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FIRE Coil System Structural Analyses

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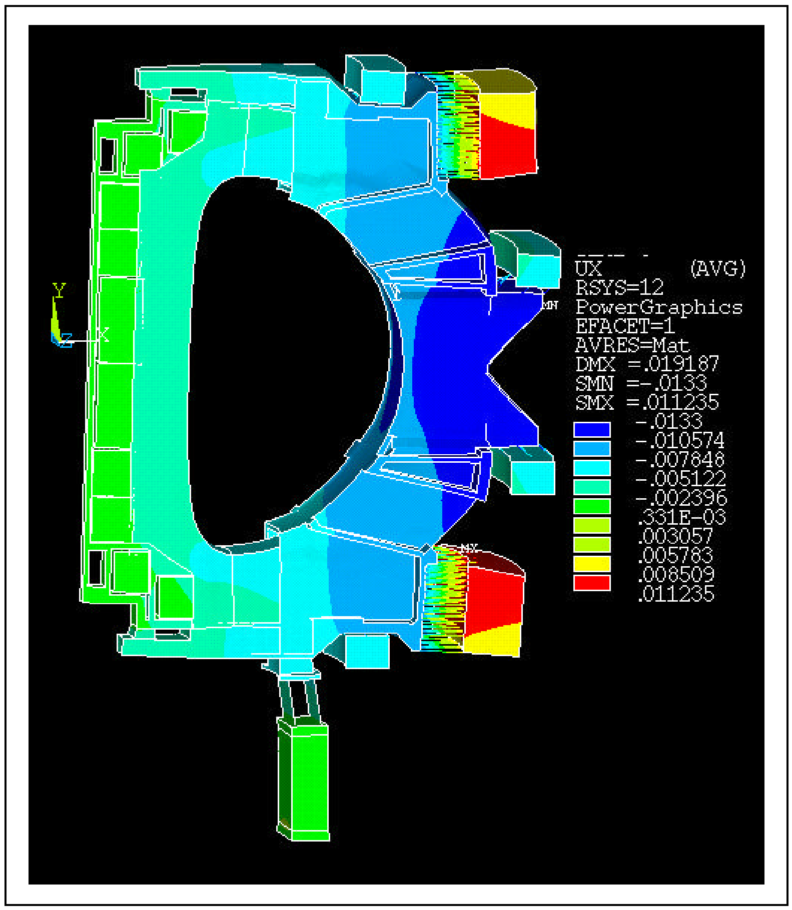
Copy Available in FIRE Documents at
http://psfc.mit.edu/vc/titus/home.html

Topics:

- **Allowable Discussion, Meeting The Primary Stress Criteria**
- **Allowable Discussion, Elastic-Plastic Analysis to Satisfy Ductility Requirement**
- **Fault Analysis**
- **Methods of Obtaining Proper Load Share Between Wedged Case, and Wedged TF**
- **Use of Cast 304 in the OIS**
- **Magnet System Costs**



FIRE Fusion Ignition Research Experiment

Conductor Allowable Stress
P.H.Titus April 2000

From FIRE Criteria:

Conductor:	Structure:
Sm=2/3 Yield	Sm =Lesser of 2/3 Yield or 1/2 Ult
And Adequate Ductility	And Adequate Ductility

Neither satisfy ASME, which is Lesser of 2/3 Yield of 1/3 Ult. - ASME is based on Failure/3

Due to a Bending-like Distribution of Stress in the Equatorial Plane We allow 1.5*Sm. - for both the TF and CS

In FIRE there is an external structure - But the coil supports most all of the Lorentz Forces.

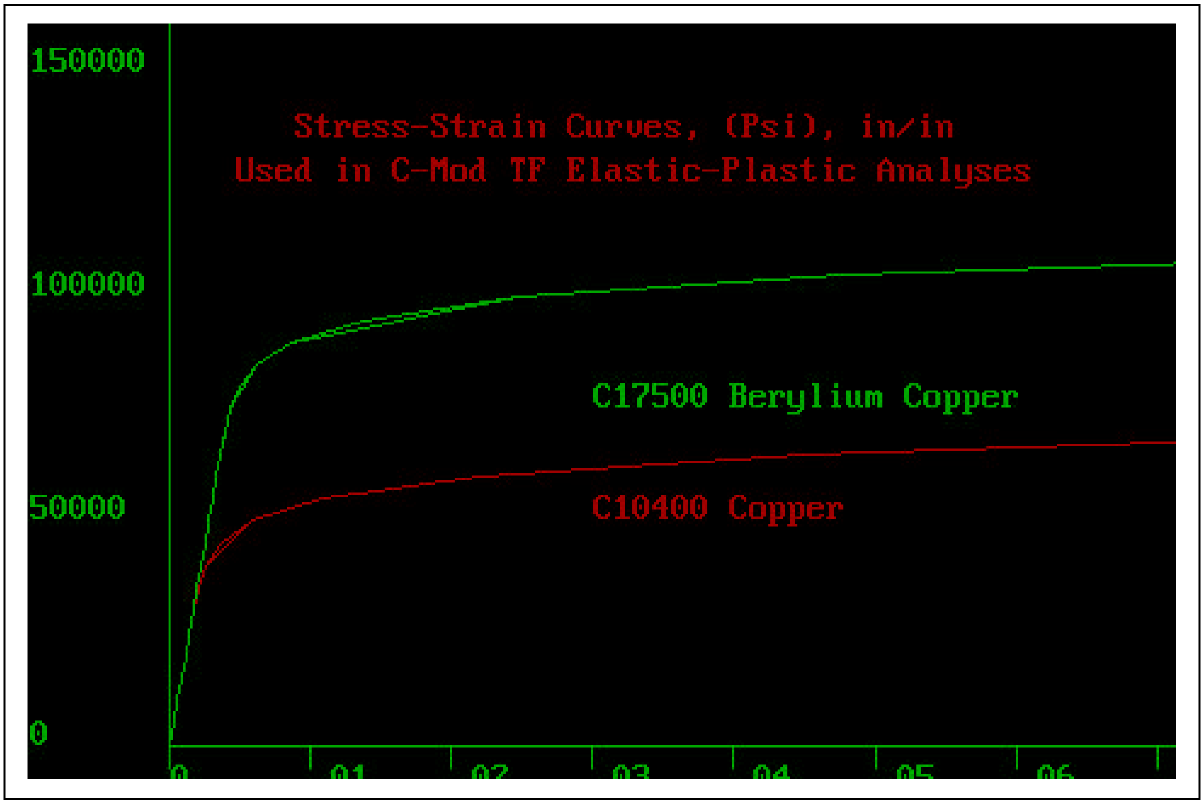
Is the coil "Conductor", or "Structure"

For Sm=- 2/3 yield , a conductor at the allowable stress is at .2% offset yield, and beyond the proportional limit. If yield and ultimate are close, the plastic region is flat, and the coil is at the onset of large scale plastic bending.

ASME Failure	Tokamak Coil Failure
Pressure Burst	Electrical Fault/Insulation Failure

Proposal: For Lowest Conductor Physicals, and Largest Possible Lorentz Forces, Demonstrate Acceptable Insulation Strains - With some Margin

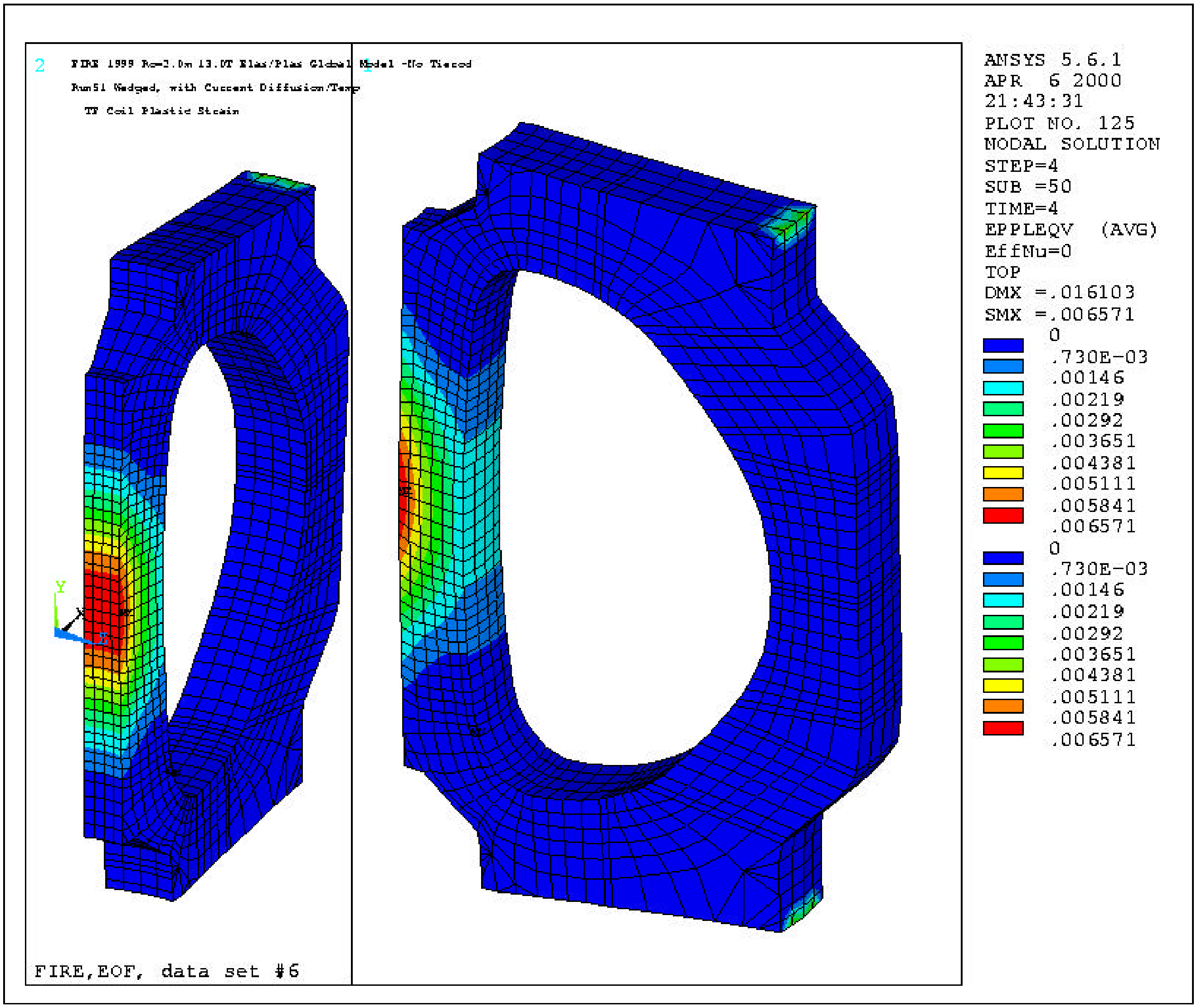
To Satisfy the Ductility Requirements
Elastic-Plastic Analysis - 13 T, 600 MPa .2% Yield



Analysis Assumes:

- **Onset of Non-Linearity at 75ksi/517 MPa .2% Yield 600 MPa , 87 ksi**
- **.65% plastic Strain results - Corresponds to about 20 ksi in the Insulation**
- **Actually 68% IACS yields at 720 MPa**

FIRE "Worst Case", 13 T Loading , With Low Spec Material (600 MPa Yield)



FIRE "Worst Case, 13 T, 600 MPa Yield" Insulation Stress= .00657*30 Gpa =197 MPa (Conservatively Assumes all Conductor Plastic Strain is in the Insulation Plane.)

Insulating Material Strengths, MPa

	@4	@77	@292
Comp.Strength Normal to Fiber			
G-10CR	**749**	**693**	**420**
G-11CR	**776**	**799**	**461**
Tensile Strength (Warp)			
G-10CR	**862**	**825**	**415**
G-11CR	**872**	**827**	**469**
Tensile Strength (Fill)			
G-10CR	**496**	**459**	**257**
G-11CR	**553**	**580**	**329**

Insulation Failure Margin= (13/12)^2 * 720/600 * 257/197 = 1.8

Primary Membrane Stress Alowable

From FIRE Criteria:

Conductor:
Sm=2/3 Yield
And Adequate Ductility

Structure:
Sm =Lesser of 2/3 Yield or 1/2 Ult
And Adequate Ductility

Properties of Several Variants of Copper Beryllium Alloy C17510

Variant of C17510	Yield Strength, Mpa at RT	Yield Strength, Mpa at 77 K	Ult. Strength, Mpa at RT	Ult. Strength, Mpa at 77K	Elec. Cond. % IACS at RT	Elec. Cond. % IACS at 77K	% elong. At RT	% elong. At 77K
Hycon 3 HP^{TM} 68105	**724**	**745**	**800**	**752**	**68**	**165**	**14**	**15**

68% IACS BeCu Conductor:
Sm=483 MPa at RT
Sm=497 MPa at 77K

Properties of Several Variants of Copper

Variant	Yield Mpa at RT	Yield Mpa at 77 K	Ult., Mpa at RT	Ult, Mpa at 77K	1.5Sm MPa at RT	1.5Sm MPa at 77K	Elec. Cond. % IACS at RT	Elec. Cond. Ratio 77°K/ RT	% elong. At RT	% elong. At 77K
OFHC [12]	280	320	310	400	232	300		8.14		
OFHC 102 60% CW[17]	320	370	350	470	262	352				

60% CW OFHC Cu Conductor:
Sm=200 MPa at RT
Sm=233 MPa at 77K

Properties of Stainless Steels

Material	Yield 4 deg K (MPA)	Ultimate 4 deg K, (Mpa)	Yield, 80 deg. K (MPa)	Ultimate, 80 deg. K (MPa)	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	992[29]	1379[29]			275.8[29]	613[29]
316 LN SST Weld	724[29]	1110[29]			324[29]	482[29]
304 SST 50% CW	1613	1896	1344	1669	1089	1241
304 Stainless Steel (Bar,annealed)	404	1721	282	1522	234	640

Annealed 304 SST
Sm=154 MPa at RT
Sm=188 MPa at 77K

50%CW 304 SST
Sm=620MPa at RT
Sm=834MPa at 80K

Satisfying the Primary Stress Criteria

Consider a thick walled cylinder representing the inner leg of the TF. It has an outside radius of 1.308 meter and an inside radius of .820 meters and uniform current density. The field at the outside of the cylinder is 10*2.0/1..308=15.3Tesla. The average field through the cylinder wall is then half this. Using a simple Pr/t analysis the hoop stress is

100e6Amps*7.645Tesla/2/pi/(1.308-.820)= 249 MPa

This gives an approximate estimate of the average hoop compressive stress in the TF build which should result from the finite element analysis.

The Net Vertical Load in a TF coil is Fvert=.5*I*Bo*R0*ln(r2/r1)

Fvert=.5*100e6*10*2.0*ln(4/1.06) = 1324 MN

Where: r1= (1.308+.820)/2=1.06 And r2=(3.701+4.304)/2=4.0m

The centroid of this load is closer to the inner leg, but the outer structure is stiffer, and cooler and is intended to pick up most of the vertical load inventory.

As an approximation, assume that 1/3 of this load appears on the central column. Then the average vertical tensile stress on the inner leg is 1324/pi/(1.308^2-.82^2)= 136. The actual average stress from the FEM analysis is about 150 MPa (read from contours), confirming that the external structure is picking up a large fraction of the vertical load.

The average tresca is then 400 MPa, Von Mises is about 350 MPa

(there is also an average torsional shear of about 15 MPa, and this doesn't contribute much to the Tresca/VM calculation). Because the wedging pressure is the biggest contributor to the equivalent stress, the packing fraction effect is only 2%.

It is not clear if the inner leg stresses being discussed are primary stresses given that the primary vertical support is from the external structure. The wedge stress should meet the primary membrane allowable.

Inner Leg Stress Summary

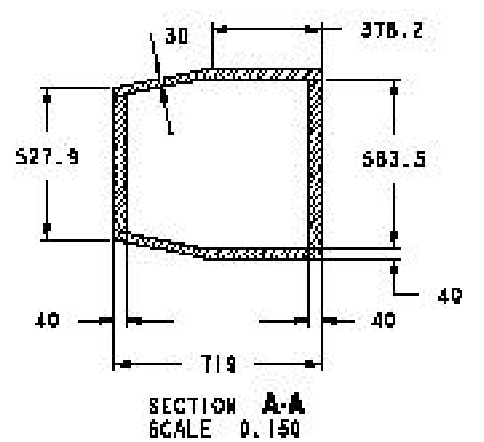
Stress Component	10T	12T
Allowable	480MPa	480MPa
Primary Stress With Vertical	400MPa	576MPa
Primary Stress Without Vertical	249MPa	358MPa

Equatorial Plane Case Stresses, Reconciling Tom Browns model and FEA Model.

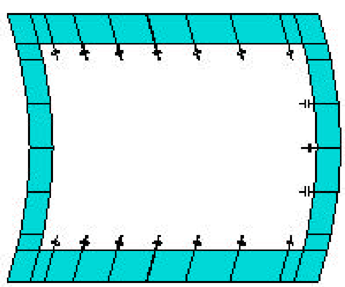
Equatorial Plane Stresses are too high for Cast Material. (80K Yield=282 MPa,41 ksi) There is about 228 MPa from Lorentz Loading and 362 MPa from Thermal

12T Run#52 Results:

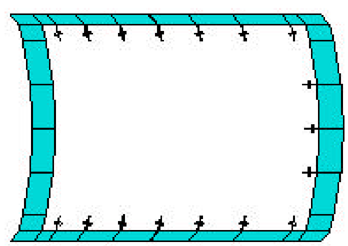
Time	Peak Stress
PRE	228 MPa
SOF	448 MPa
EOB	585 MPa
EOF	617 MPa
EOP Hot	362 MPa



Case Cross Section from the Drawings, May 2000. The Area is .030*2*.719+.040*(583.5+527.9)=.0876m^2

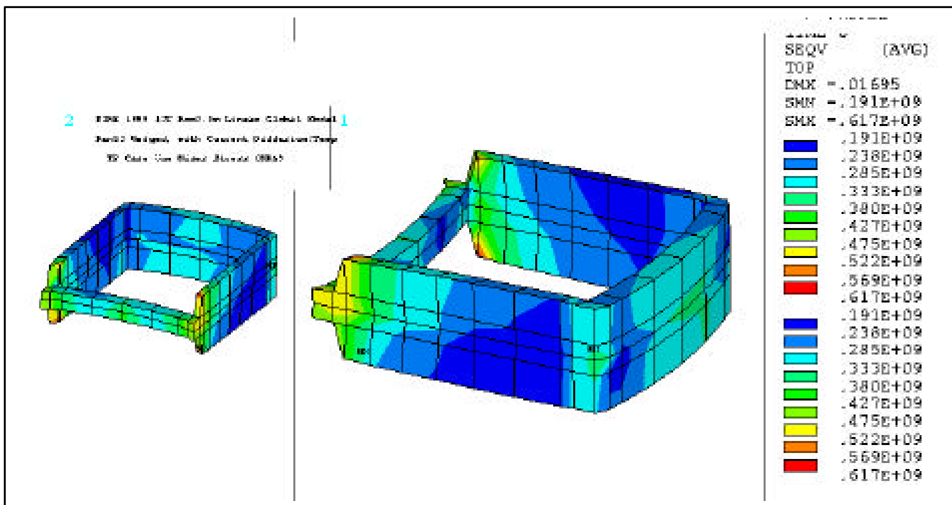


Case cross section used in runs earlier than #52



Cross section at the equatorial plane used in Run#52

Sidewalls are .035m thick



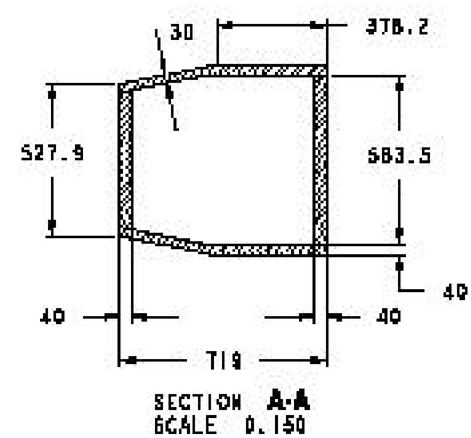
Is the Vertical Separating Force a Primary Load for the Inner or Outer Leg?

We want to claim that the case in concert with the heavy outer legs of the TF will serve as the primary support of vertical separating loads in the TF field Coil.

This is intended to eliminate the vertical load as a primary load in the inner leg.

The case, along with the ring structure supports the radially outward load of the outer legs of the TF coil. The net vertical load from the TF coils is 69.89 MN per coil for 10T, from the FEA Loading. From Fvert = .5*I*Bo*R0*ln(r2/r1)/16 = 83MN

There are some differences in current centers in these two calculations which accounts for the difference. Use the more accurate of these loads. The primary membrane stress is then 70MN/.0876=800 MPa . Sm=188 MPa at 77K for annealed 304 and Sm=834MPa at 80K for 50% CW 304. Cast material is not good enough if the case is to be the primary load carrier



Case Cross Section from the Drawings, May 2000. The Area is .030*2*.719+.040*(583.5+527.9)=.0876m^2

If the same load is applied to the outer leg cross section the stress would be 70MN/(.528*.639) = 207 MPa.

Actually the load is shared between Coil and Case. From the FEA analysis a case average vertical stress of 200 MPa can be expected. This reduces the load in the coil to 70-200*.0876 = 52 MN

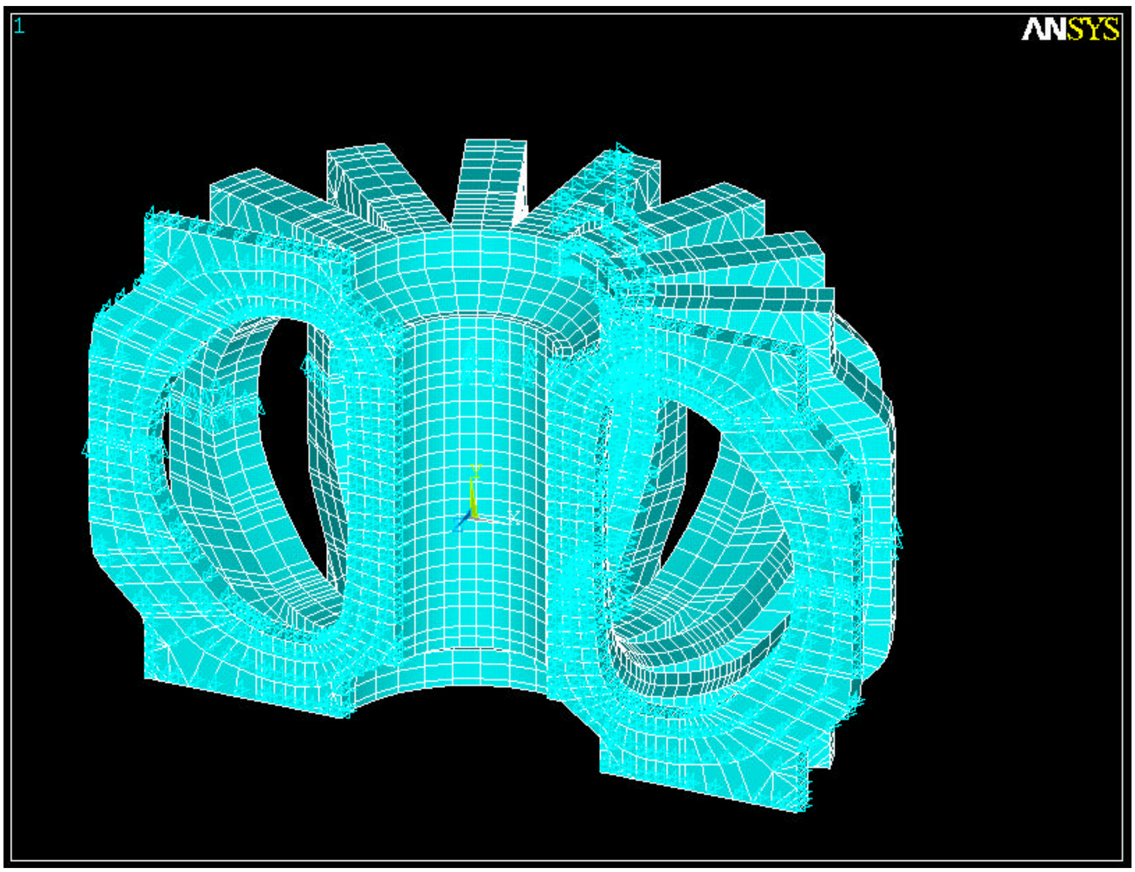
Outer Leg Conductor Stress Summary

Stress Component	10T	12T
Allowable	233MPa	233 MPa
Primary Stress With 100% Vertical	207MPa	298 MPa
Primary Stress With 200 MPa (at 10T) Contribution from the Case	155MPa	223MPa (But this requires 300 MPa Sm for the case

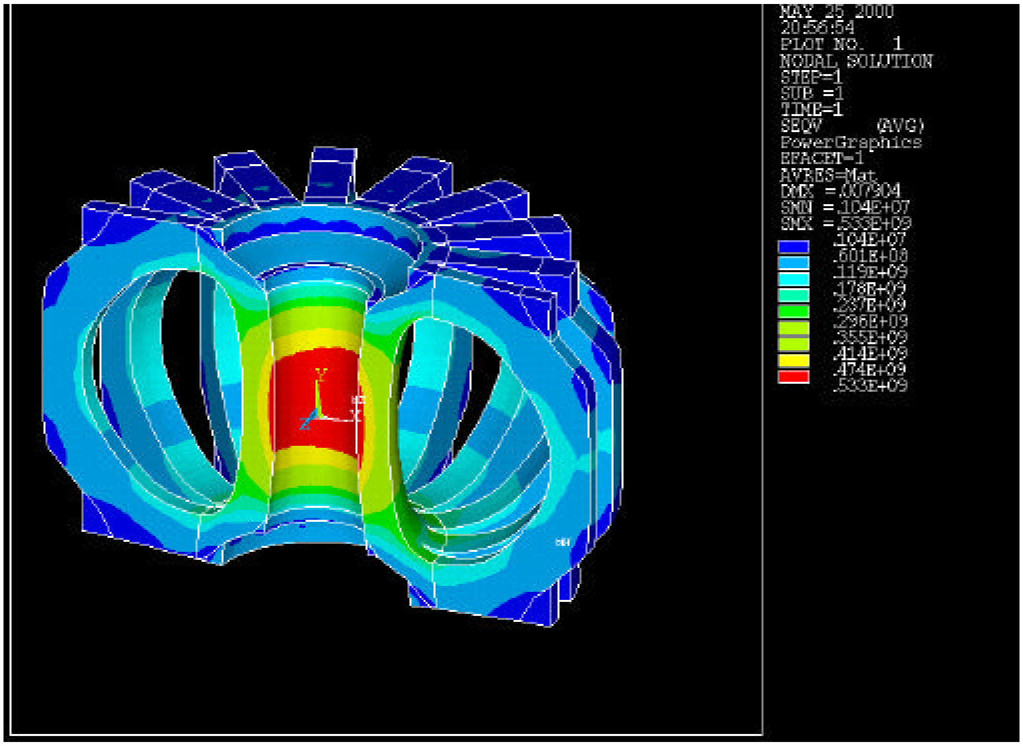
Survivability in Off-Normal or Faulted Loading Also is a Measure of Design Margin

Simplified Fault Analysis

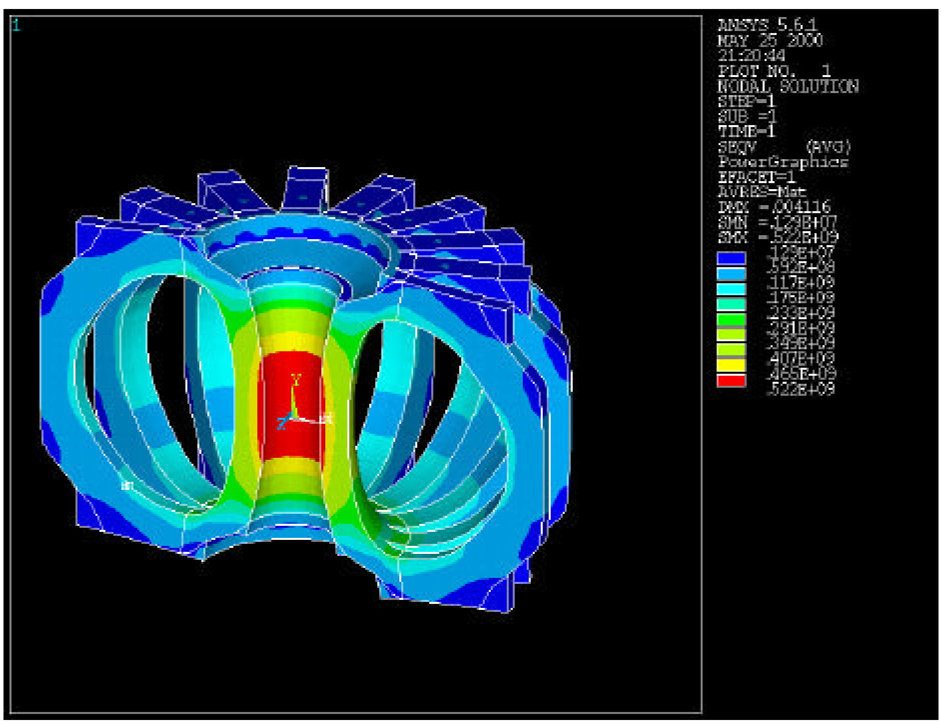
Model and Current/Loading	Peak TF Stress
Nominal 10T No Tierod Detailed Model	469 MPa
Fault Model Nominal 10T	522 MPa
Fault Model Single Coil 10% Over Nominal	533 MPa
Fault Model Single Coil 20% Over Nominal- the Rest 20% Under	441 MPa



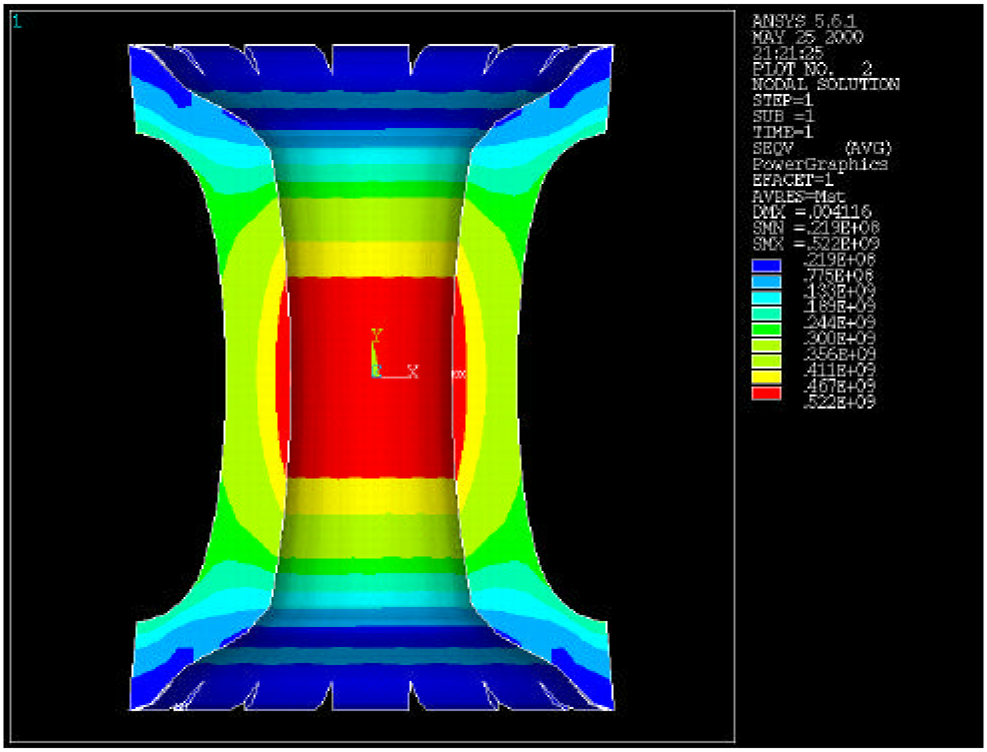
Simplified Fault Model, No Casees, Only In-Plane Loads



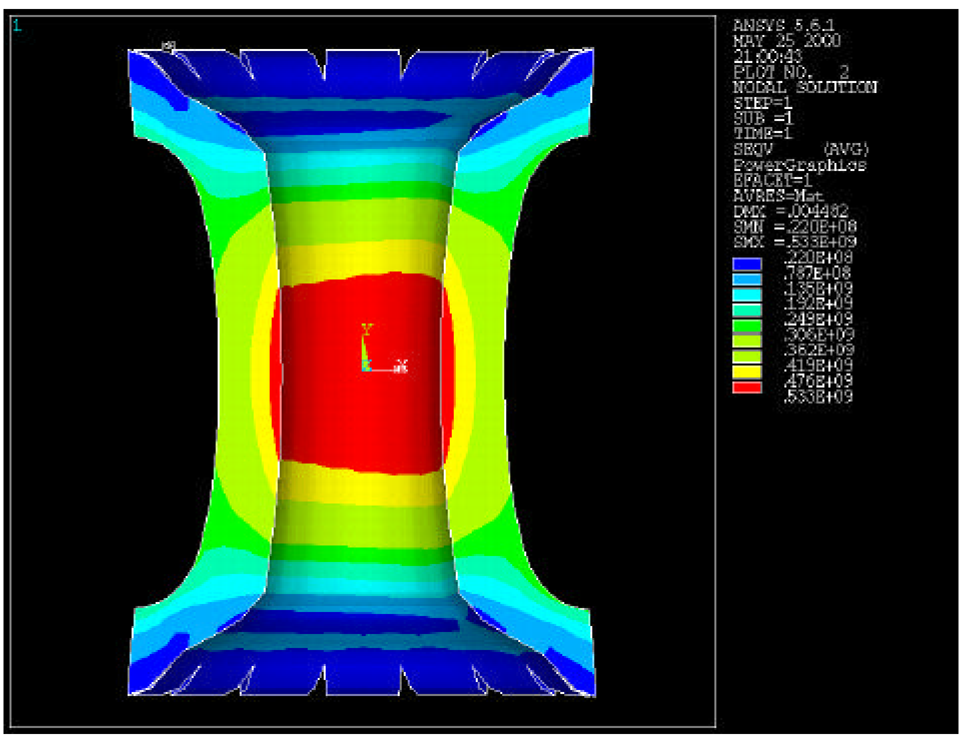
Single Coil 10% over Nominal 10T Current 533 MPa VM Simplified Model - No Case



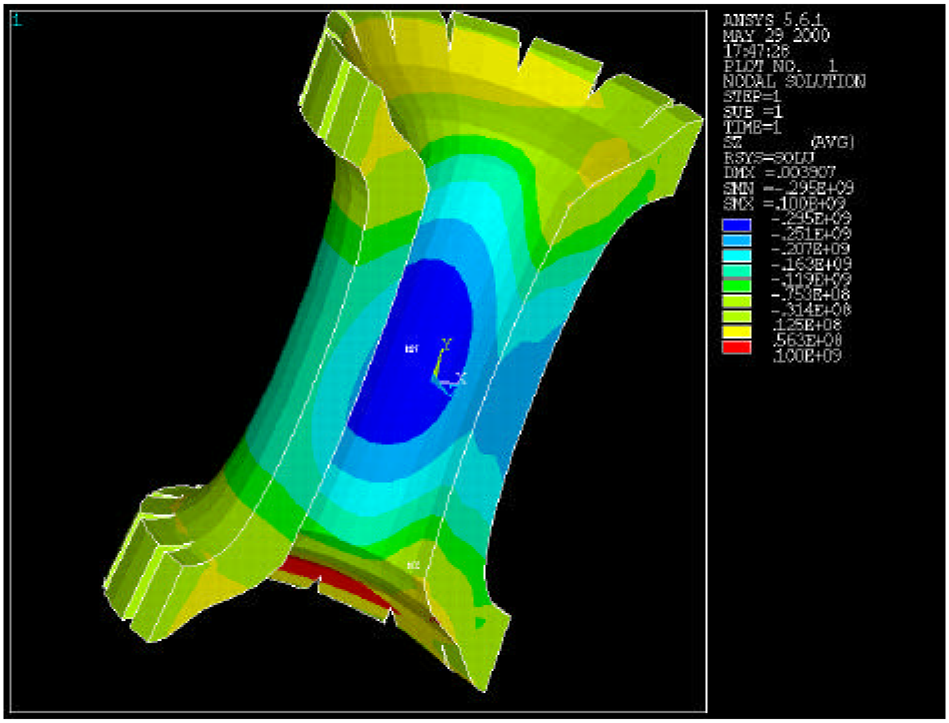
Baseline 10 T 522 MPa VM - Simplified Model - No Case



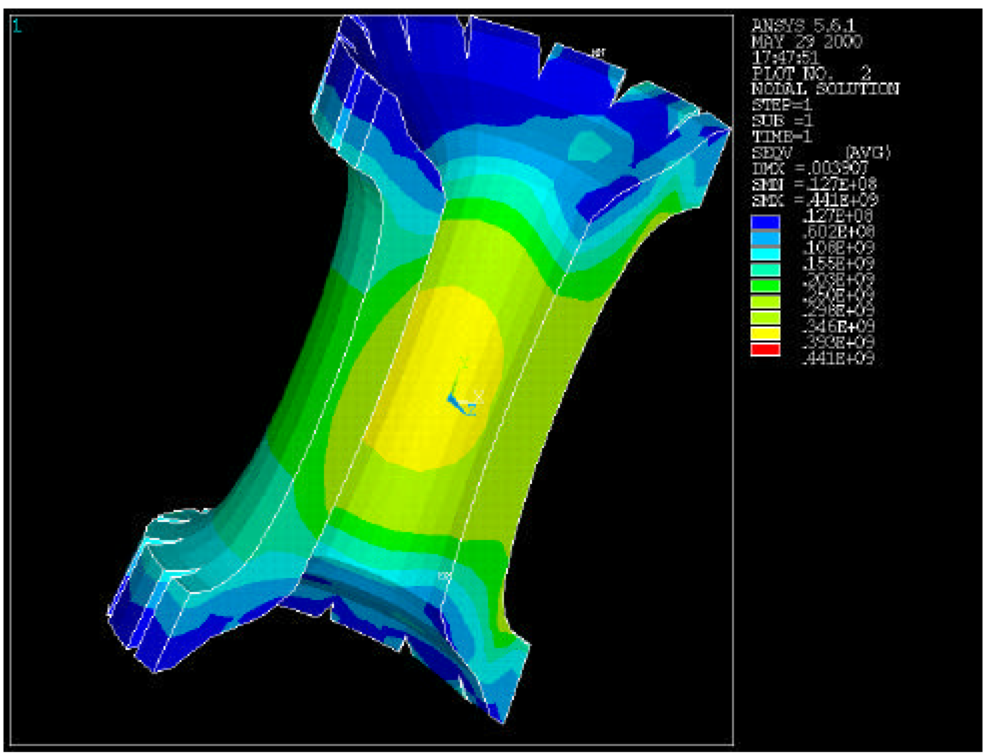
Baseline 10 T 522 MPa VM



Single Coil 10% over Nominal 10T Current - 533 MPa VM



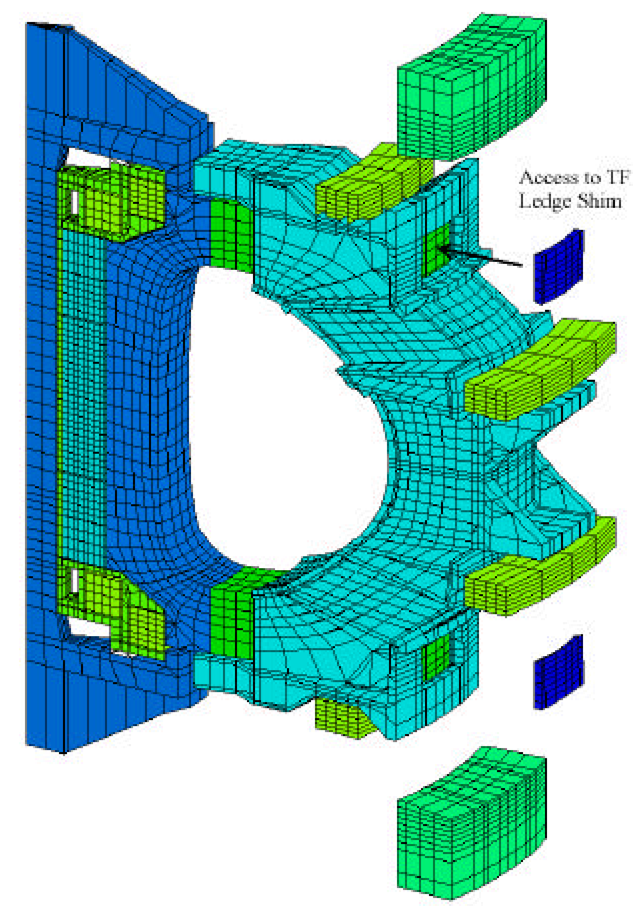
Fault Model Single Coil 20% Over Nominal- the Rest 20% Under - Wedge Stresses



Fault Model Single Coil 20% Over Nominal- the Rest 20% Under - Von Mises Stresses

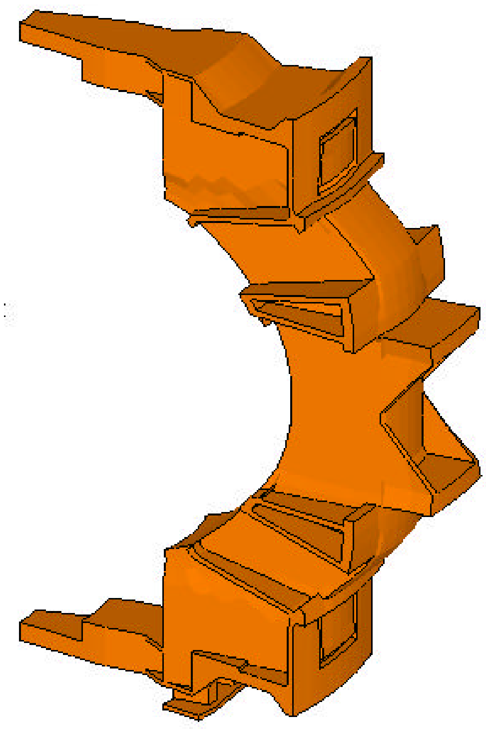
Load Share between The TF Inner Corner and Case Outer-Intercoil Structures

- **The large compression rings primarily are intended to support TF OOP loads in the inner corners of the TF inner leg.**
- **In addition, the rings provide compression in the outer inter-coil structures of the case, where substantial tensile and shear connections are needed.**
- **The compression in the case provided by the ring allows support of the outer out-of-plane loads by friction at the parting planes between the case sectors.**
- **Small mechanical interconnections are provided to support assembly, but do not contribute after the ring is tensioned.**



"Window to Access Shim. Elastic Interactions Provide Appropriate Load Share

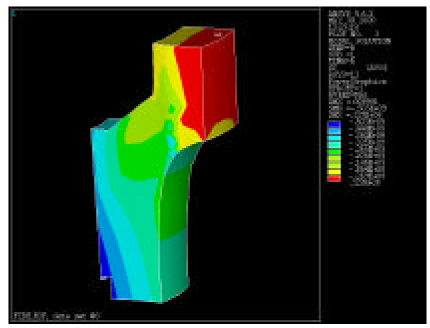
- **Use of the ring to supply two toroidal compressive loads requires either a very accurate understanding of the elastic interactions of the load paths, or some discrete way of loading the inner leg corner separate from the outer case flanges**



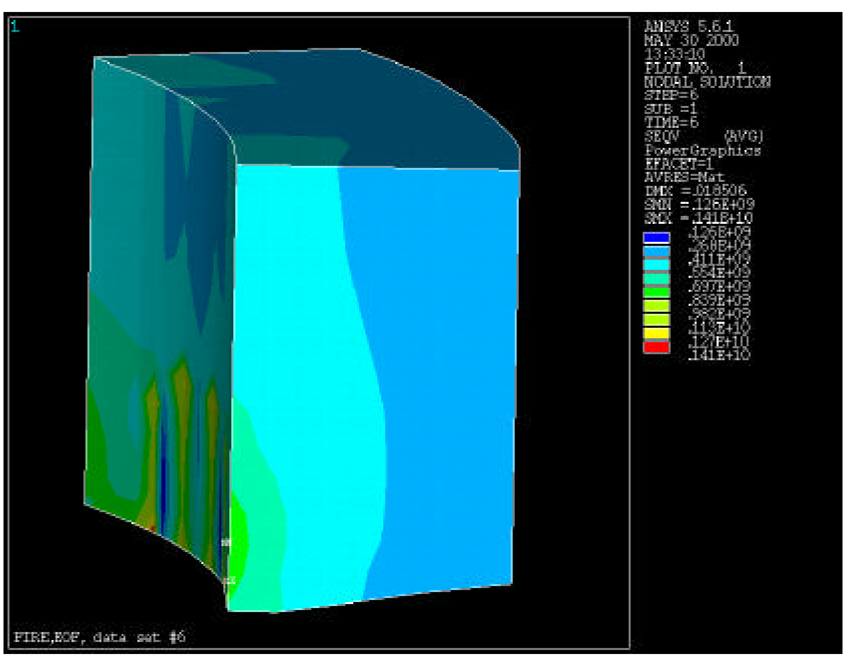
Case Model with "Window" to Apply Jack Load Directly on the Coil Ledge

Load Share between The TF Inner Corner and Case Outer-Intercoil Structures
Case "Window" for Directly Loading the TF Ledge.

- **In Run#53 the jack gap element interference was not changed, "Windows were Added.**
- **12T analyses were used.**
- **TF inner corner wedging stresses did not change. - Satayed at ~-200 MPa**

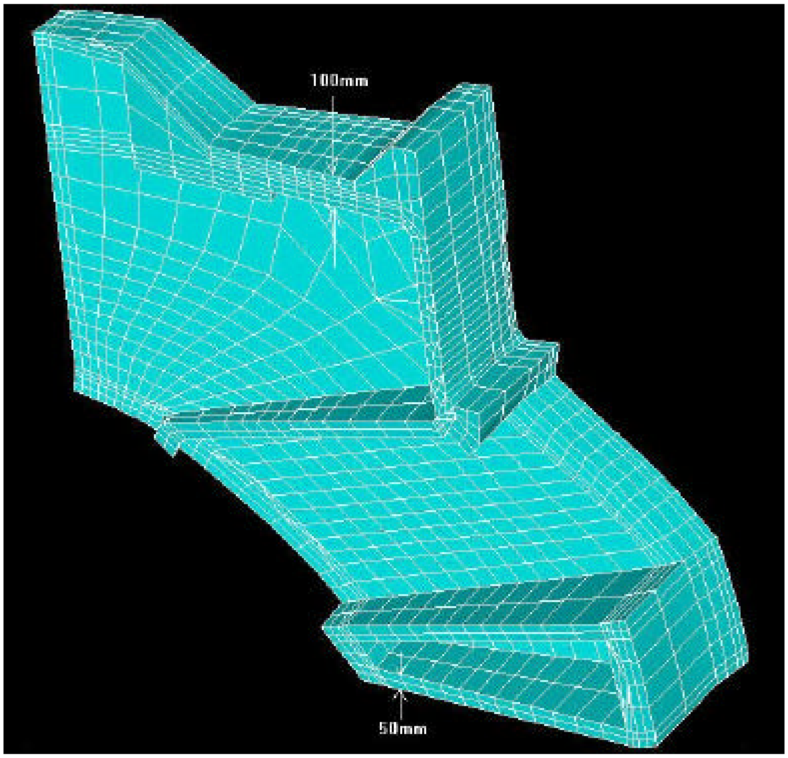


- **Local Ring Stresses May be a Problem (1200 to 1400 MPa)**
- **Access to TF Ledge Jacks Looks Difficult**

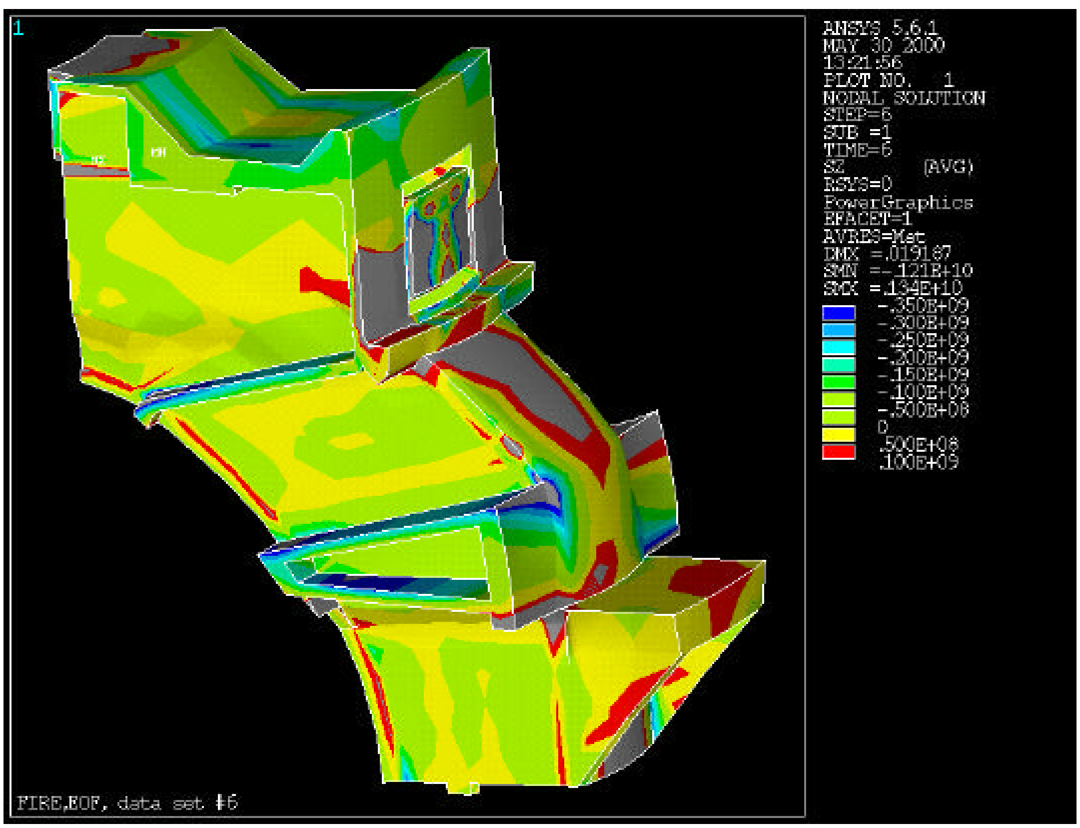


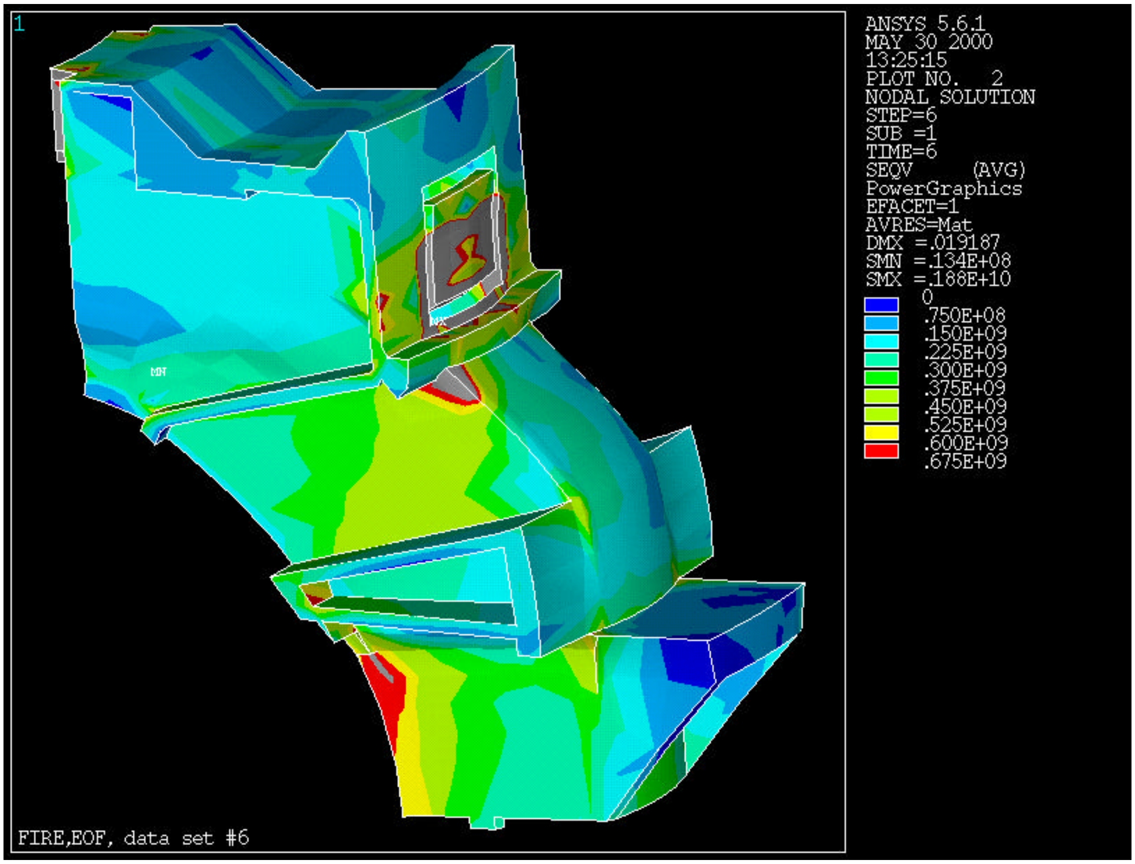
Von Mises Stress in the Ring

- **Use of Cast Material in Outer-Inter-Coil Structures**



Sections Used in the FE mesh, Up Through Run #53





Von Mises Stress in The Case

Material	Yield 4 deg K (MPA)	Ultimate 4 deg K, (Mpa)	Yield, 80 deg. K (MPa)	Ultimate, 80 deg. K (MPa)	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	992[29]	1379[29]			275.8[29]	613[29]
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304 SST 50% CW	1613	1896	1344	1669	1089	1241

Annealed 304 SST
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Sm=188 MPa at 77K

50%CW 304 SST
Sm=620MPa at RT
Sm=834MPa at 80K

- **Outer-Inter-Coil Assemblies can be Cast if Webs are Thickened**
- **Case Sidewalls Should be Work Hardened Material**

TF and Case Assembly