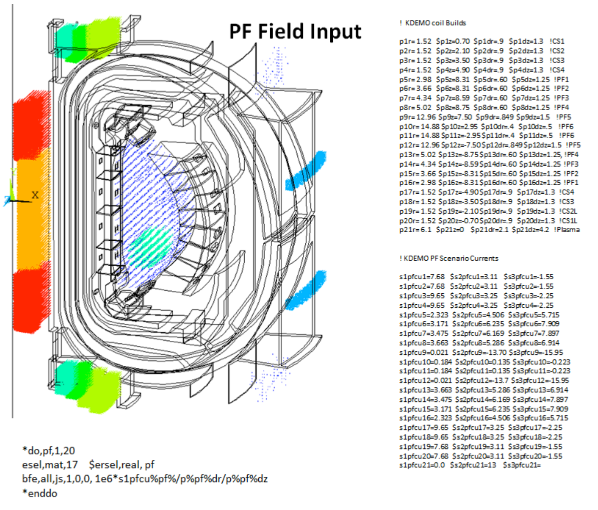
The TF currents are input to a representation of the TF coil at a gap in the outboard leg of the coil model. The field at the plasma centerline is 7.0 T The TF coil geometry is somewhat arbitrary in toroidal extent, so the ripple field is not precisely produced. As the analyses progress this will be improved.



```
! TF Currents
esel,mat,40
nelem
f,all,amps,ICTotal/NumTFCoils/25
d,all,volt,0.0
nelem
esel,mat,41
nelem
f,all,amps,-ICTotal/NumTFCoils/25
nall
eall
```

```
Bdesired=7.4
NumTFCoils=18
Ro=6.8
ICtotal=5e6*bdesired*Ro
/com
```

Fig. 8. TF Current Input and TF Background Field



```
! KDEMO coil Builds

p1r=1.52  $p1z=0.70  $p1dr=.9  $p1dz=1.3  !CS1
p2r=1.52  $p2z=2.10  $p2dr=.9  $p2dz=1.3  !CS2
p3r=1.52  $p3z=3.50  $p3dr=.9  $p3dz=1.3  !CS3
p4r=1.52  $p4z=4.90  $p4dr=.9  $p4dz=1.3  !CS4
p5r=2.98  $p5z=8.31  $p5dr=.60  $p5dz=1.25  !PF1
p6r=3.66  $p6z=8.31  $p6dr=.60  $p6dz=1.25  !PF2
p7r=4.34  $p7z=8.59  $p7dr=.60  $p7dz=1.25  !PF3
p8r=5.02  $p8z=8.75  $p8dr=.60  $p8dz=1.25  !PF4
p9r=12.96 $p9z=7.50  $p9dr=.849 $p9dz=1.5  !PF5
p10r=14.88 $p10z=2.95  $p10dr=.4  $p10dz=.5  !PF6
p11r=14.88 $p11z=-2.95 $p11dr=.4  $p11dz=.5  !PF6
p12r=12.96 $p12z=-7.50 $p12dr=.849 $p12dz=1.5  !PF5
p13r=5.02 $p13z=-8.75 $p13dr=.60 $p13dz=1.25, !PF4
p14r=4.34 $p14z=-8.59 $p14dr=.60 $p14dz=1.25 !PF3
p15r=3.66 $p15z=-8.31 $p15dr=.60 $p15dz=1.25 !PF2
p16r=2.98 $p16z=-8.31 $p16dr=.60 $p16dz=1.25 !PF1
p17r=1.52 $p17z=-4.90 $p17dr=.9  $p17dz=1.3  !CS4
p18r=1.52 $p18z=-3.50 $p18dr=.9  $p18dz=1.3  !CS3
p19r=1.52 $p19z=-2.10 $p19dr=.9  $p19dz=1.3  !CS2L
p20r=1.52 $p20z=-0.70 $p20dr=.9  $p20dz=1.3  !CS1L
p21r=6.1  $p21z=0   $p21dr=2.1 $p21dz=4.2  !Plasma


! KDEMO PF Scenario Currents

s1pfcu1=7.68   $s2pfcu1=3.11   $s3pfcu1=-1.55
s1pfcu2=7.68   $s2pfcu2=3.11   $s3pfcu2=-1.55
s1pfcu3=9.65   $s2pfcu3=3.25   $s3pfcu3=-2.25
s1pfcu4=9.65   $s2pfcu4=3.25   $s3pfcu4=-2.25
s1pfcu5=2.323  $s2pfcu5=4.506  $s3pfcu5=5.715
s1pfcu6=3.171  $s2pfcu6=6.235  $s3pfcu6=7.909
s1pfcu7=3.475  $s2pfcu7=6.169  $s3pfcu7=7.897
s1pfcu8=3.663  $s2pfcu8=5.286  $s3pfcu8=6.914
s1pfcu9=0.021  $s2pfcu9=-13.70 $s3pfcu9=-15.95
s1pfcu10=0.184 $s2pfcu10=0.135 $s3pfcu10=-0.223
s1pfcu11=0.184 $s2pfcu11=0.135 $s3pfcu11=-0.223
s1pfcu12=0.021 $s2pfcu12=-13.7 $s3pfcu12=-15.95
s1pfcu13=3.663 $s2pfcu13=5.286 $s3pfcu13=6.914
s1pfcu14=3.475 $s2pfcu14=6.169 $s3pfcu14=7.897
s1pfcu15=3.171 $s2pfcu15=6.235 $s3pfcu15=7.909
s1pfcu16=2.323 $s2pfcu16=4.506 $s3pfcu16=5.715
s1pfcu17=9.65  $s2pfcu17=3.25  $s3pfcu17=-2.25
s1pfcu18=9.65  $s2pfcu18=3.25  $s3pfcu18=-2.25
s1pfcu19=7.68  $s2pfcu19=3.11  $s3pfcu19=-1.55
s1pfcu20=7.68  $s2pfcu20=3.11  $s3pfcu20=-1.55
s1pfcu21=0.0   $s2pfcu21=13    $s3pfcu21=
```

```
*do,pf,1,20
esel,mat,17    $ersel,real, pf
bfe,all,js,1,0,0, 1e6*s1pfcu%pf%/p%pf%dr/p%pf%dz
*enddo
```

Fig. 9. PF Current Input for PF Background Field

The PF Scenario comes from the systems studies by C. Kessel. There are three equilibria tabulated in figure 14. The first of the three is used for the background PF field. TH others will be run in the future .

III DISRUPTION SIMULATION RESULTS

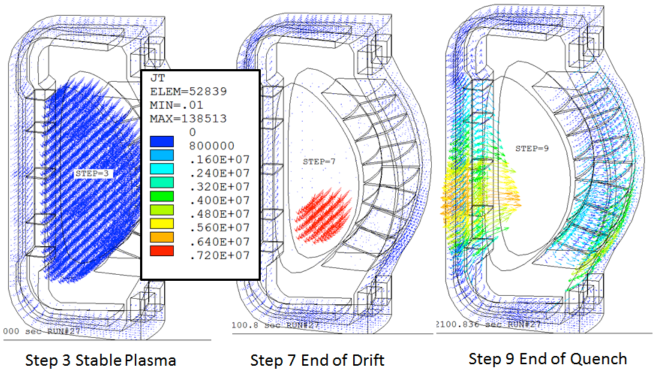


Fig. 10. Plasma Currents and Induced Currents in the Blanket Support Shell

III.A. Blanket Design and Electromagnetic Modeling

K-DEMO uses a solid breeder concept. Blanket sectors are toroidally subdivided into 16 inboard sectors and 32 outboard sectors. The disruption model currently has 15 and 16 sectors, so the module loads reported are over-estimates. The structure of the breeder module is RAFM steel. Coolant holes in plates dividing the breeding segments are represented in the disruption model. Ceramic breeder pebbles of lithium ortho-silicate (Li_4SiO_4) are used as a mixture with beryllide ($Be_{12}Ti$) neutron multiplier pebbles. Currently electrical conductivity of the breeder solid material is lacking, so at this point, results of the disruption loads are qualitative.

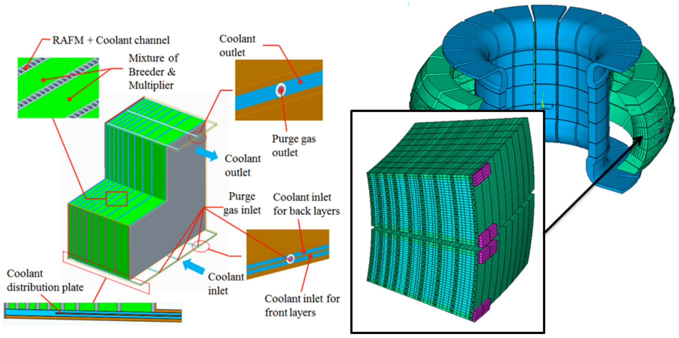


Fig. 11. Blanket Concept and Electromagnetic Model

III.B. Vessel Currents and Stresses

The vessel is not well modeled at this time. Ports are represented by large void regions so the stresses are not realistic. however it does have currents induced in the representation that is included in the simulation.

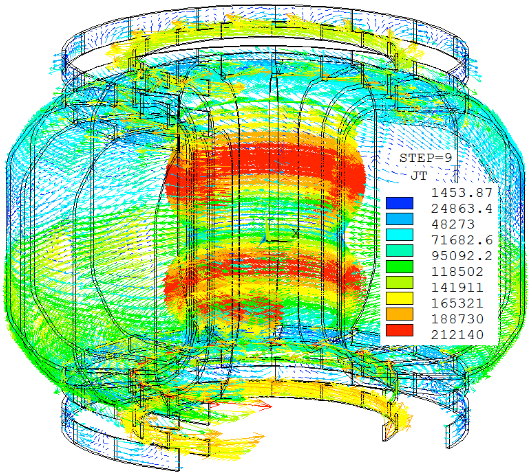


Fig. 12. Induced Vessel Currents During the Quench

The large blanket support shells are toroidally continuous and provide shielding of the vessel. The low stress (39 MPa) in the vessel is an indication of the shielding provided by the blanket structures.

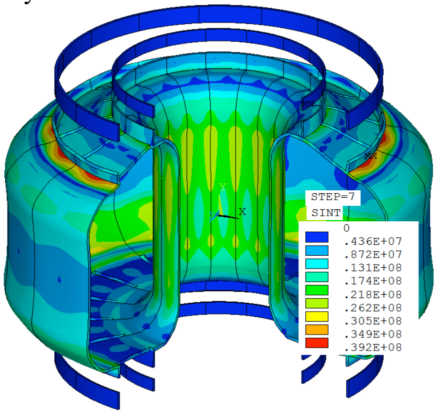


Fig. 13 Vessel Disruption Stress

III.C. Blanket Support Shell Stresses and Net Loads

The inner shield/blanket support structure has a peak stress of only 11 MPa.

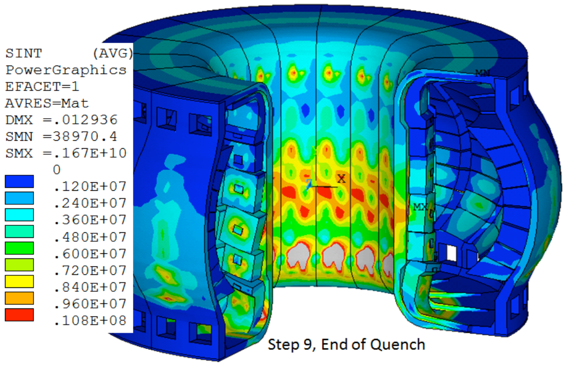


Fig. 14. Blanket Modules and Support Stress

In figure 14, note the twisting of the modules. The loads from the inner modules on the shield/blanket support is a series of torques about a radial axis, which will sum to zero. A vertical key/slot will resist this. The local magnitudes of the key slot stress will depend on the details of the key and its structural connection to the blanket structure. These have not yet been designed.

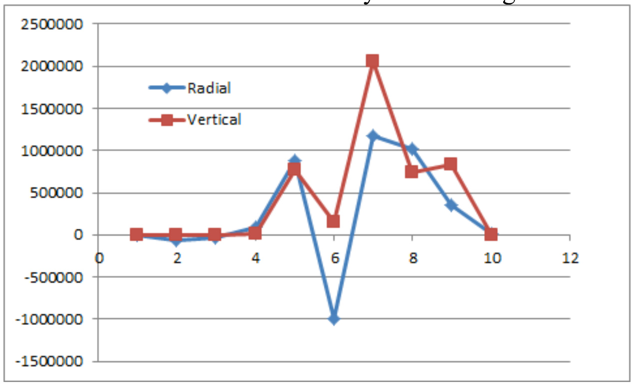
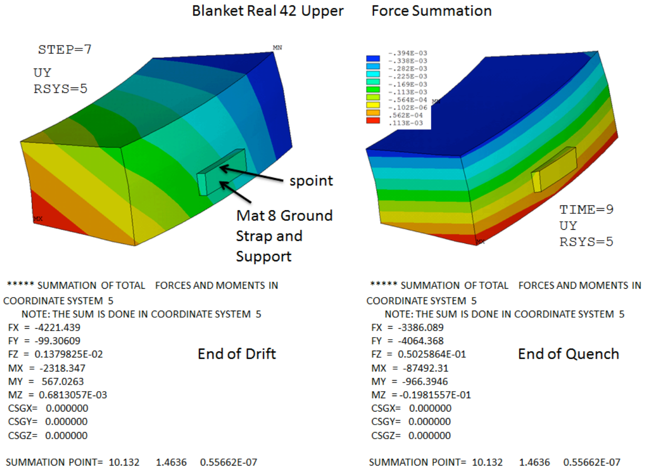


Fig. 15. Blanket Support Structures Loading (Newton). 1/16 sector

The most important load experienced by the inner structure is the net vertical load due to the vertically offset plasma current after the drift and quench. This produces a very large poloidal current in the support shells below the equatorial plane which reacts with the up-down symmetric poloidal coil currents. This load must be reacted through the shield supports with some load path that eventually reacts the PF coil net loads. The current structural concept employs a large frame below the magnet system that supports magnets and vessel, and shields.

III.D. Typical Blanket Module Support Reactions

Loads and moments in figure 16 should be a very conservative estimate of the loads.



```
***** SUMMATION OF TOTAL   FORCES AND MOMENTS IN
COORDINATE SYSTEM  5
   NOTE: THE SUM IS DONE IN COORDINATE SYSTEM  5
 FX  =  -4221.439
 FY  =  -99.30609
 FZ  =  0.1379825E-02
 MX  =  -2318.347
 MY  =   567.0263
 MZ  =  0.6813057E-03
 CSGX=   0.000000
 CSGY=   0.000000
 CSGZ=   0.000000

 SUMMATION POINT=  10.132     1.4636     0.55662E-07
```

```
***** SUMMATION OF TOTAL   FORCES AND MOMENTS IN
COORDINATE SYSTEM  5
   NOTE: THE SUM IS DONE IN COORDINATE SYSTEM  5
 FX  =  -3386.089
 FY  =  -4064.368
 FZ  =  0.5025864E-01
 MX  =  -87492.31
 MY  =  -966.3946
 MZ  = -0.1981557E-01
 CSGX=   0.000000
 CSGY=   0.000000
 CSGZ=   0.000000

 SUMMATION POINT=  10.132     1.4636     0.55662E-07
```

Fig. 16. Outer Blanket Module Loads

In the electromagnetic model, the outboard sectors were not divided into 32 sectors . This is an error that will be corrected. The internal detailed modeling of the blanket still needs a lot of work, but these loads are useful for an upper bound on the expected loading. The loads from the inner modules have not yet been fully post processed.

III.E. CS and PF Coil Stresses

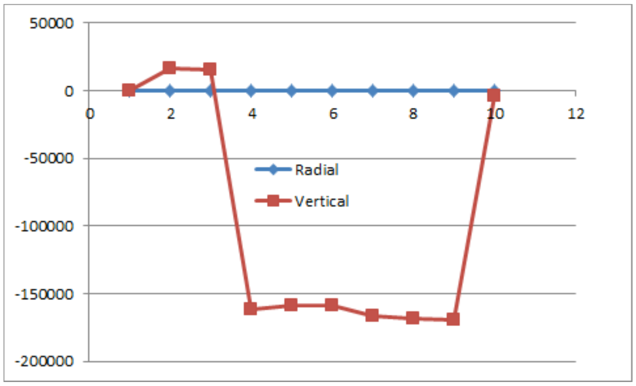


Fig. 16. **PF Coil Loading (Newton). 1/16 sector**

The vacuum vessel, blanket shield structures and TF cases all provide electromagnetic shielding for the PF coils. However the VDE is slow enough that the fields of the vertically displaced plasma penetrate through these structures and effect the CS hoop stress. In figure 16 the radial load was set to zero in the plots because it is not a net load on the PF system. The hoop stresses that result from the radial loading are shown in figures 17 and 18.

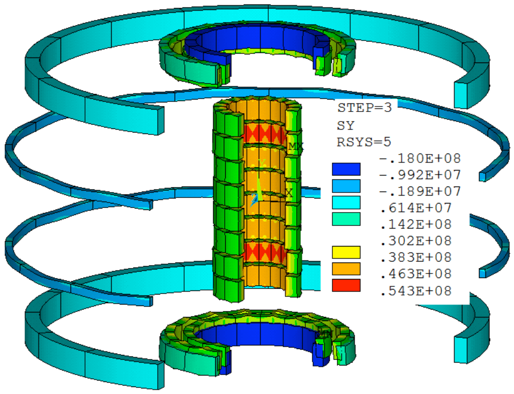


Fig. 17. CS and PF Hoop Stress at Beginning of VDE Drift

IV. CONCLUSIONS

Blanket support system loads have been quantified. The VDE shifts the current center downward and when the plasma quenches, the induced currents are below the mid plane. This reacts with the up-down symmetric PF coil field and puts a large net vertical load on the in-vessel components., and an opposing vertical load on the magnets. The support scheme proposed for the internals is a warm column support to the building foundation. The disruption loads on the magnets and passive structures will be reacted through the foundation embedments.
Moments on the blanket modules are internally reacted by the continuous shells of the blanket support structure.
Blanket Structure stresses are modest owing to the heavy walled construction. The drift phase of the VDE causes significant changes in the CS lower module hoop stress

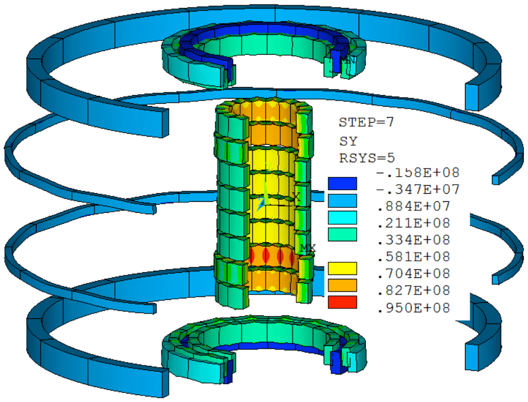


Fig. 18. CS and PF Hoop Stress at End of VDE Drift

V. FUTURE WORK

Vessel modeling needs a lot of improvement to properly capture the effects of port geometry. TF Modeling needs improvement to be useful in structural simulations and quantifying ripple effects. Blanket module properties will be updated as details of the design are developed. Plasma disruptions need to be postulated at more time points in the flat top.

ACKNOWLEDGMENTS

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REFERENCES

1. “Disruption Load Calculations Using ANSYS Transient Electromagnetic Simulations for the ALCATOR C-MOD Antennas”, P Titus Plasma Sci. & Fusion Center, MIT, Cambridge, MA 19th Symposium on Fusion Engineering 02/2002
2. “Design Concept of K-DEMO for Near-Term Implementation “ , Keeman Kim IAEA Conference 2014

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