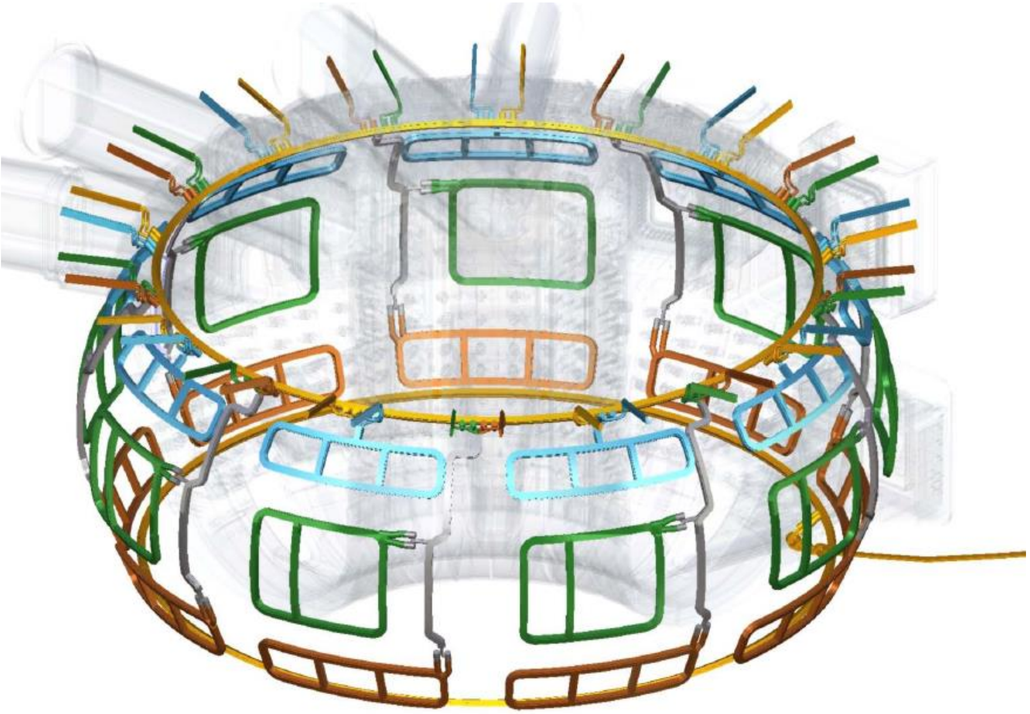
THERMAL & MECHANICAL ANALYSIS
ELM COIL
PDR Review
October 18-20, 2010



OUTLINE

- **ASSUMPTIONS**
- **ALLOWABLES & ACCEPTANCE CRITERIA**
- **MATERIAL PROPERTIES**
- **DESIGN DESCRIPTION**
- **BOUNDARY CONDITIONS**
  - OPERATING MODES
  - NUCLEAR & RESTISTIVE HEAT GENERATION
  - LORENTZ & PRESSURE LOADS
  - RADIATION ; CONDUCTION ; COOLING WATER @ 3 m/sec

OUTLINE

- **STEADY STATE TEMPERATURE & STRESS RESULTS :**
  - **ELM**
    - TEMPERATURES FOR BASIC INDUCTIVE & FAULT
    - DISPLACEMENT & OPERATING REACTION LOADS
    - THERMAL + PRESSURE LOAD RESULTS
    - THERMAL + PRESSURE + LORENTZ LOAD RESULTS
    - NSTX EQUIVALENT FATIGUE STRESS CONTOURS
    - LORENTZ COMPONENT STRESS INTO AND AWAY FROM WALL
    - NATURAL FREQUENCY MODE SHAPES
    - BRACKET OPTIMIZATION
  - **CROSSOVER (First Run)**
    - TEMPERATURES 500 MW
    - TEMPERATURE + PRESSURE LOAD RESULTS
- **CONCLUSIONS; ISSUE RESOLUTION PLAN**

ASSUMPTIONS

- The interface between the MGO insulation and the Coil is assumed to be bonded contact.
  - Conservative since transverse Lorentz loads could cycle the coil in tension.
  - Additional work to characterize and calibrate the load transfer is in process.

- A reference temperature of 100 C is applied to all materials.
  - This accounts for displacements of the reactor to boundary interface.
    - Error is small since thermal expansion coefficients are similar
  - Future work will map boundary thermal displacements with APDL script
    - Additional reactor displacement to be added based on 100 C temperatures.

- Bonded thermal Contact is assumed between the brackets and coils although mechanical constraint is limited to end points

- Surrounding Blanket and reactor structures are uniform 100 C
- All analysis is steady state

Allowables and Acceptance Criteria

Stress Limits (SDC -IC), MPa				
	CuCrZr-IG		316L(N)-IG	
Temperature	100C	200C	100C	200C
Minimum Ultimate Tensile Strength, Su	359	323	458	425
Minimum Yield Strength, Sy	253	235	172	144
Design Stress Intensity Limit, Sm	120	108	147	130
Stress Endurance Limit, Se (=30% Su)	108	97	137	128

Metalic Structure Acceptance Criteria (SDC-IC Appendix D)						
			CuCrZr-IG		316L(N)-IG	
			100C	200C	100C	200C
Primary Stress (PM, PL, PB)						
	General Primary Membrane	1.0 K Sm	120	108	147	130
	Local primary membrane	1.5 K Sm	180	162	220.5	195
	Primary Membrane plus bending	1.5 K Sm	180	162	220.5	195
Secondary (Q) (ie thermal)		3.0 K Sm	360	324	441	390

Design Life		
Machine Pulses (Thermal Cycles)	30000	
EM Cycles per Pulse (5Hz)	5000	
Total Cycles	**1.50E+08**	ie Infinite Life
Fatigue Criteria - factor of 2 on stress, 20 on cycles		
Since Total Cycles exceed infinite life limit, Alternating Stress, Sa, must be less than half the endurance limit, Se		
Including Mean Stress, Smean, we have the following limit:		
Sa/Se + Smean/Su < 1.0		

Material Properties

Component	Young's Modulus (Pa)	Shear Modulus (Pa)	Poisson Ratio	Thermal Conductivity (W/m C)	Thermal Expansion (1/C)
Stainless Steel	1.85e11	7.06e10	0.31	16.98	1.78e-5
Copper	1.21e11	4.51e10	0.34	343	1.75e-5
MGO	0.96e9	2.5e6	0.42	2.363	1e-5

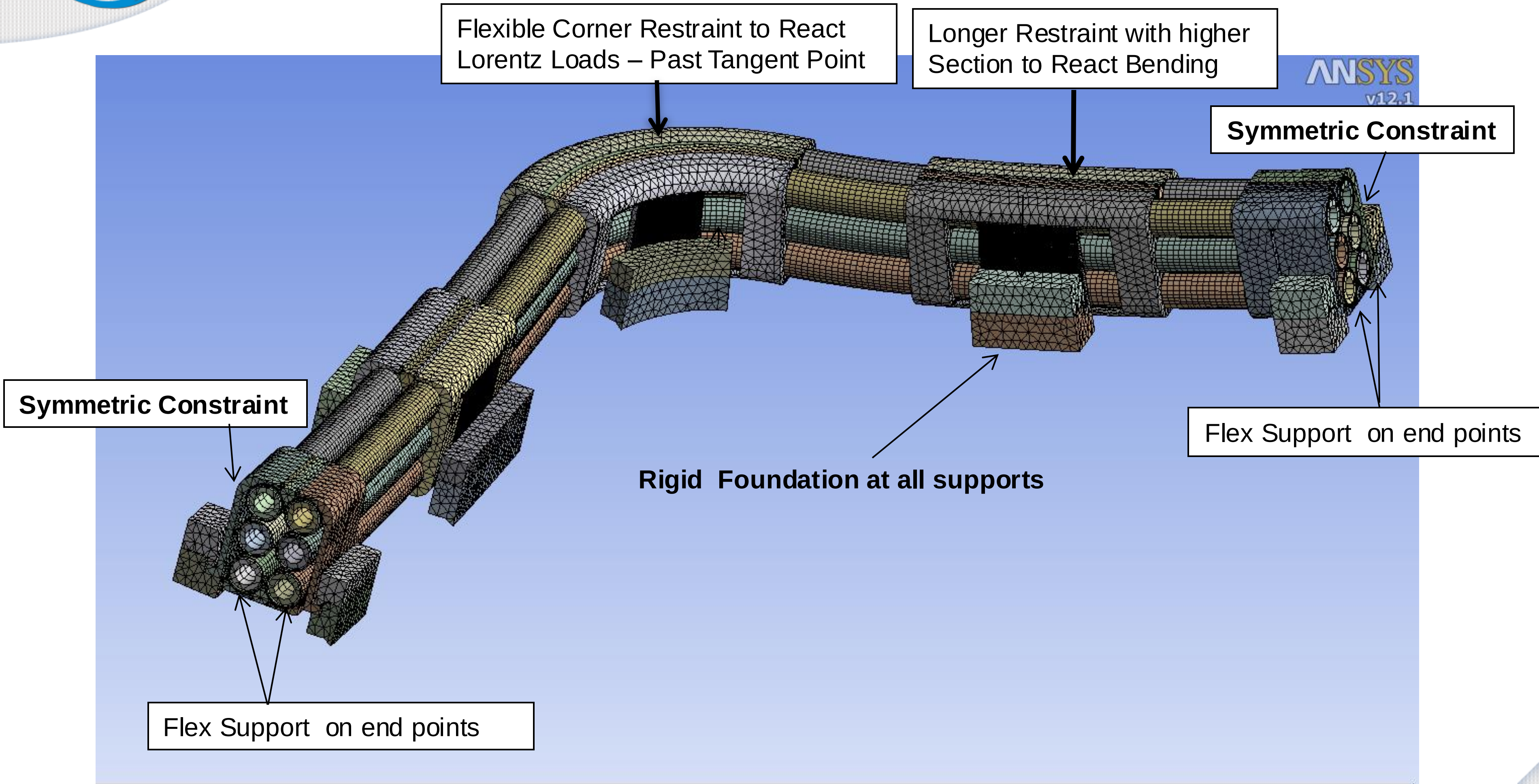
** All data for 200 C taken from ITER references – excluding MGO properties

Nuclear Heat Operating Modes

Parameter	Inductive Operation	Hybrid Operation	Non-inductive Operation
Fusion power (MW)	500	400	356
Burn time (sec)	300-500	1000	3000
Minimum repetition time (sec)	1800	4000	12000

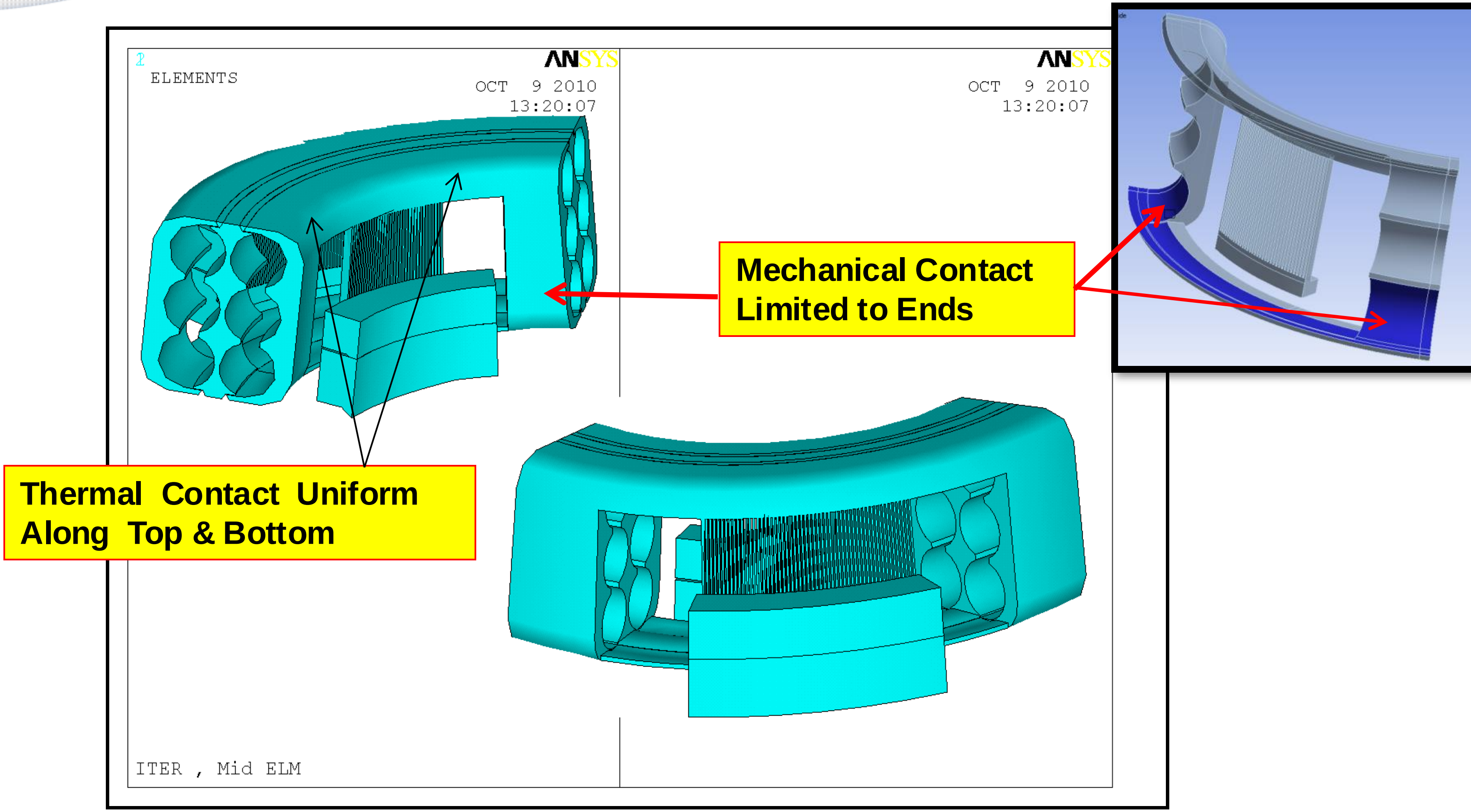
This Presentation Considers Only the Steady State Portion of the Basic Inductive Operation Case

SANDWICH BOX SUPPORT DESIGN



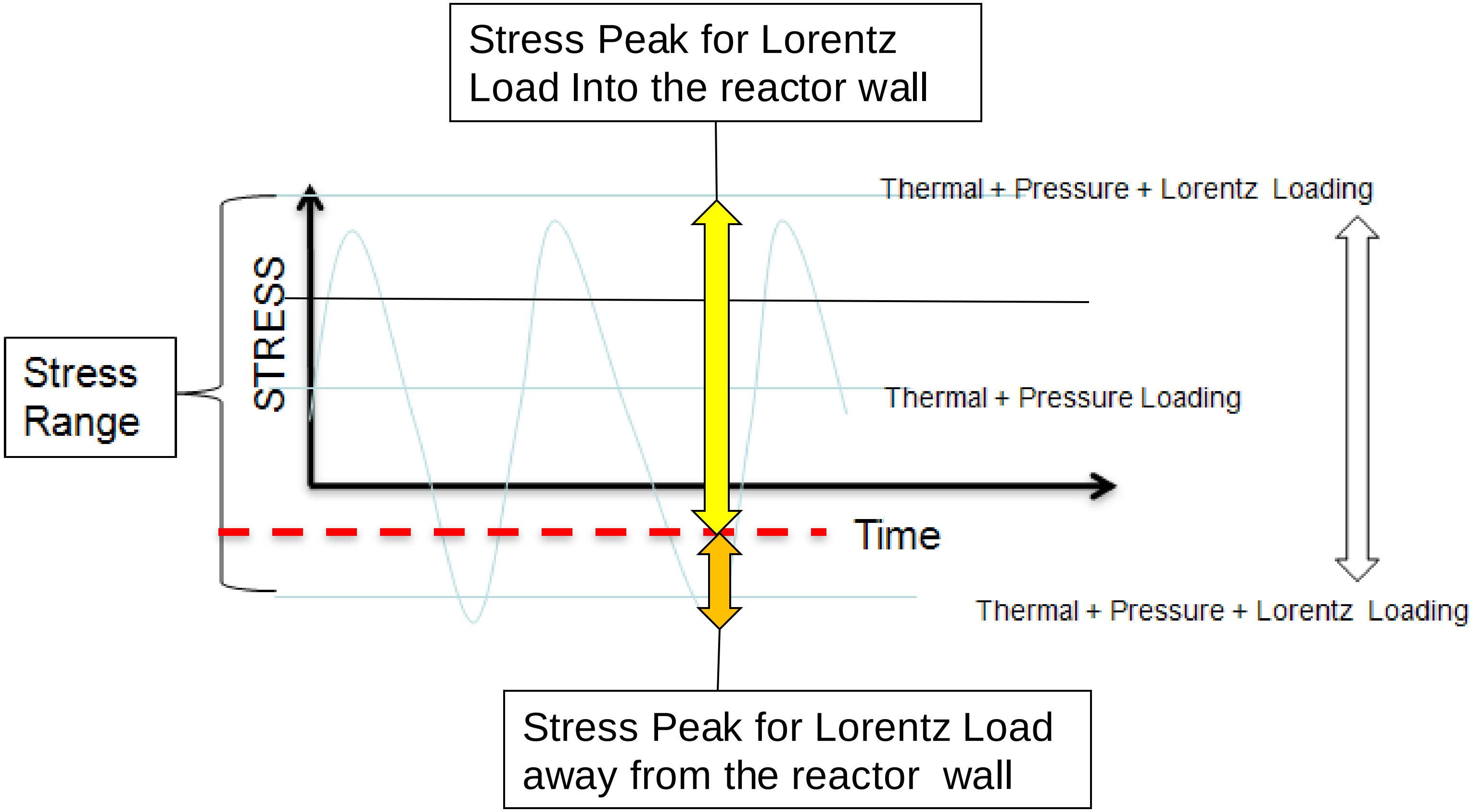
The New Sandwich Design Box Support is Meshed with Hexhedral Elements
On the Coil Components

Revised Support Design



Support to Pass the Tangent Point on the Coil to Reacting out Bending loads
Bonded Mechanical Contact is Limited to Ends

IDEALIZED LOAD DIAGRAMS



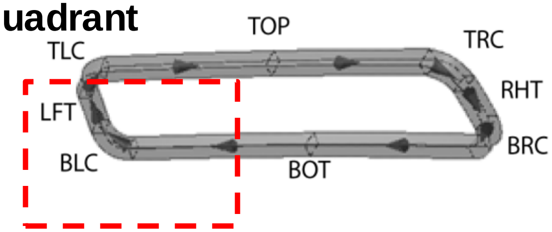
$$R = \frac{\sigma_{Min}}{\sigma_{Max}}$$

$$-1 \geq R \geq 0$$

This unsymmetrical stresses resulting from differences in directional stiffness as the Lorentz Loads react through the structure are the primary issue to be resolved for fatigue fracture life.

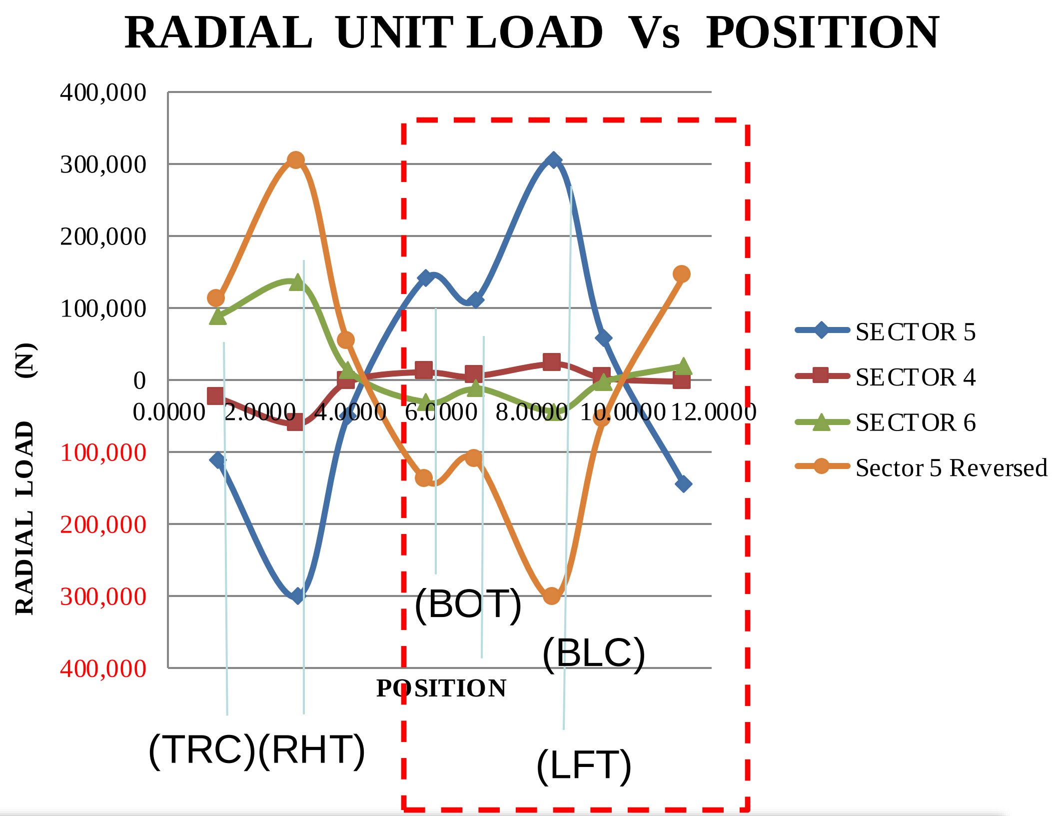
ELM LORENTZ LOAD VS POSITION

Critical Quadrant



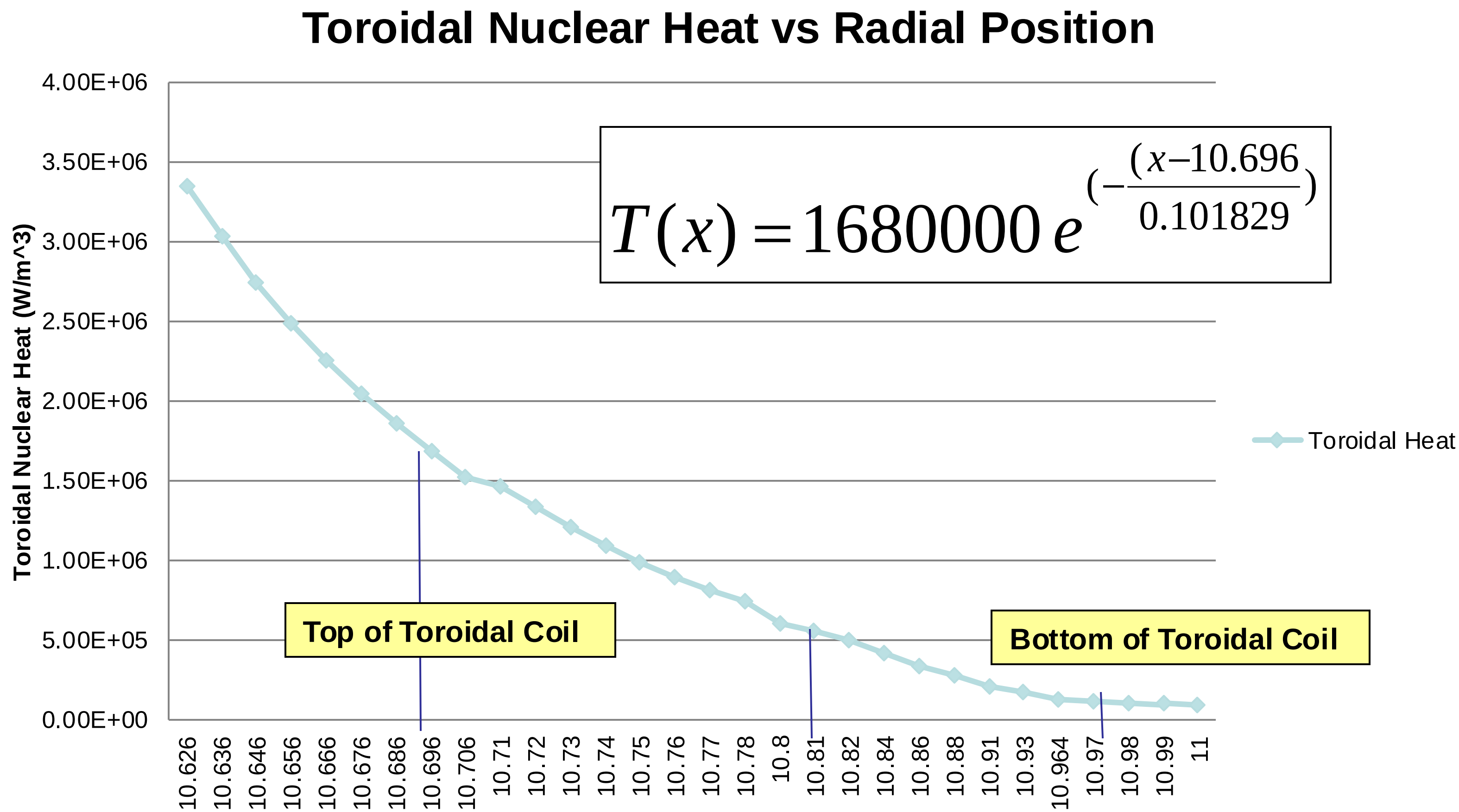
SECTOR 5 FE MODEL LOADS in GLOBAL COORDINATES

	Fx	Fy	Fz
ELM_MD_BOT	132,271	-31,397	-32,429
ELM_MD_BLC	130,406	-8,635	-41,265
ELM_MD_LFT	300,308	-10,272	7,491
OPPOSITE DIRECTION LOADING			
ELM_MD_BOT	-132,271	+31,397	+32,429
ELM_MD_BLC	-130,406	+8,635	+41,265
ELM_MD_LFT	-300,308	+10,272	-7,491



Applied Maximum Lorentz Loads For Stress Range Calculation

NUCLEAR HEAT FUNCTION - UPDATE

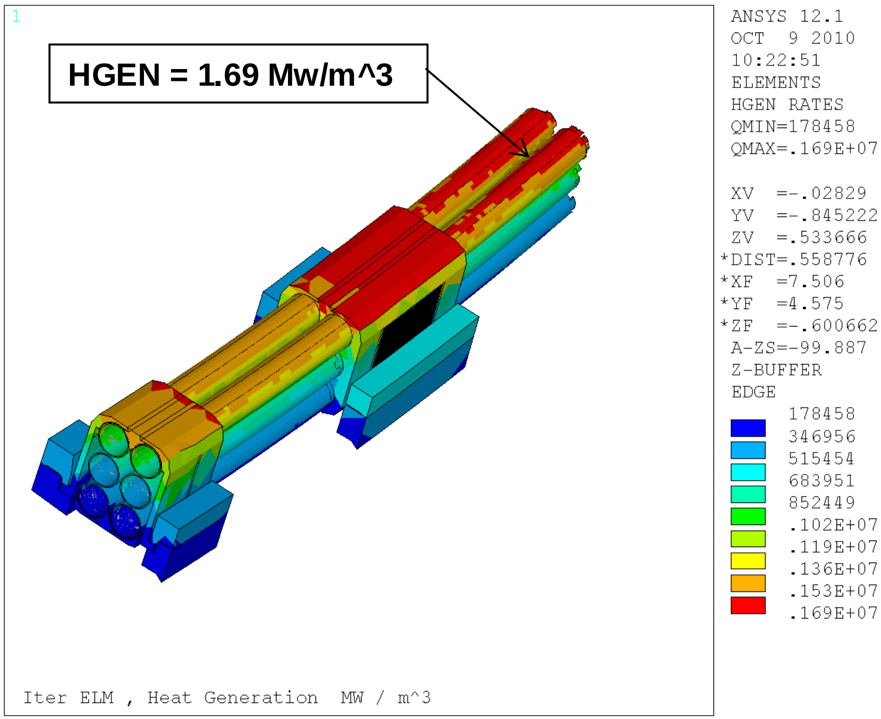


$$T(x) = 1680000\, e^{\left(-\frac{(x-10.696)}{0.101829}\right)}$$

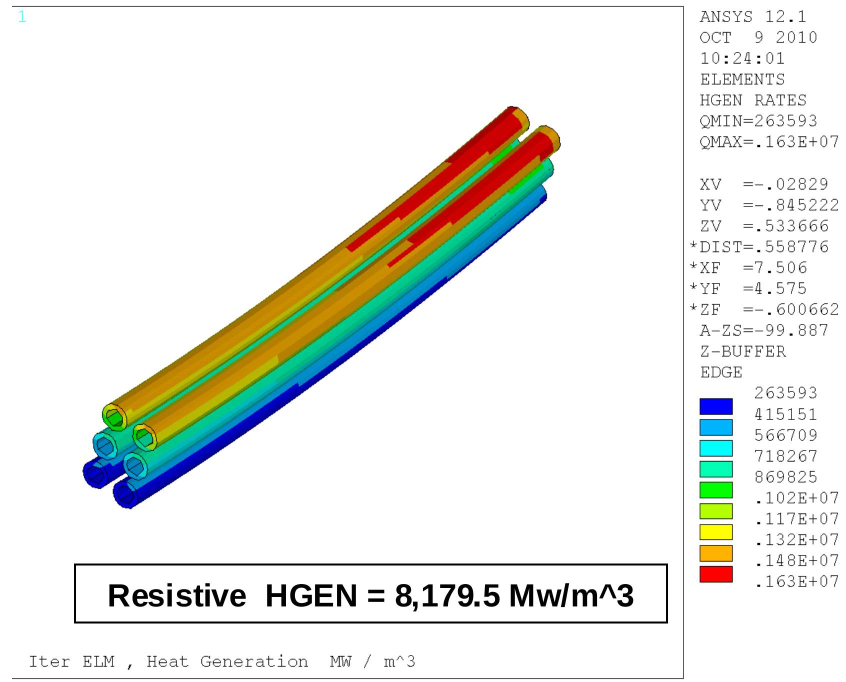
The Toroidal Data from University of Wisconsin Neutronics Team (7-22-10)
Adjusted and Fitted to the equation above to Match ELM Coil Geometry

TOROIDAL HEAT GENERATION

STAINLESS JACKETS

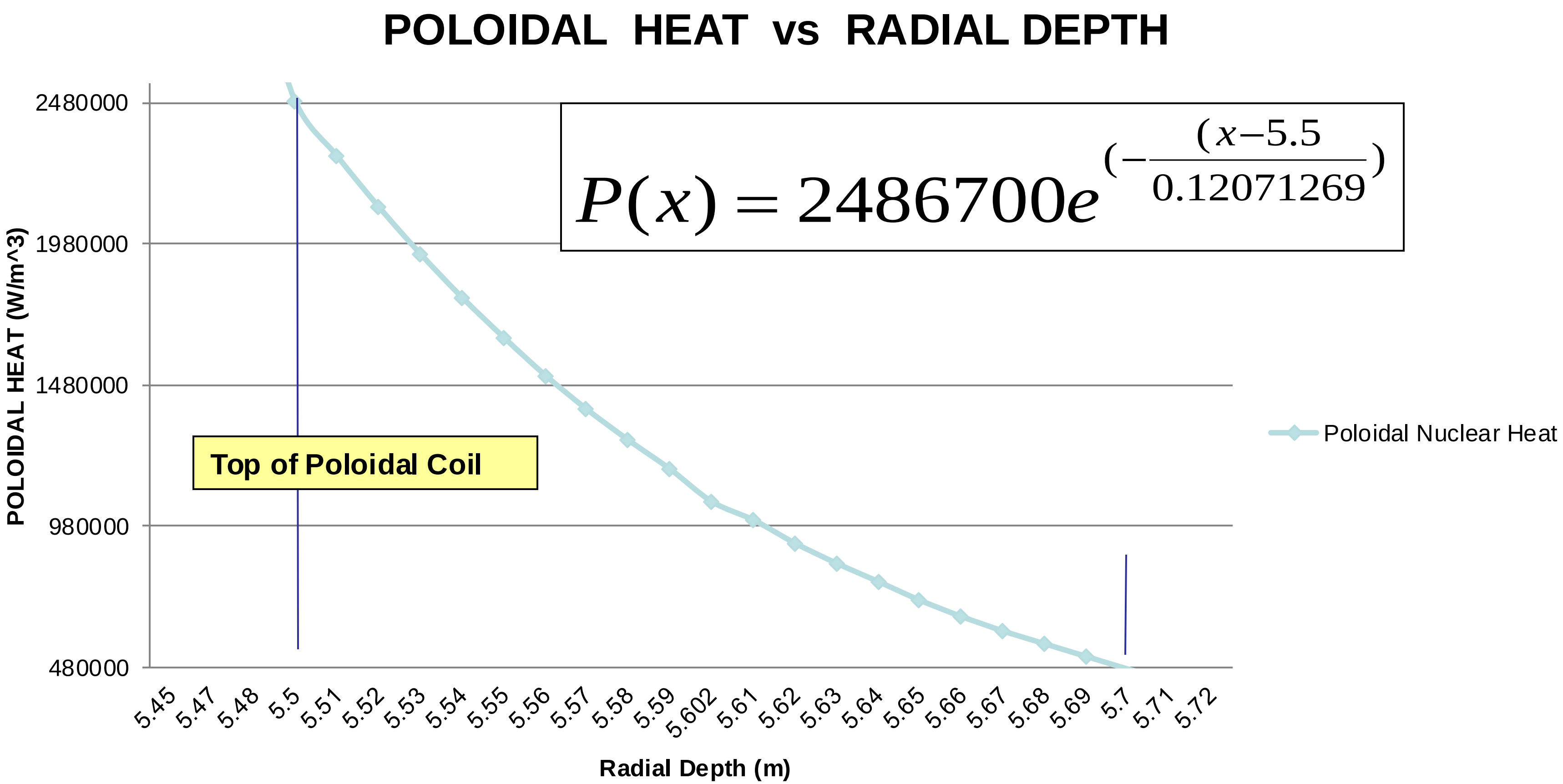


COPPER COIL



The Toroidal Data from University of Wisconsin Neutronics Team (7-22-10)
Heat Generation Contours Match Specified Equation

NUCLEAR HEAT FUNCTION - UPDATE

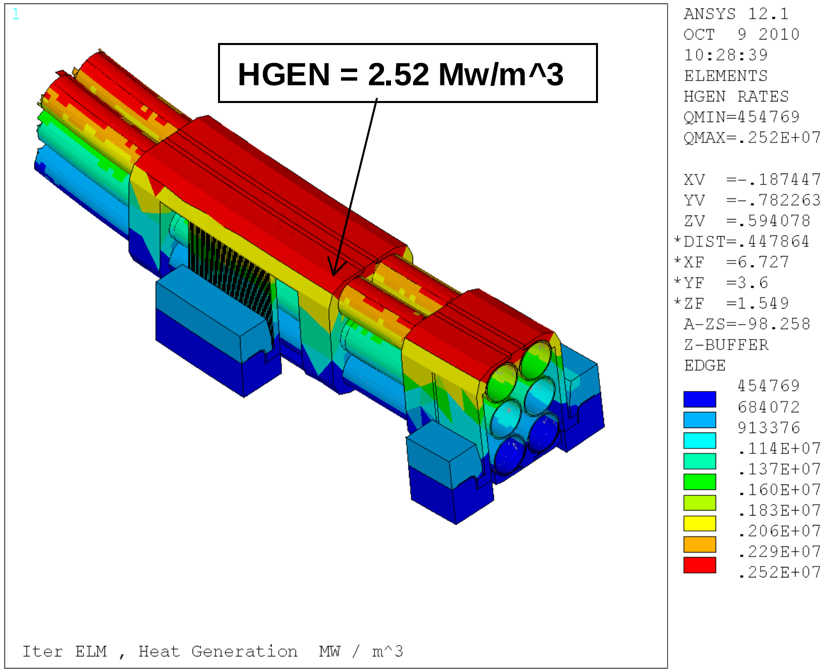


$$P(x) = 2486700e^{\left(-\frac{(x-5.5}{0.12071269}\right)}$$

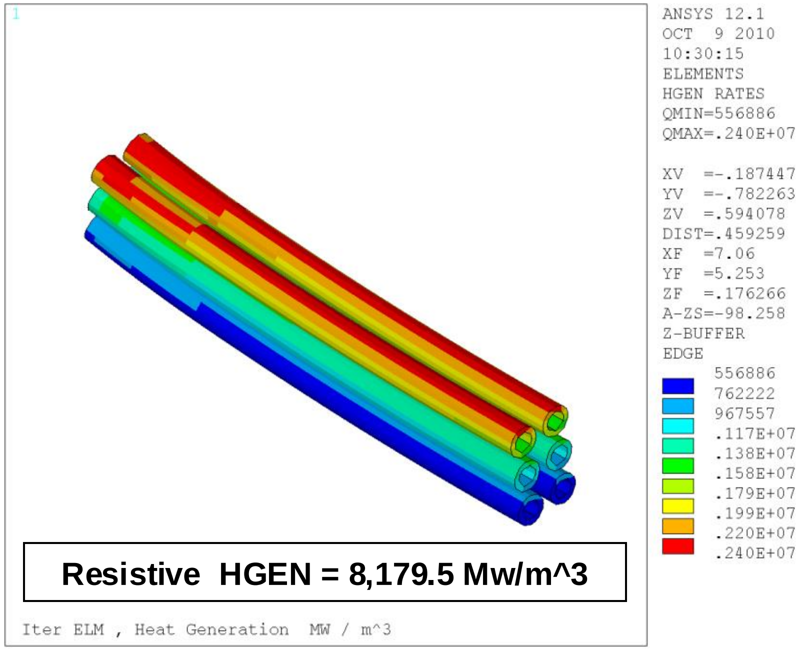
The Poloidal Data from University of Wisconsin Neutronics Team (7-22-10)
Adjusted and Fitted to the equation above to Match ELM Coil Geometry

POLOIDAL HEAT GENERATION

STAINLESS JACKETS

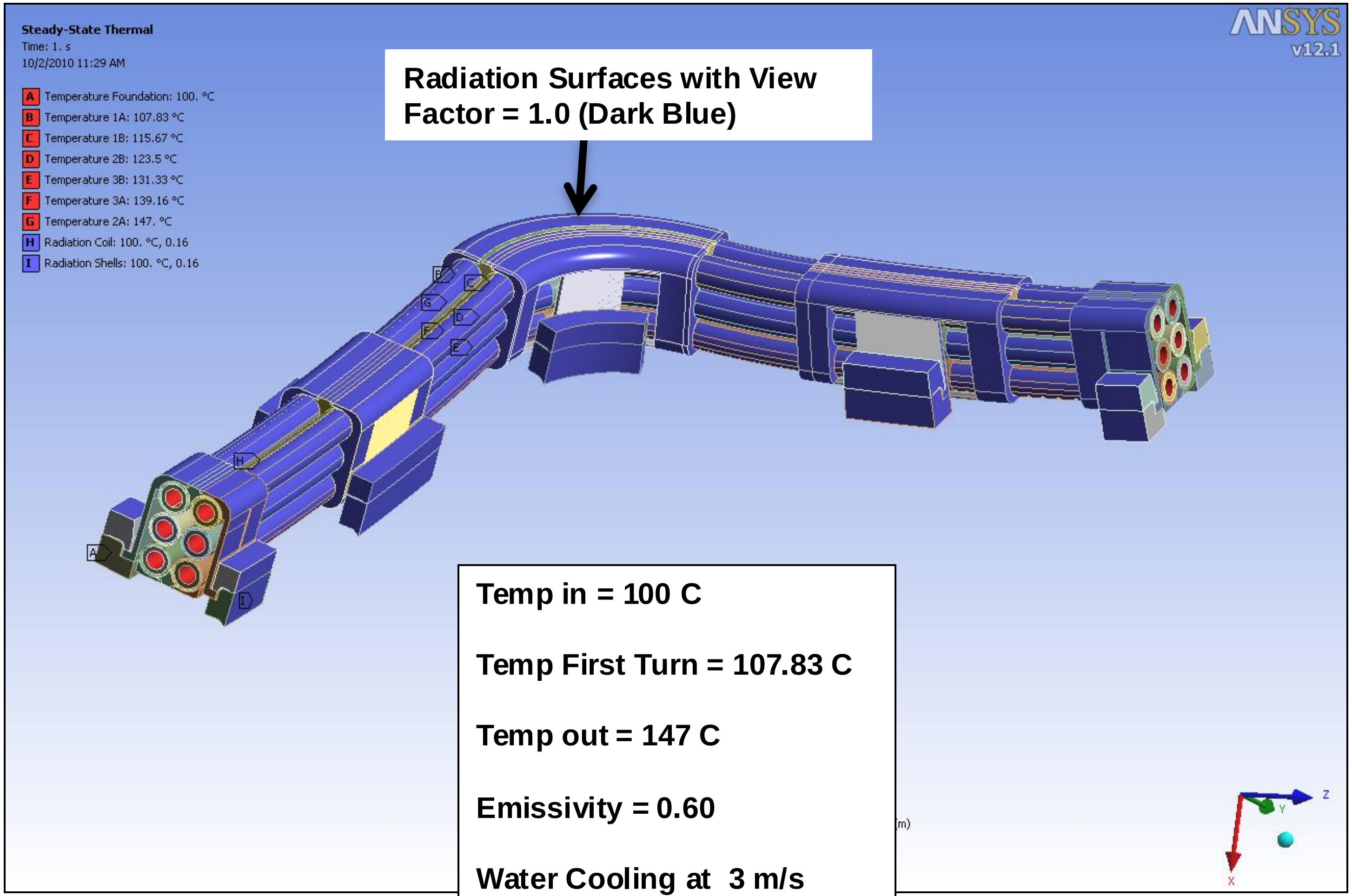


COPPER COIL



The Poloidal Data from University of Wisconsin Neutronics Team (7-22-10)
Heat Generation Contours Match Specified Equation

THERMAL BOUNDARY CONDITIONS



Radiation Surfaces with View Factor = 1.0 (Dark Blue)

Temp in = 100 C

Temp First Turn = 107.83 C

Temp out = 147 C

Emissivity = 0.60

Water Cooling at 3 m/s

The Thermal Boundary Conditions are Defined

RADIATION ASSUMPTIONS

$$Q_{i-j} = A_i F_{ij} \varepsilon \sigma (T_i^4 - T_j^4)$$

Where:

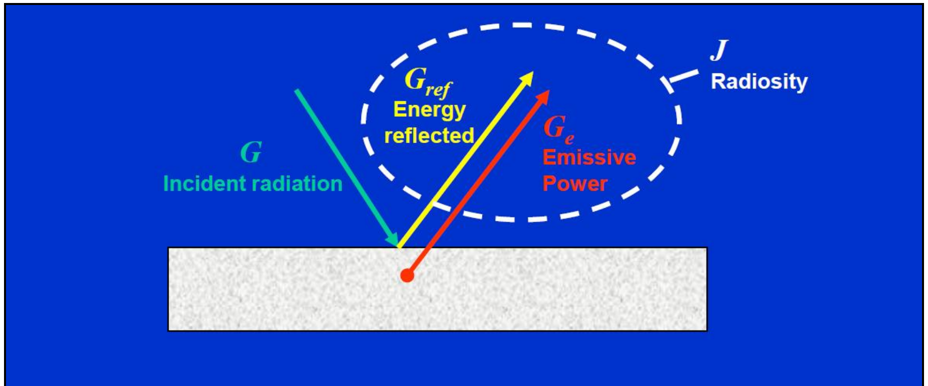
E = total emissive power

A = area of surface

ε = total, hemispherical emissivity of surface

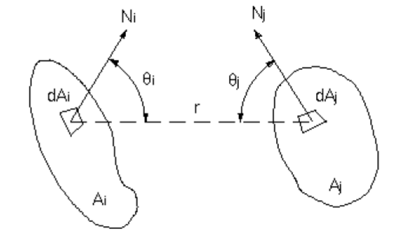
σ = Stefan - Boltzmann constant

T = absolute temperature of surface



Since ANSYS does not directly account for surface reflectivity, the radiosity and emissivity are assumed to be equivalent (E=J).

All Form / View Factors equal to 1.0



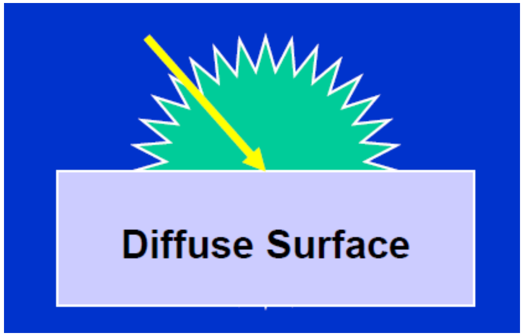
$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi r^2} \, d(A_j) \, d(A_i)$$

where:

A_i, A_j	=	area of surface i and surface j
r	=	distance between differential surfaces i and j
θ_i	=	angle between N_i and the radius line to surface $d(A_i)$
θ_j	=	angle between N_j and the radius line to surface $d(A_i)$
N_i, N_j	=	surface normal of $d(A_i)$ and $d(A_j)$

Incident Radiation is very small from 100 C Far Field

Emissivity is a Hemispherical Average
Across all wavelengths and directions



316 Stainless and 718 Inconel Emissivity

316 STAINLESS

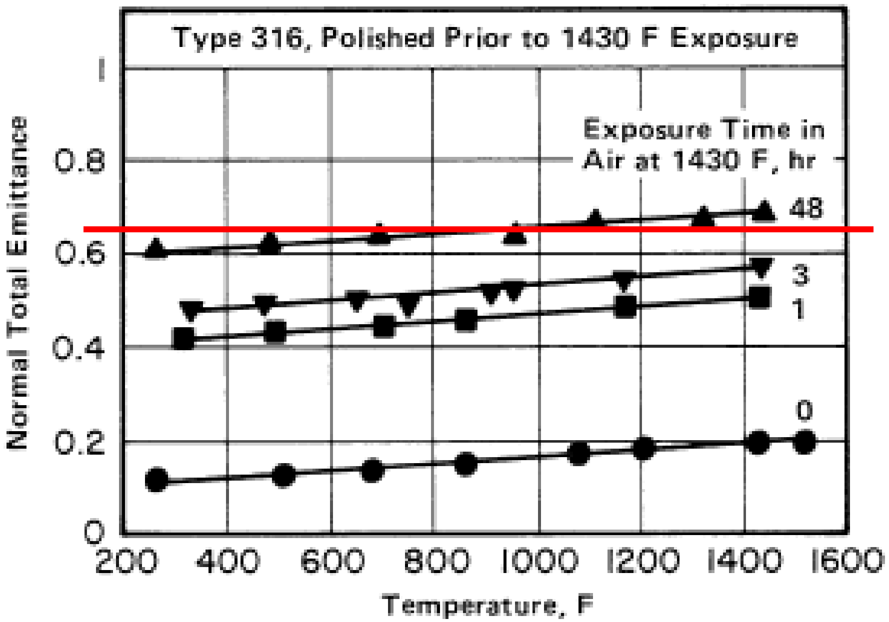
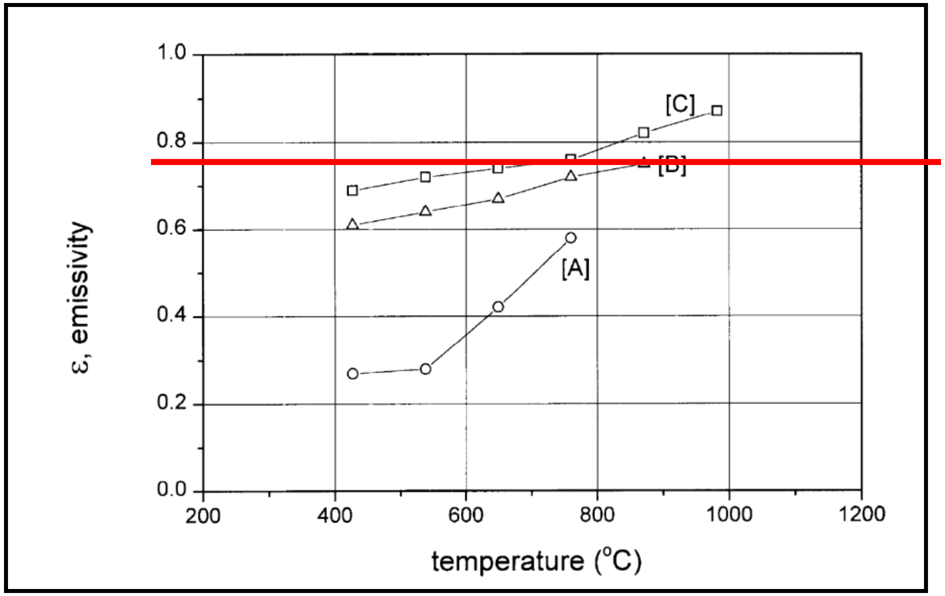


FIGURE 2.0242. EFFECTS OF TEMPERATURE AND PRE-OXIDATION ON EMITTANCE (60)

Ref: Aerospace Structural Metals Handbook June 1988

718 Inconel



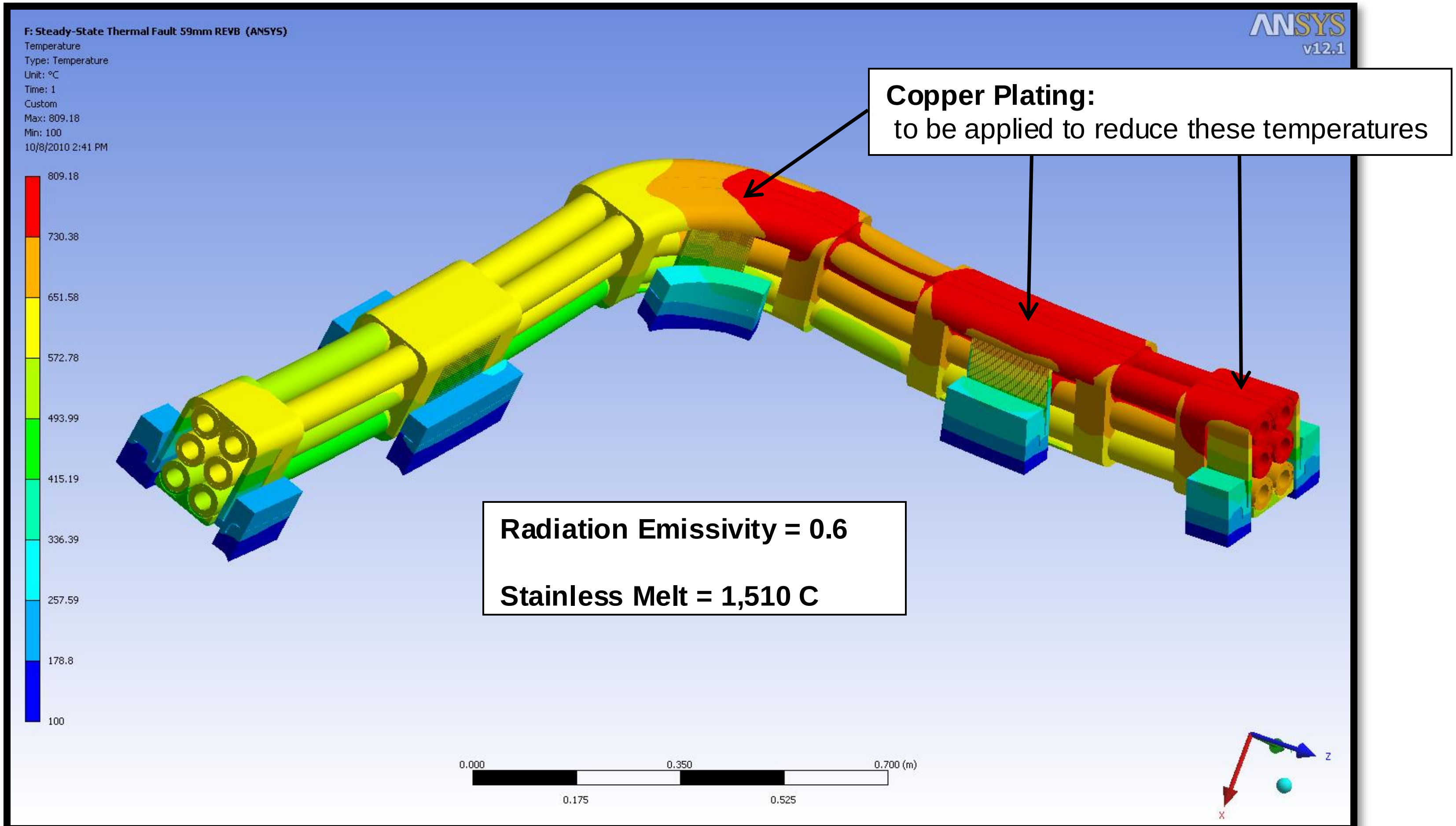
A=As received
B = As received & Oxidized for 15 minutes
C = Sandblasted & Oxidized for 15 minute

Ref: BrookHaven National Laboratory DOE Contract Sep 1999

ELM FAULT TEMPERATURE CONDITIONS

Fault Temperatures

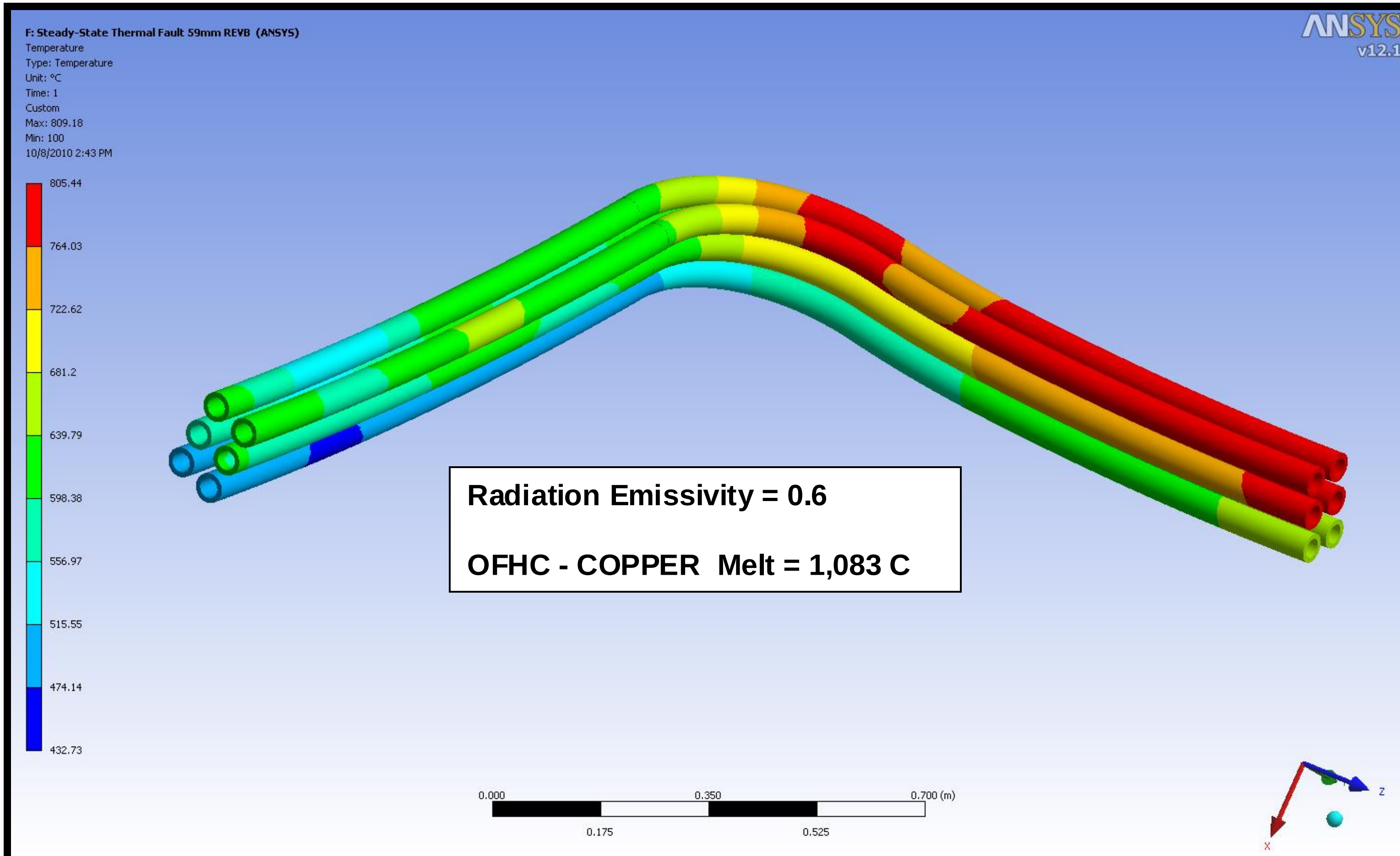
No Water Cooling or Resistive Heat



**The Max Fault Temperature is 809 C with the highest published Emissivity
Copper Plating is planned to reduce these temperatures further**

Fault Temperatures

No Water Cooling or Resistive Heat

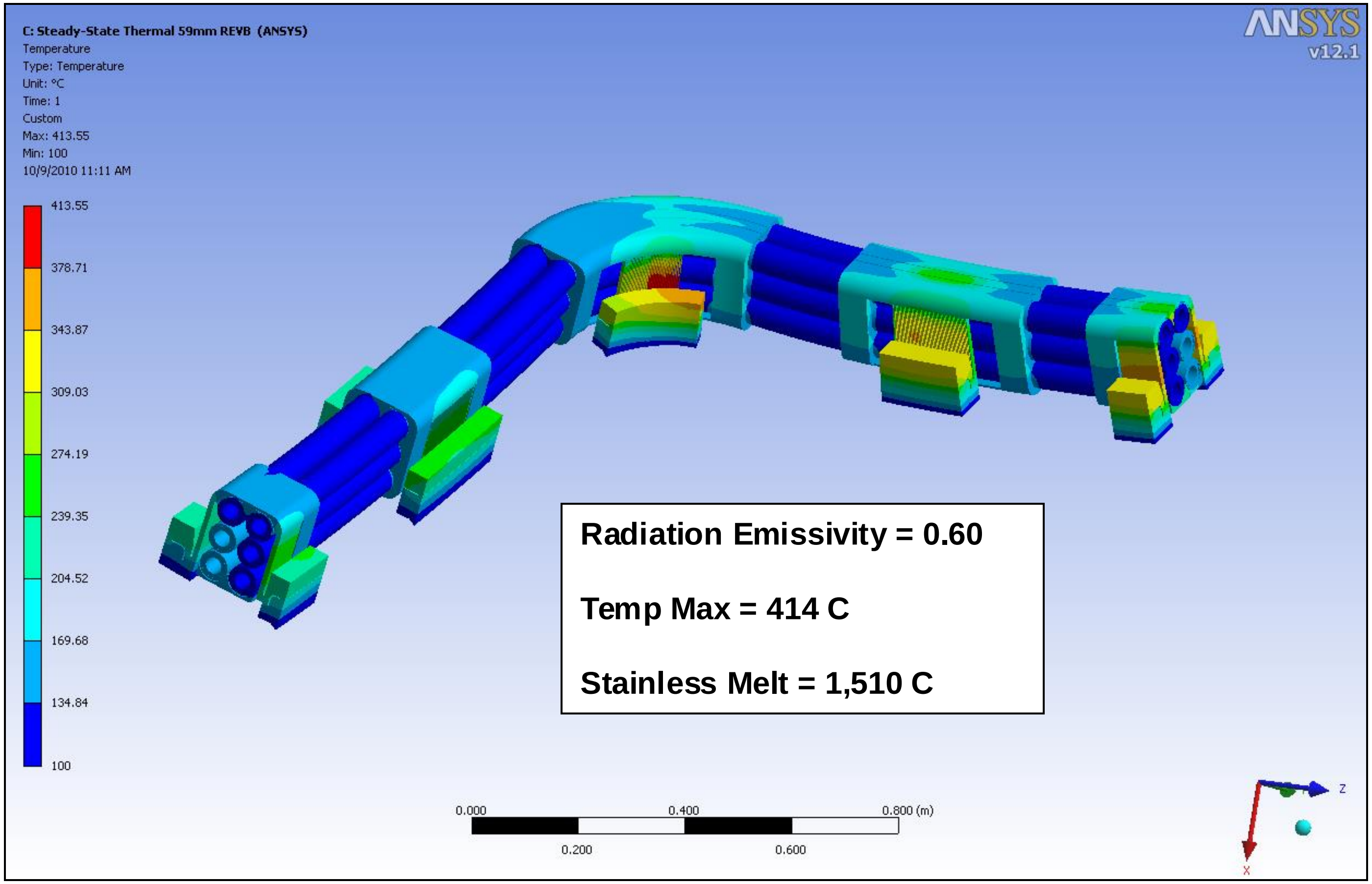


The Max Fault Temperature on the Copper is 805 C with the highest published Emissivity

ELM STRESS

STEADY STATE – BASIC INDUCTIVE SCENARIO

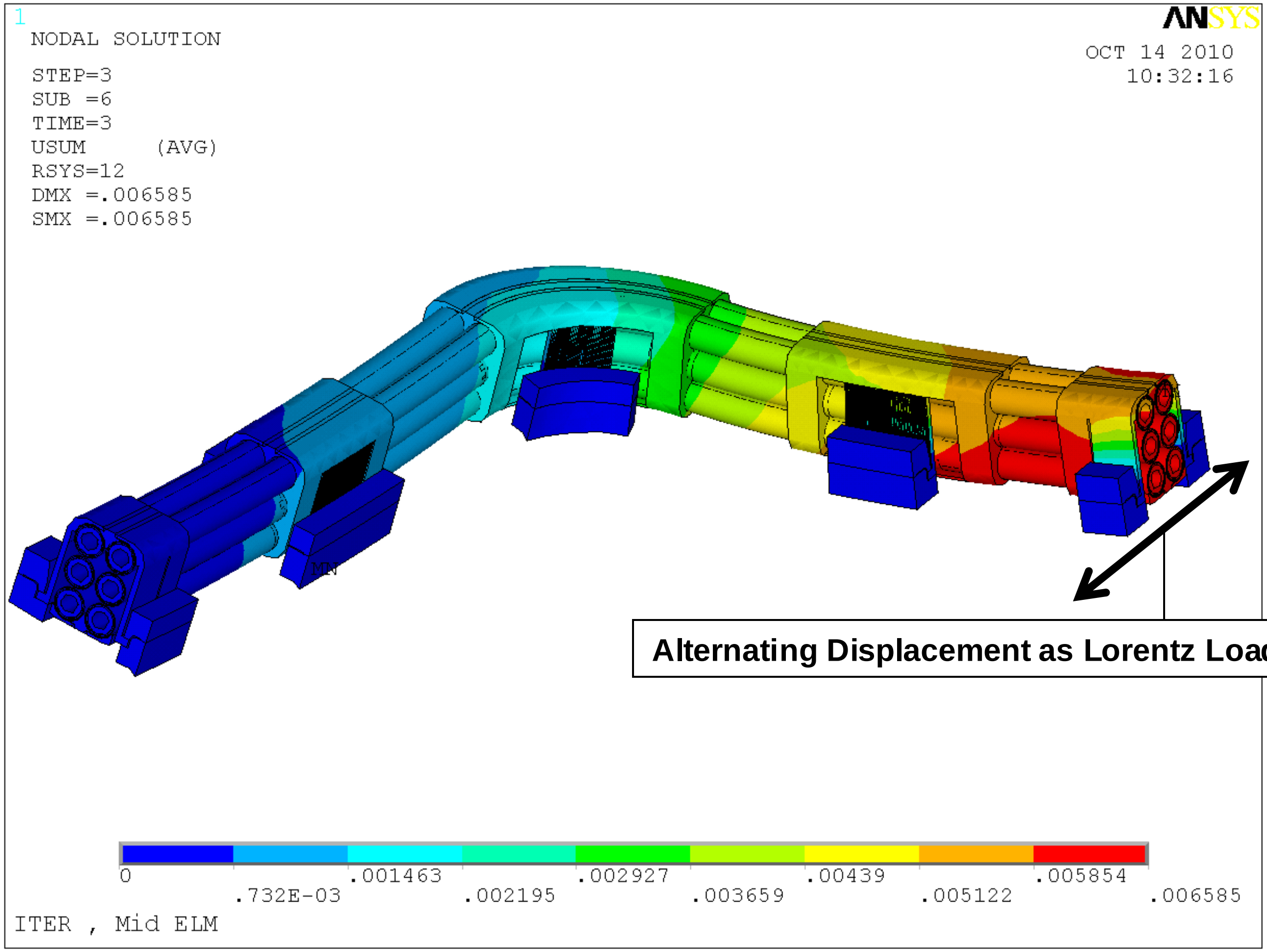
ELM TEMPERATURES
Steady State Basic Inductive Scenario with Water Cooling at 3 m/sec



The Max Temperature is 413.5 C with the Increased Emissivity Results in a drop of 38.5 degrees compared to emissivity = 0.16

Steady State

Thermal + Pressure + Lorentz (UP) Displacements



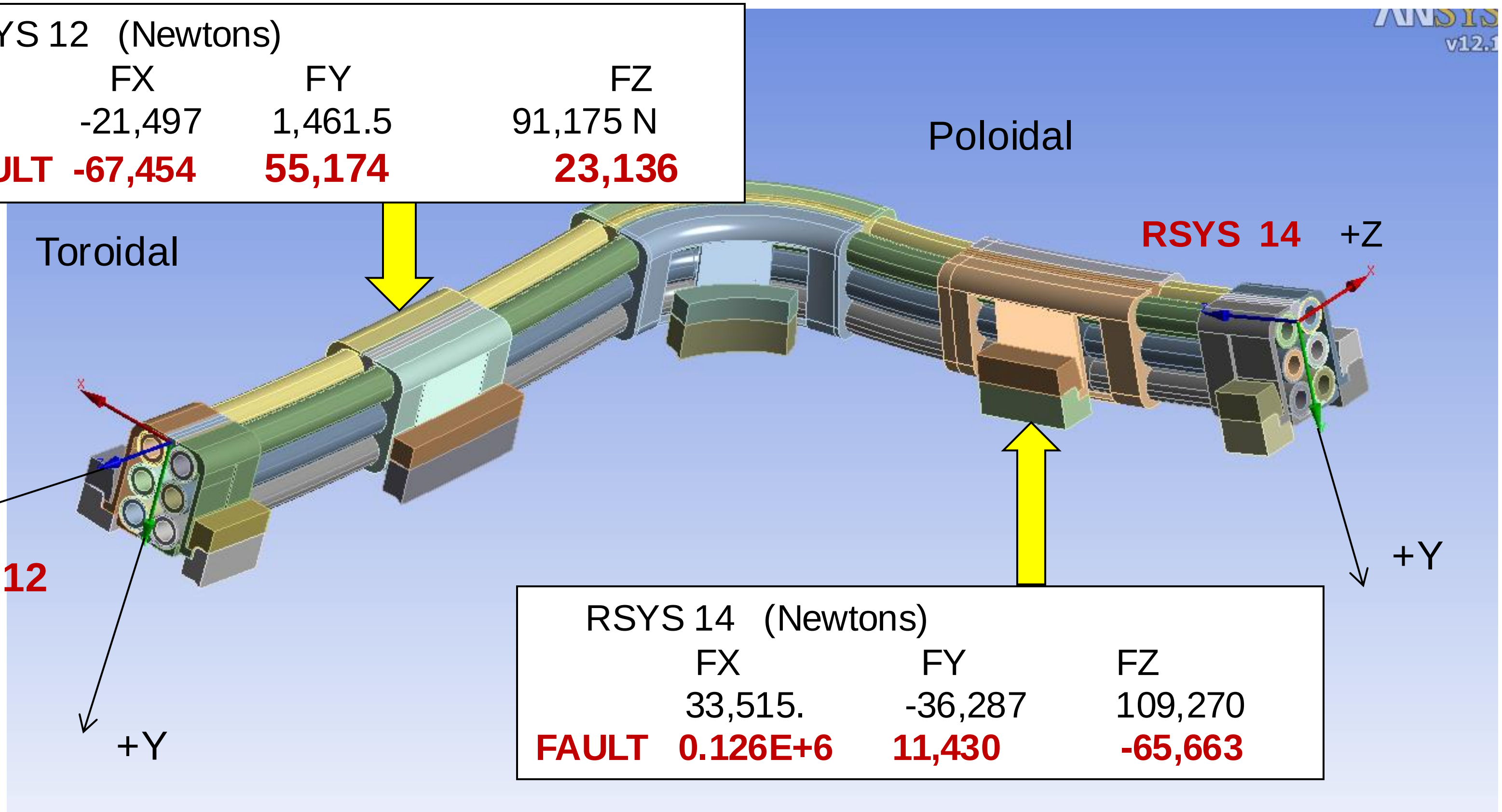
Alternating Displacement as Lorentz Load Reverses

The Displacement on the Poloidal Leg Alternates 6.5 millimeters As the Lorentz Load Reverses

Support Reaction Loads Comparison Operating & Fault Temperatures

RSYS 12 (Newtons)

	FX	FY	FZ
	-21,497	1,461.5	91,175 N
FAULT	**-67,454**	**55,174**	**23,136**



RSYS 14 (Newtons)

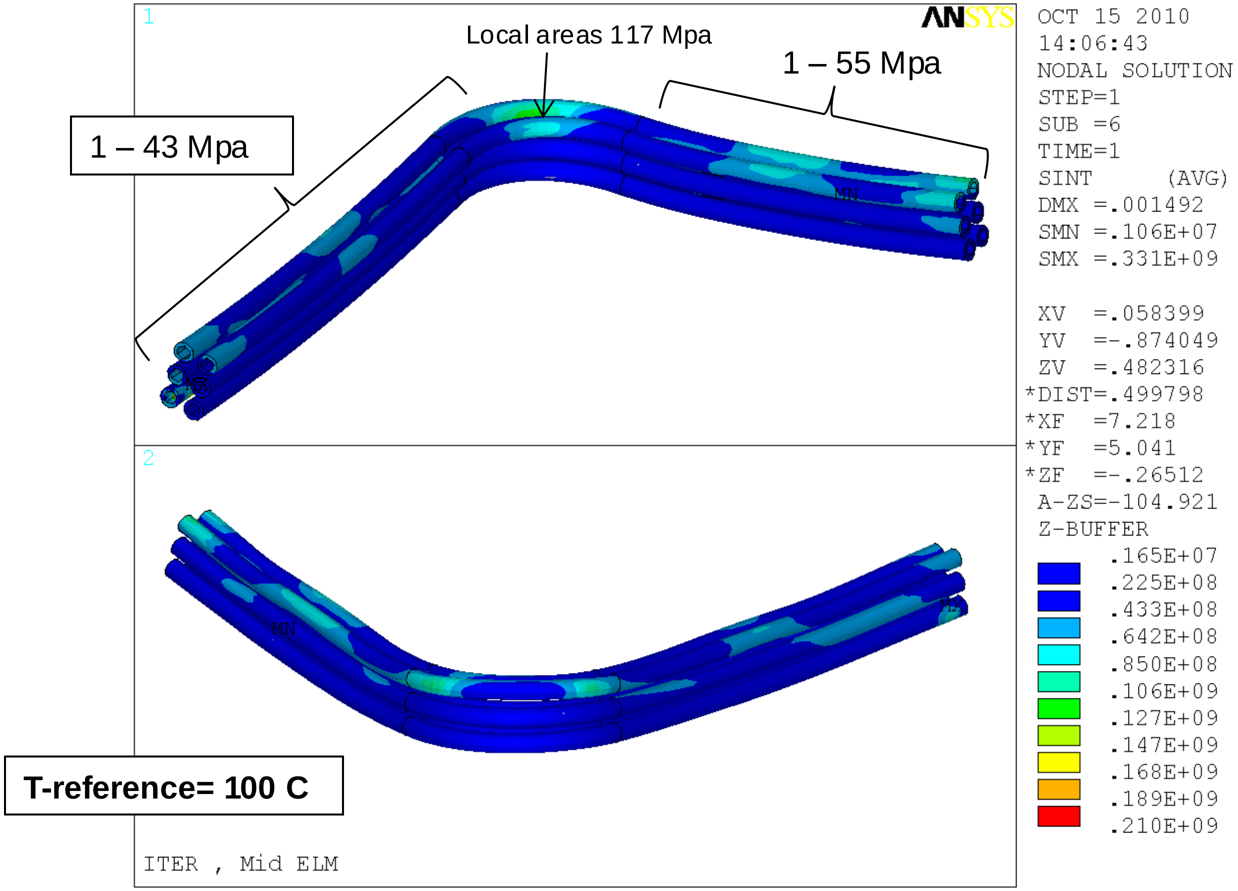
	FX	FY	FZ
	33,515.	-36,287	109,270
FAULT	**0.126E+6**	**11,430**	**-65,663**

- Fault Temperatures exclude Lorentz or Pressure Loads

Reaction Loads Increase Significantly During Fault Temperatures
Loads are for only the two brackets indicated

Steady State

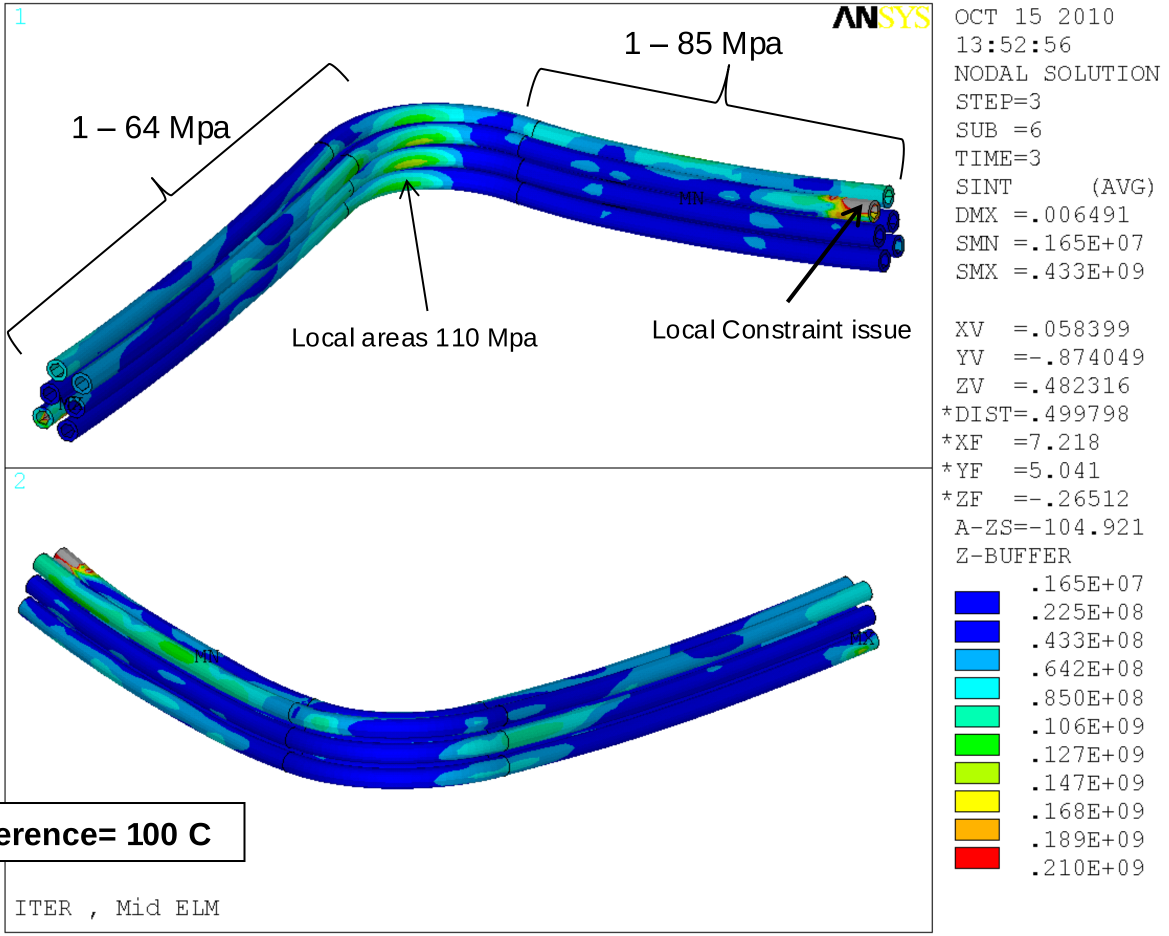
Thermal + Pressure Tresca Stress



The Tresca Stress is less than 64 Mpa in most regions of the coil
Localized regions less than 117 Mpa

Steady State

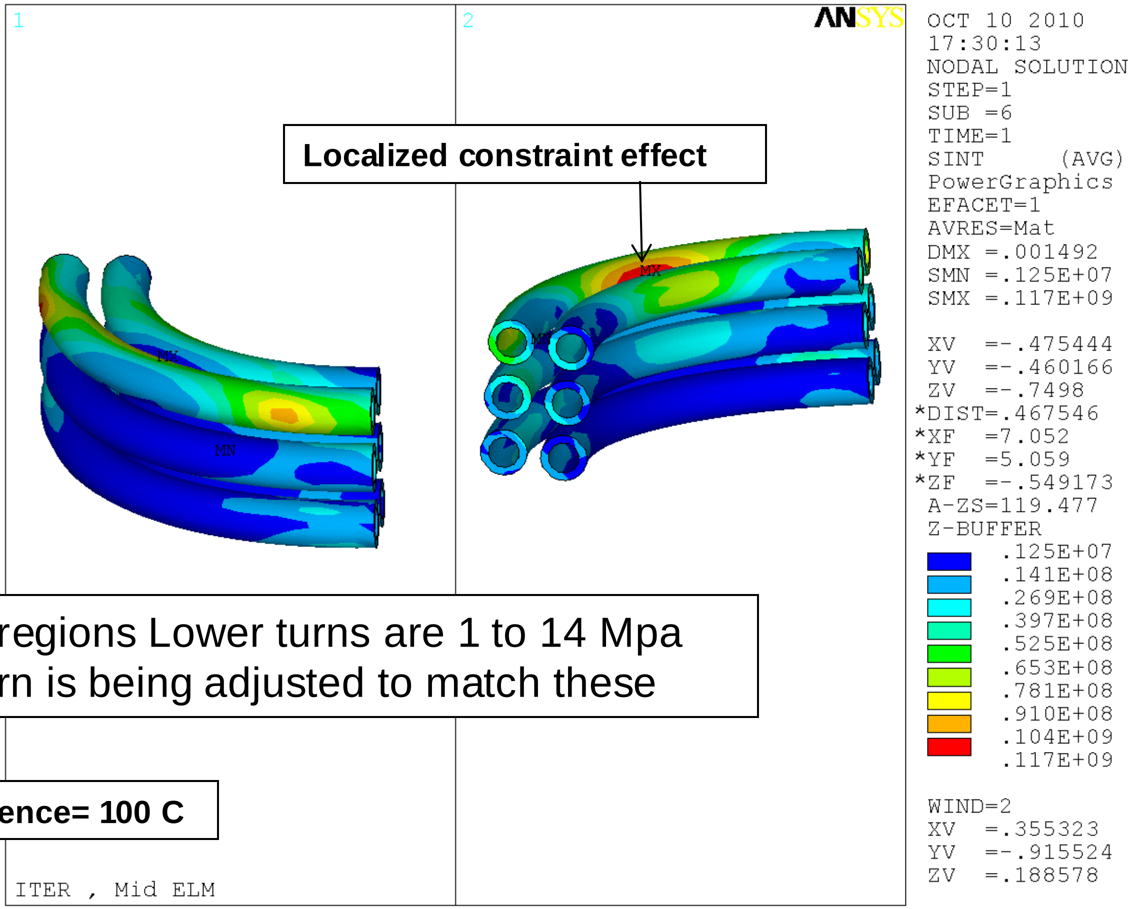
Thermal + Pressure + Lorentz Load Tresca Stress



T-reference= 100 C

The Tresca Stress is less than 64 Mpa in most regions of the coil
Localized regions approximately 110 Mpa

Steady State
Thermal + Pressure Stress



Most regions Lower turns are 1 to 14 Mpa
Top turn is being adjusted to match these

T-reference= 100 C

The Corner Stresses to Thermal + Pressure Loading is very low

Steady State

Thermal + Pressure + Lorentz Load Tresca Stress

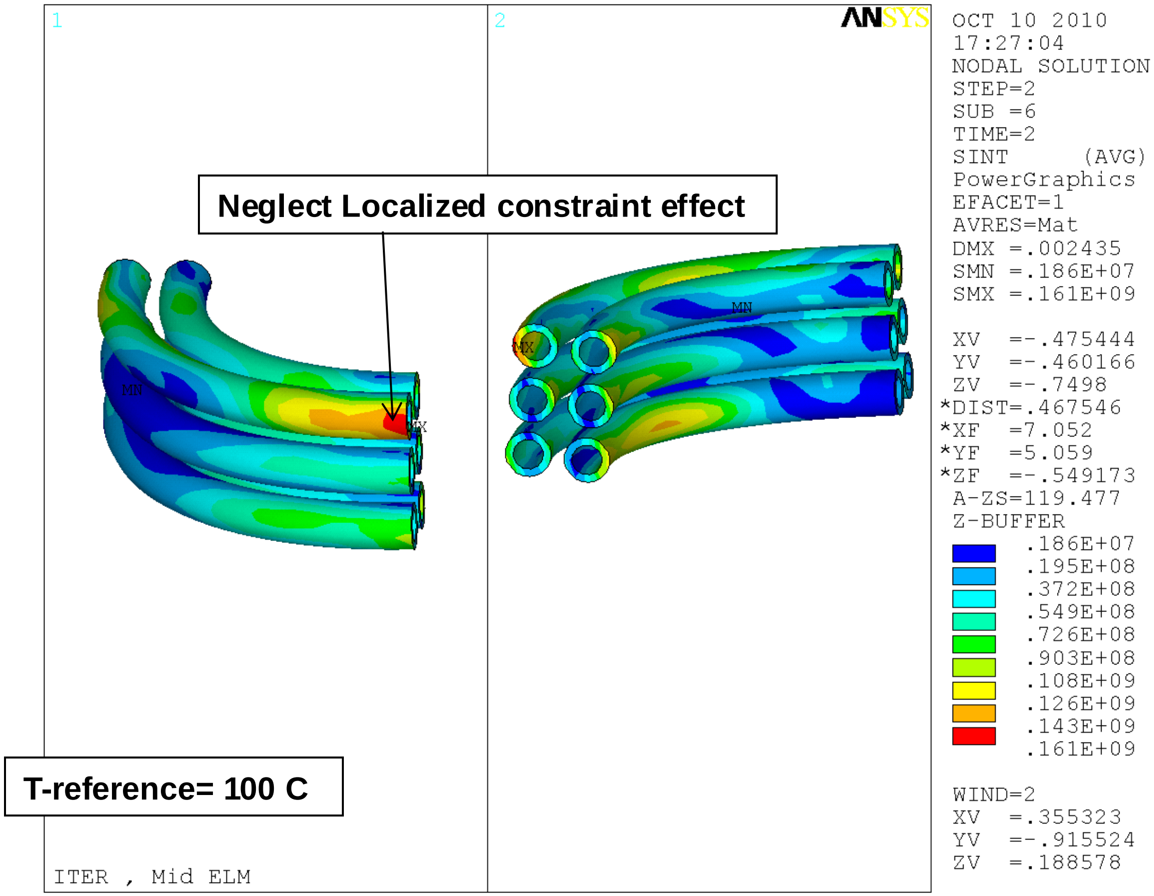


Table 2.2 Tensile Property (average) [1]

Material	Yield strength (MPa)	UTS (MPa)	Average over
Low strength (L)	78	248	3
Intermediate strength (I)	199.4	318.6	3
High strength (H)	297	405.3	5

Table 2.5 Endurance limit [4]

Material	Endurance (MPa)
Low strength (L)	~ 74
Intermediate strength (I)	~ 96
High strength (H)	~ 122

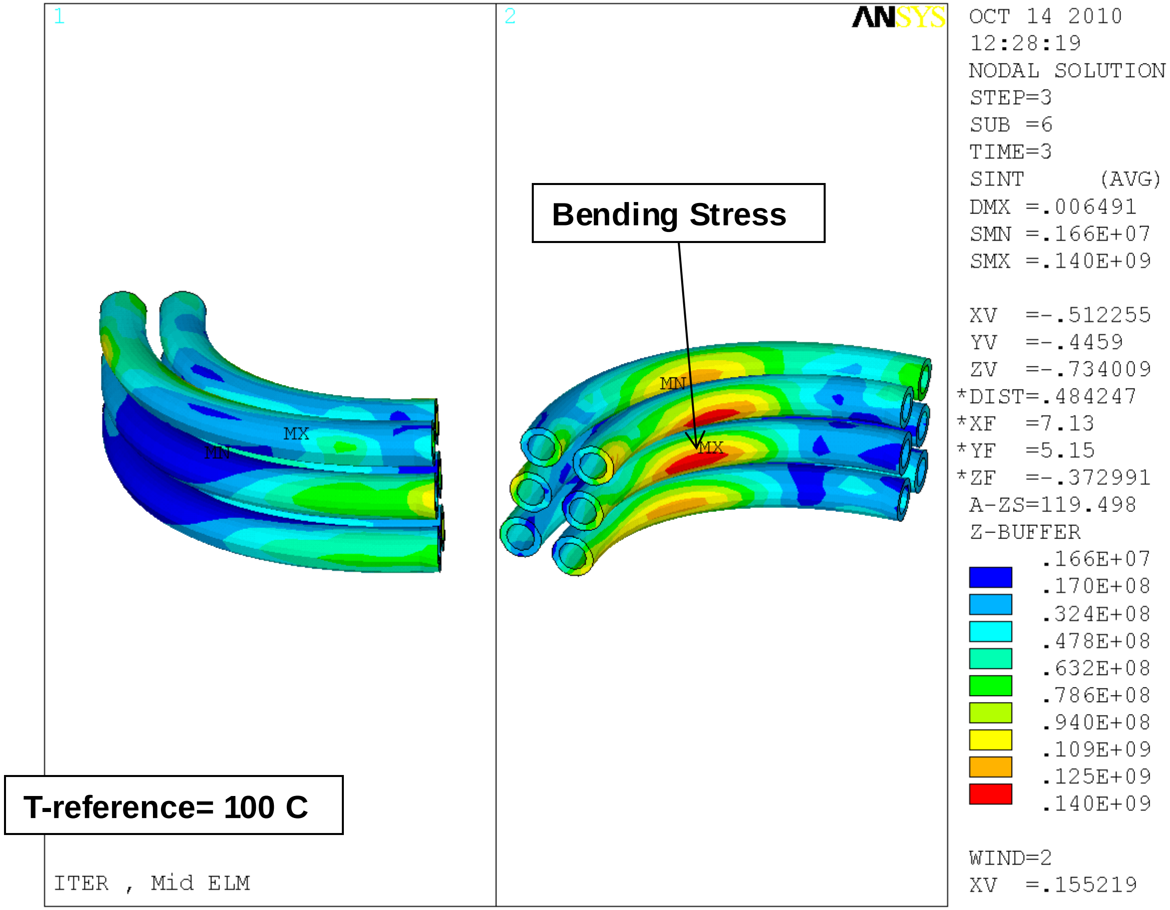
$$M_{FTY} = \frac{(\frac{2}{3})(\beta_s)F_{ty}}{\sigma} = \frac{\frac{2}{3}(\frac{3}{2})(235)}{140} - 1 = +\underline{\underline{0.67}}$$

$\beta_S = 1.5$ **Bending shape factor**

The Tresca Stress is less than 54 Mpa in most regions of the coil
The Static Limit Margin is Positive

Steady State

Thermal + Pressure + Lorentz Load Up Tresca Stress



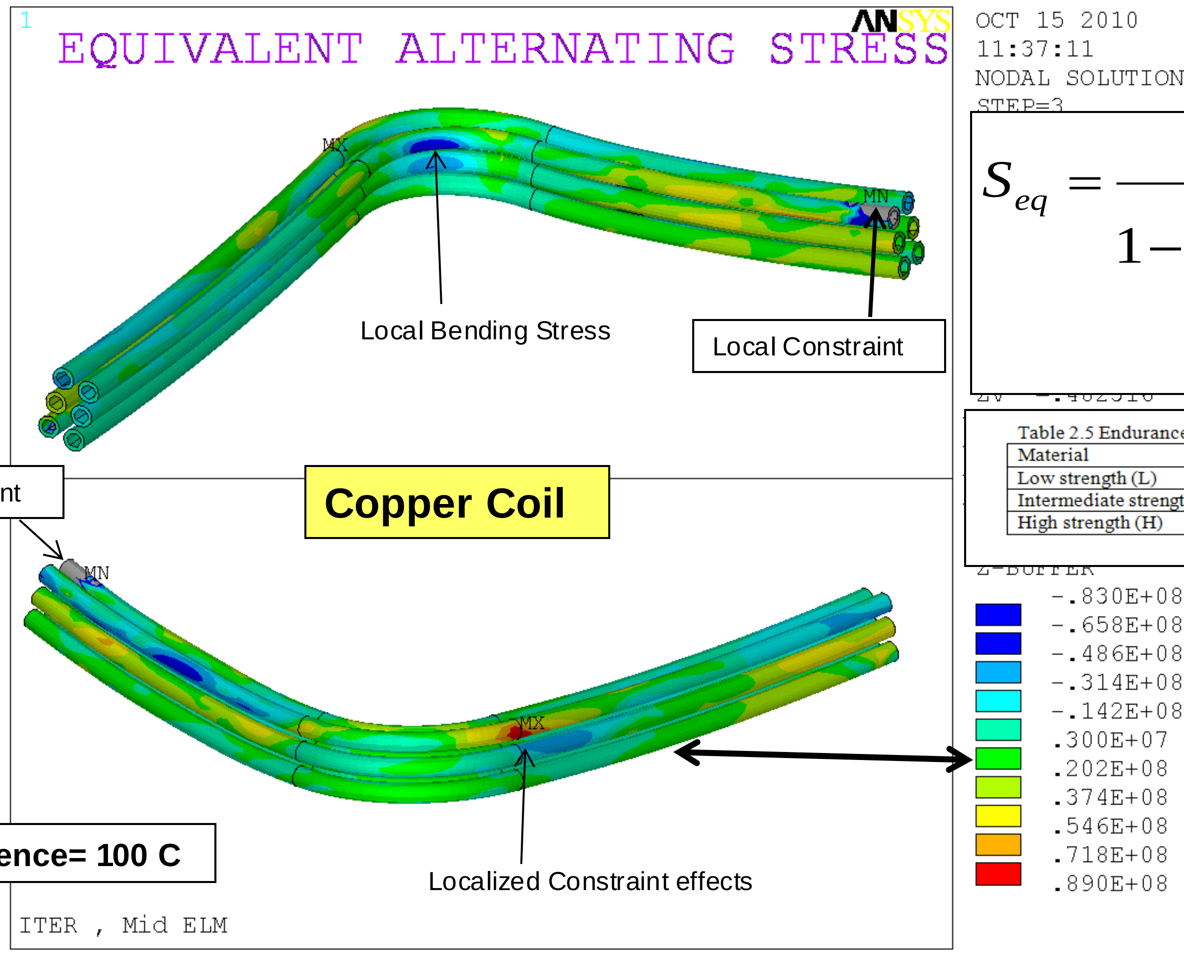
$$M_{FTY} = \frac{(\frac{2}{3})(\beta_s)F_{ty}}{\sigma} = \frac{\frac{2}{3}(\frac{3}{2})(235)}{140} - 1 = +\underline{\underline{0.67}}$$

$\beta_S = 1.5$ **Bending shape factor**

The Tresca Stress is less than 78 Mpa in most regions of the coil
The Static Limit Margin is Positive

FATIGUE RESULTS

NSTX – Equivalent Alternating Stress



$$S_{eq} = \frac{S_{alt}}{1-\left(\frac{S_{mean}}{S_u}\right)}$$

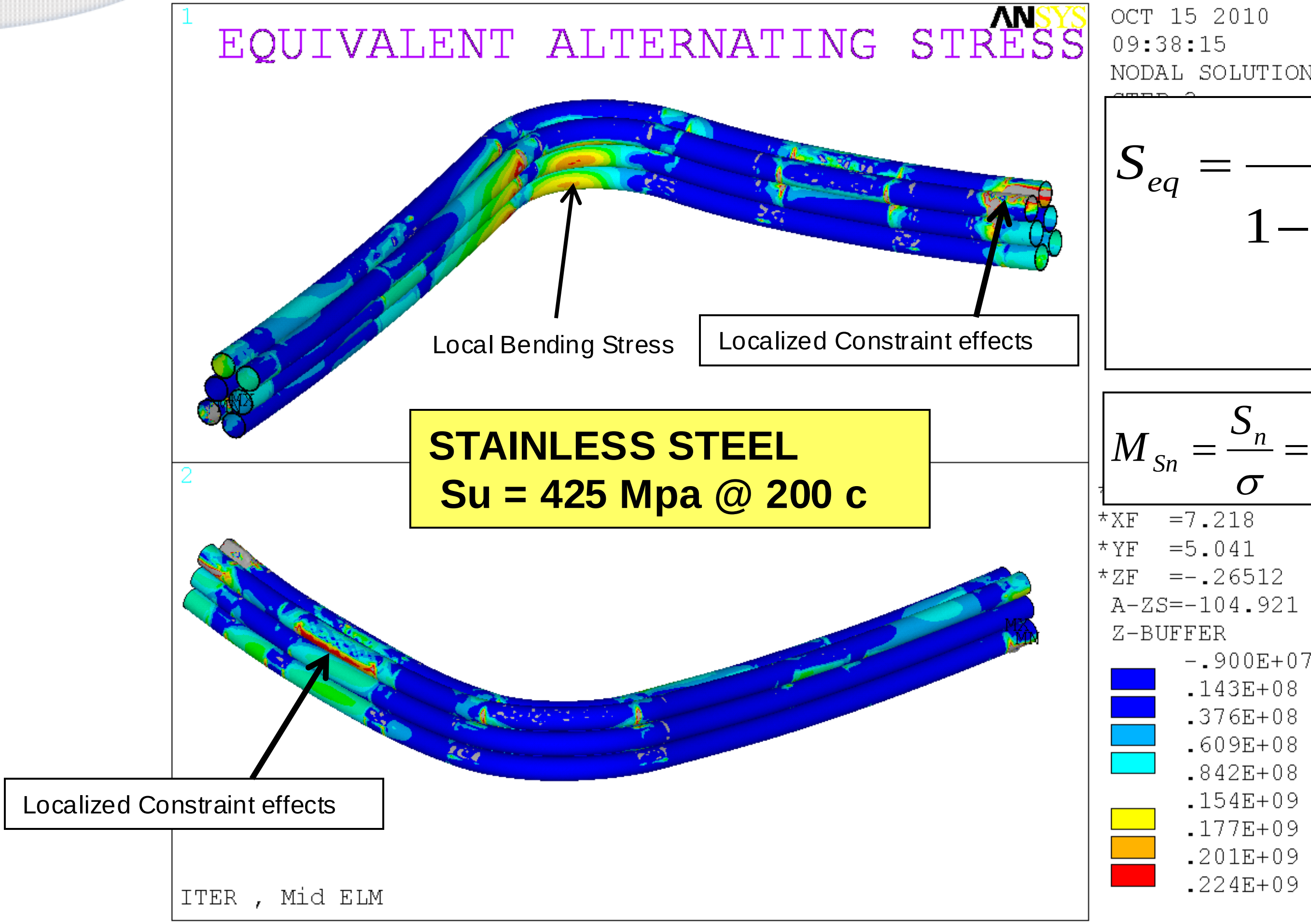
Table 2.5 Endurance limit [4]

Material	Endurance (MPa)
Low strength (L)	~ 74
Intermediate strength (I)	~ 96
High strength (H)	~ 122

$$M_{Sn} = \frac{S_n}{\sigma} = \frac{96}{89} - 1 = +0.078$$

The NSTX Equivalent Alternating Stress on the Coil is approximately 20 Mpa
Fatigue Initiation life is within the required limits

NSTX – Equivalent Alternating Stress

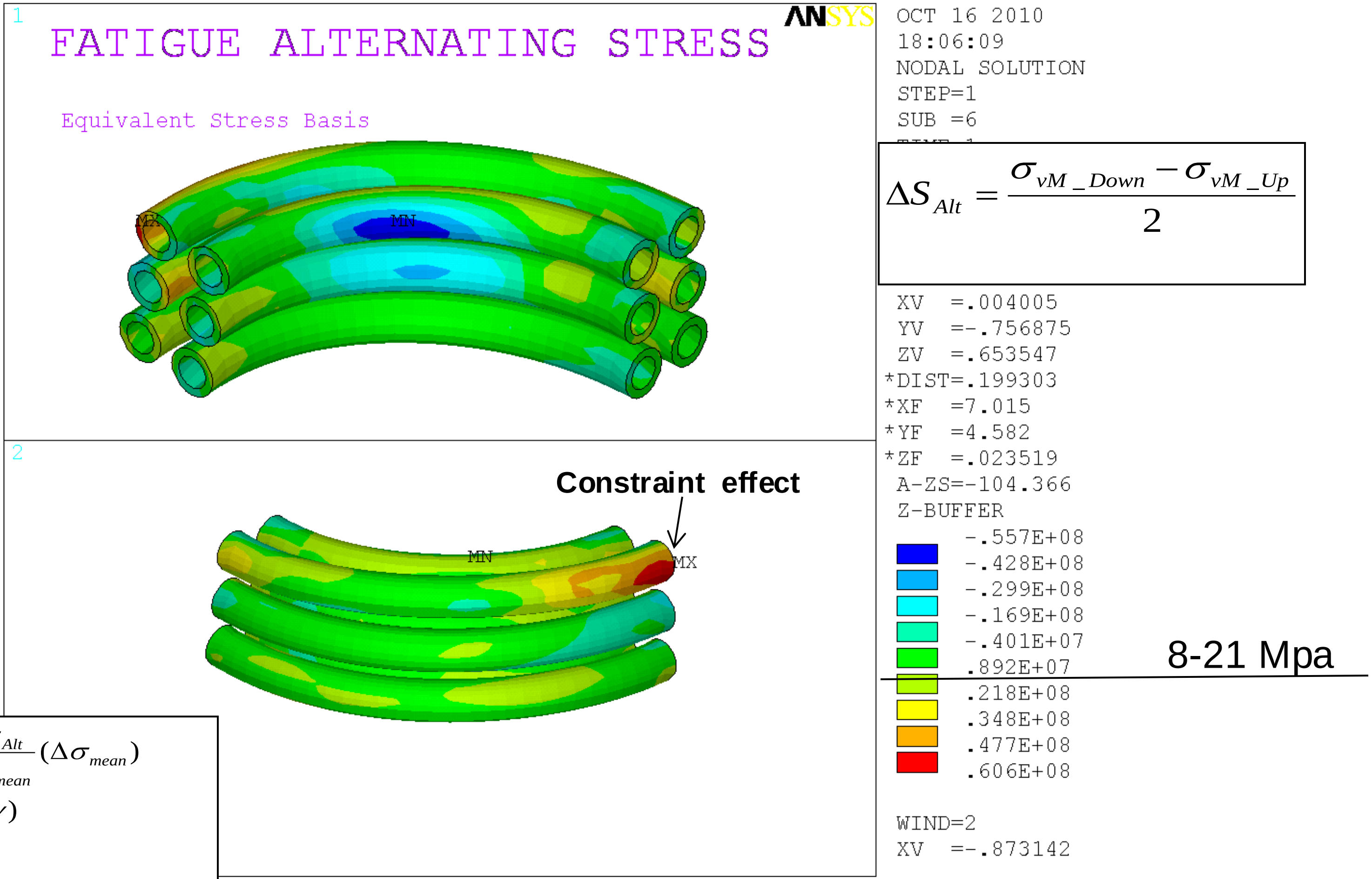


$$S_{eq} = \frac{S_{alt}}{1-\left(\frac{S_{mean}}{S_u}\right)}$$

$$M_{Sn} = \frac{S_n}{\sigma} = \frac{128}{84.2} - 1 = +0.52$$

The NSTX Equivalent Alternating Stress on the Stainless Jackets is approximately 37 Mpa across most regions with a positive Fatigue Initiation Life

Alternating Stress



$$\Delta S_{Alt} = \frac{\sigma_{vM\_Down} - \sigma_{vM\_Up}}{2}$$

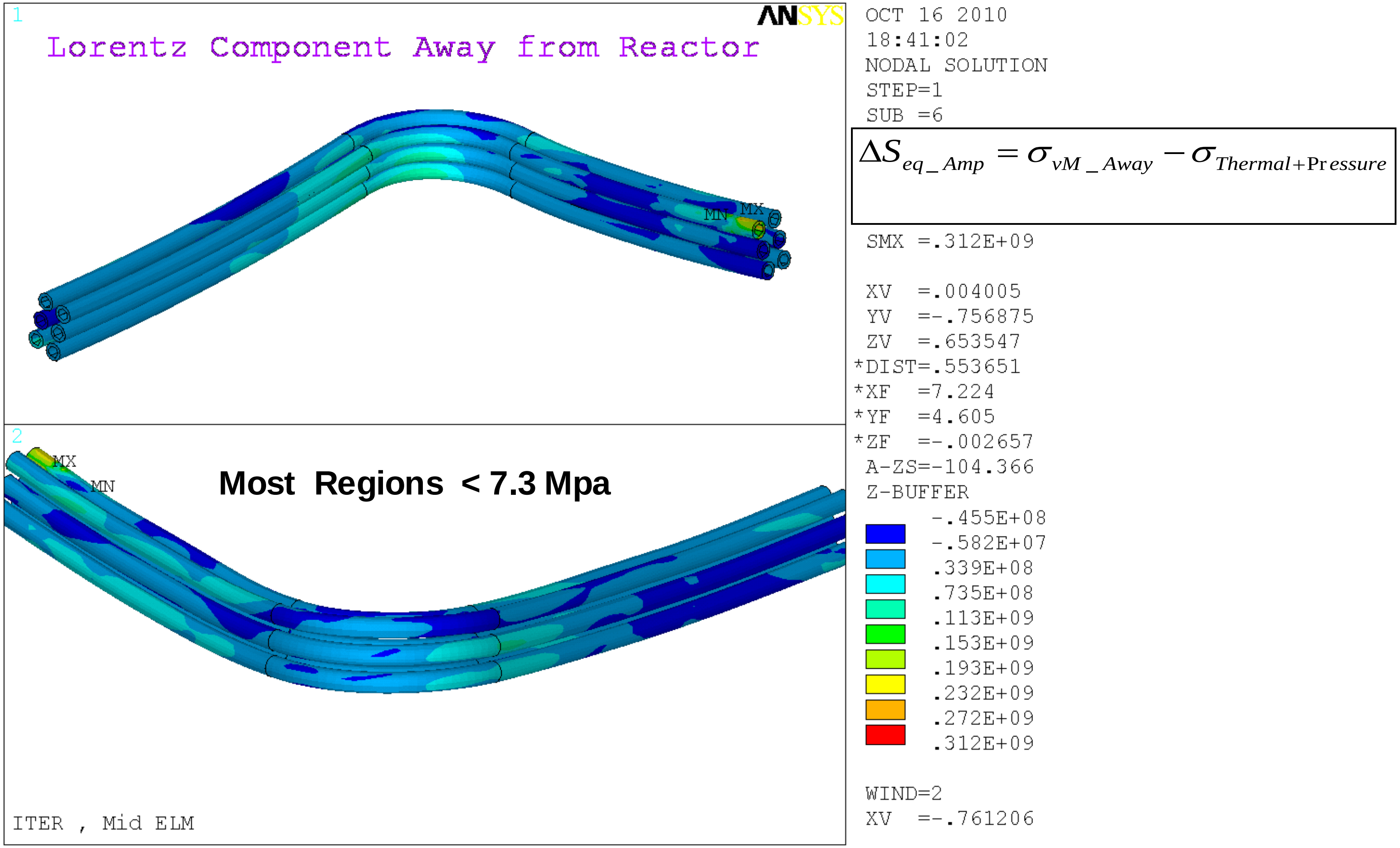
$$\Delta\sigma_{Alt} = \sigma_{Alt\_Old} - \frac{\sigma_{Alt}}{\sigma_{mean}}(\Delta\sigma_{mean})$$

$$\Delta\sigma_{Alt} = \sigma_{Alt\_Old}(1-\gamma)$$

$\gamma =$ **Mean Stress Reduction Fraction**

The Fracture Fatigue Life is Dependent on a Max Lorentz Amplitude of 10 Mpa
Reducing the mean (thermally) driven stress will reduce the alternating stress

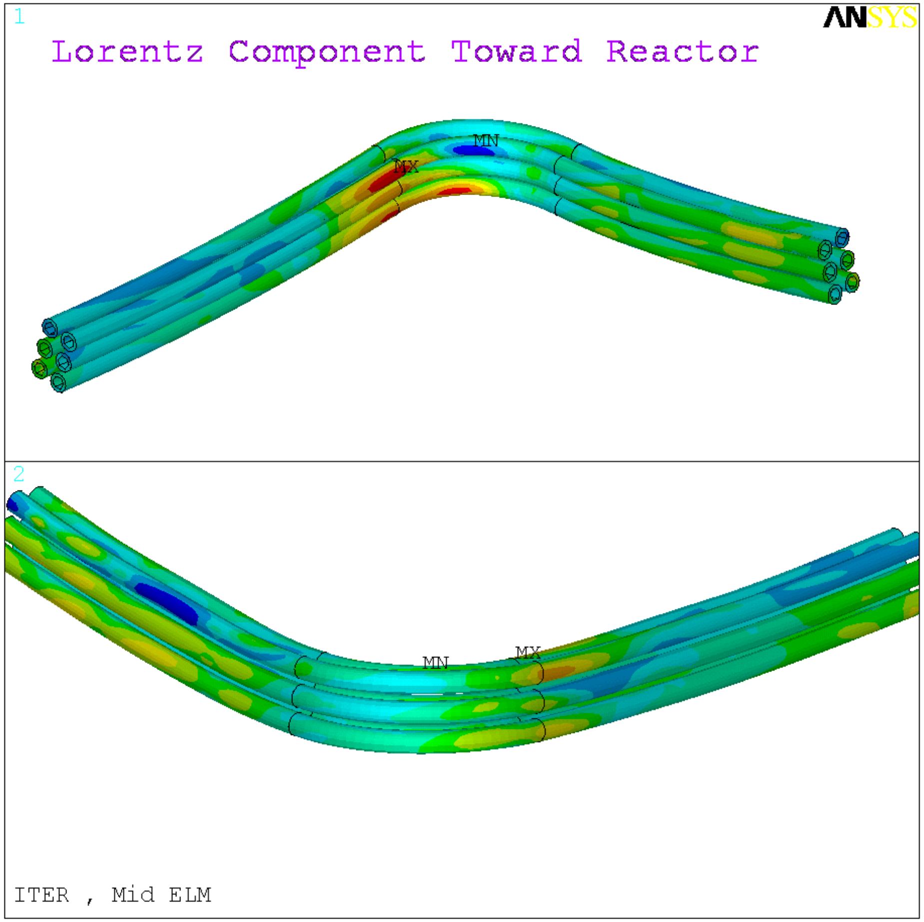
Lorentz Component Away From Reactor



$$\Delta S_{eq\_Amp} = \sigma_{vM\_Away} - \sigma_{Thermal+Pressure}$$

The Lorentz Component Away from the Reactor is 7.3 Mpa
And Within the Limiting Fracture Criteria

Lorentz Component Toward Reactor



OCT 16 2010
18:43:39
NODAL SOLUTION
STEP=1
SUB =6

$$\Delta S_{eq\_Amp} = \sigma_{vM\_Down} - \sigma_{Thermal+Pressure}$$

SMX =.119E+09

XV =.004005
YV =-.756875
ZV =.653547
*DIST=.553651
*XF =7.224
*YF =4.605
*ZF =-.002657
A-ZS=-104.366
Z-BUFFER

-.509E+08
-.320E+08
-.131E+08
.575E+07
.246E+08
.435E+08
.624E+08
.813E+08
.100E+09
.119E+09

WIND=2
XV =-.761206

The Lorentz Component Toward the Reactor is Limiting the Fracture Life
The Design Stiffness Toward the Reactor will need to be significantly reduced to Levels that are similar to the reversed direction

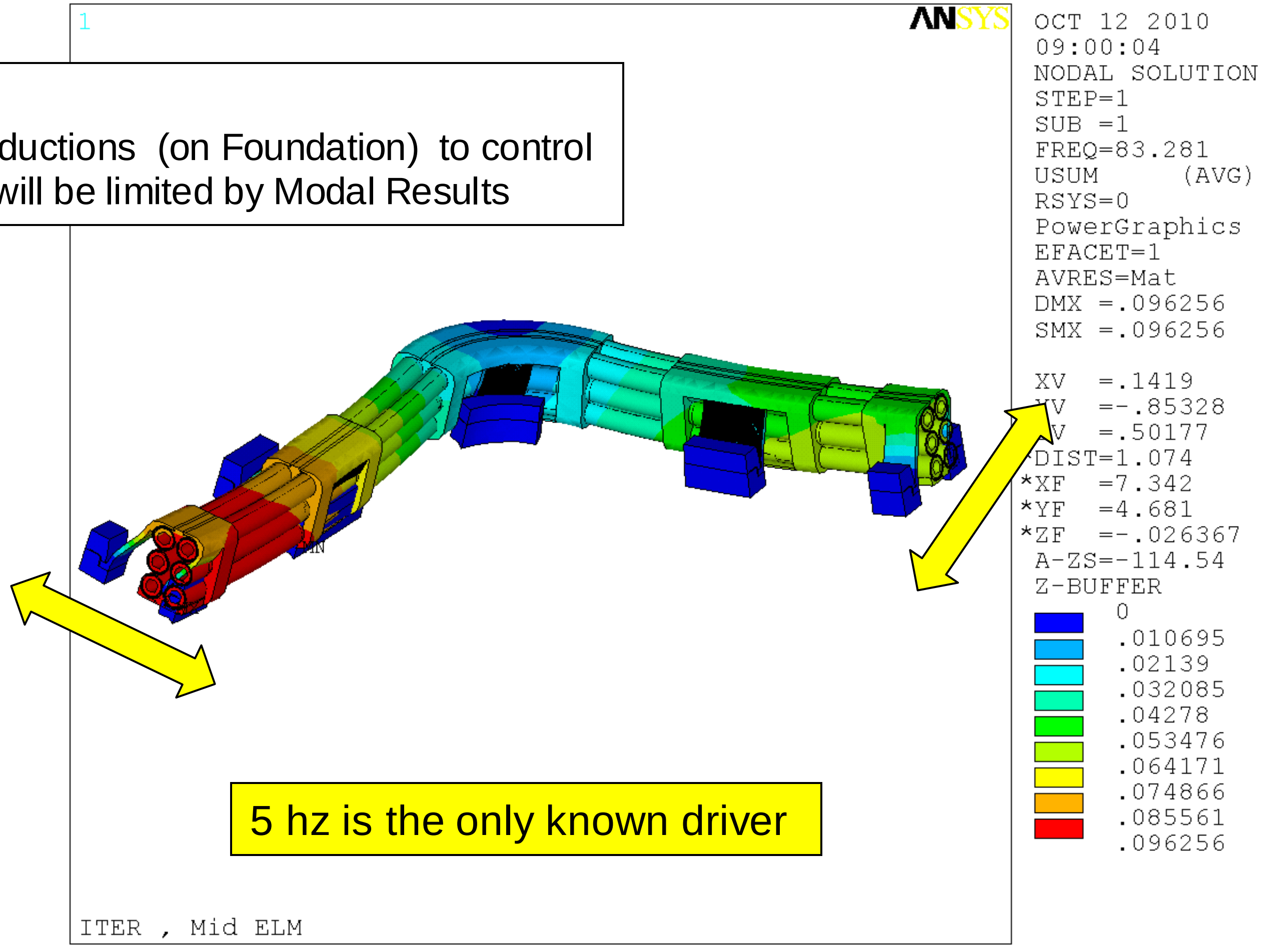
Modal Results

*****	PARTICIPATION	FACTOR	CALCULATION	*****			
MODE	FREQUENCY (HZ)	PERIOD	PARTIC.FACTOR	RATIO			
1	**83.2809**	**1.20E-02**	**6.44E-02**	**0.006919**	**Z**	**DIRECTION**	**RIGID TRANSLATION**
2	**104.434**	**9.58E-03**	**-6.8931**	**0.740244**	**Y**	**DIRECTION**	**SPREADING DISPLACEMENT**
3	195.564	5.11E-03	-2.0498	0.220125			
4	**246.212**	**4.06E-03**	**9.312**	**1**	**X**	**DIRECTION**	**PARALLELS LORENTZ LOAD**
5	285.029	3.51E-03	-1.6634	0.178633			
6	303.79	3.29E-03	1.7516	0.1881			
7	442.065	2.26E-03	6.5605	0.704527			
8	463.866	2.16E-03	3.8786	0.416523			
9	490.446	2.04E-03	6.2397	0.670076			
10	517.385	1.93E-03	1.2826	0.137739			

The Natural Frequencies are Defined Based on the Operating Temperatures

Modal Results for 83 Hz

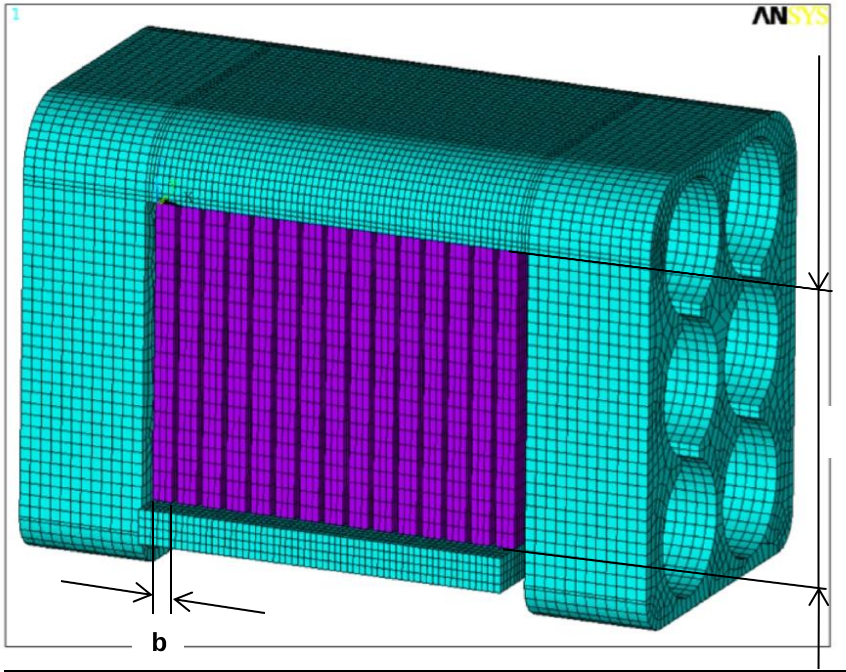
Note:
Stiffness Reductions (on Foundation) to control fracture life will be limited by Modal Results



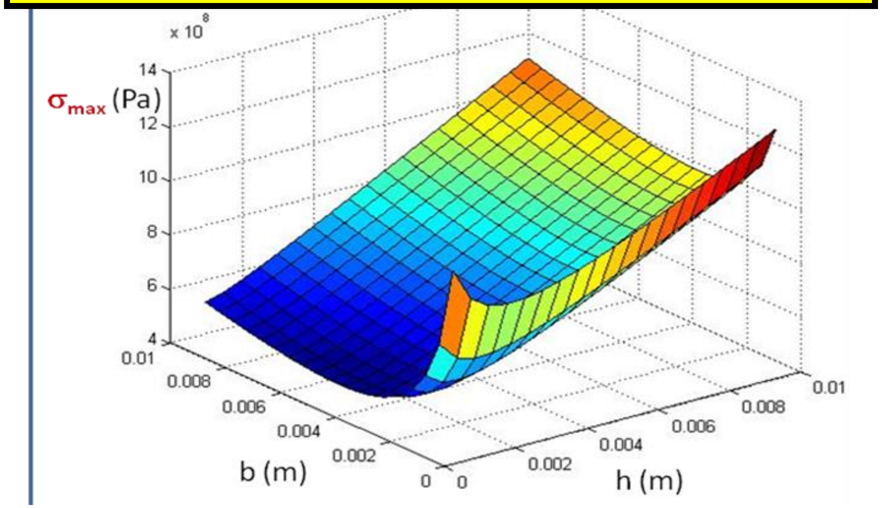
The Lowest Natural Frequency of 83 Hz is a Rigid Body Translation Mode That has no known excitation sources and therefore no concerns for vibration.

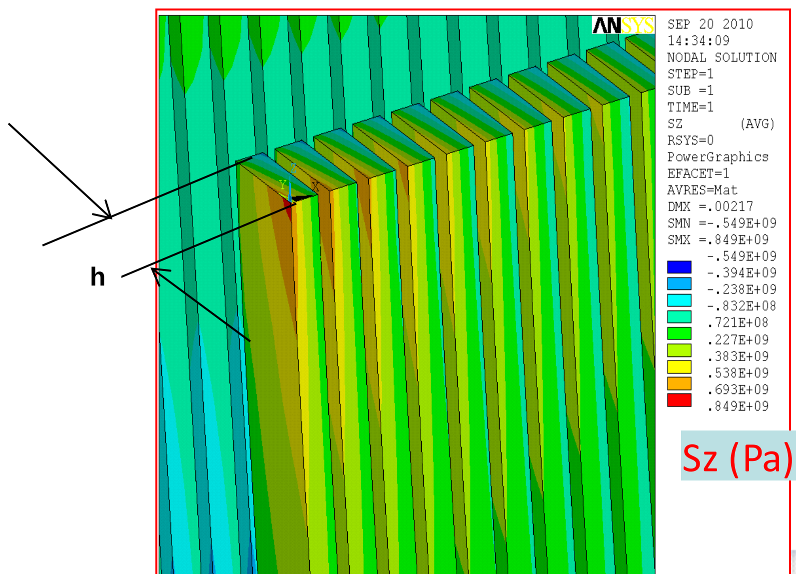
Bracket Optimization
Created with ANSYS Script Language

Design 1



Response Envelope



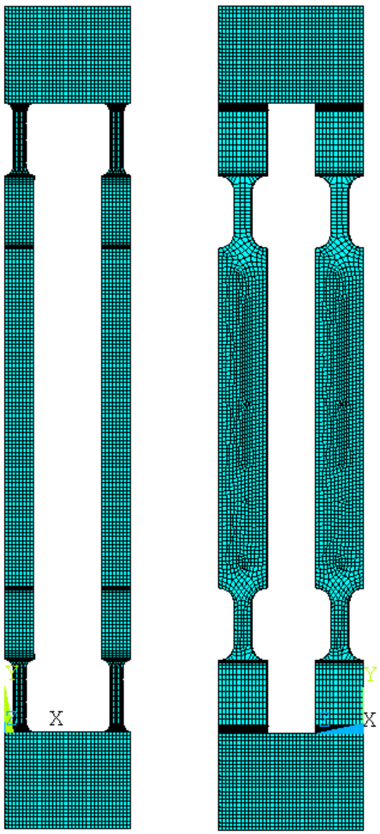


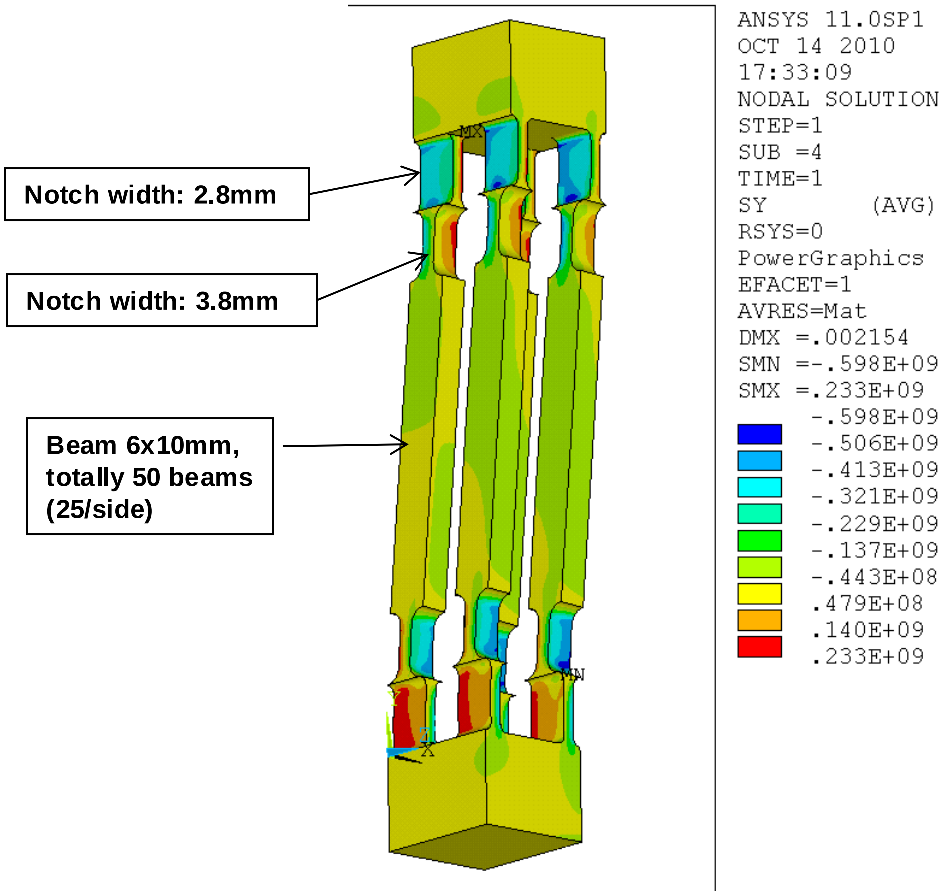
Variables Include:
Beam dimensions (Length, Width, & Height) Number Of Beams

Coil axial displacement 2mm, transverse displacement 1mm, Vertical load 160KN.

b=3mm, h=10.5mm, L=130mm, totally 80 beams (40/side)

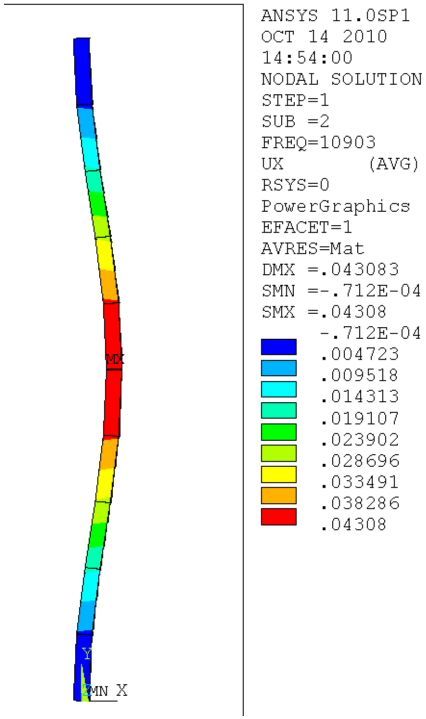
Alternative design





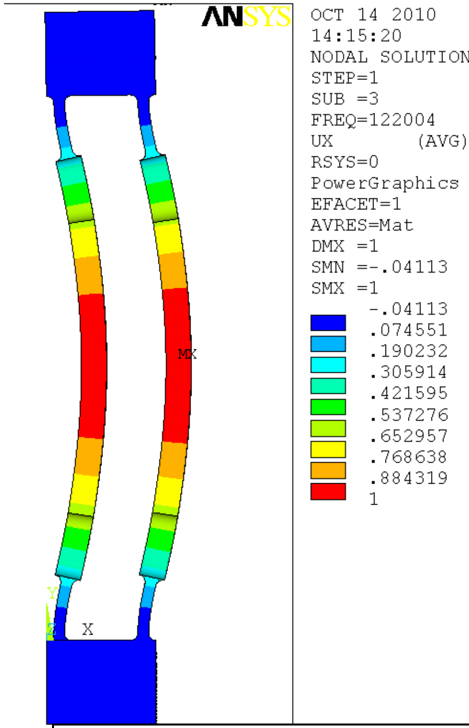
Cut the rectangular beams with notches: coil axial bending can be accommodated by notches at the ends and coil transverse bending be accommodated by the remaining notches.

Linear buckling



Rectangular beam:
10.9KNx80=872KN

3^{rd} order buckling mode (because the ends are fixed by coil)



Beam with notches:
122KNx12.5=1525KN

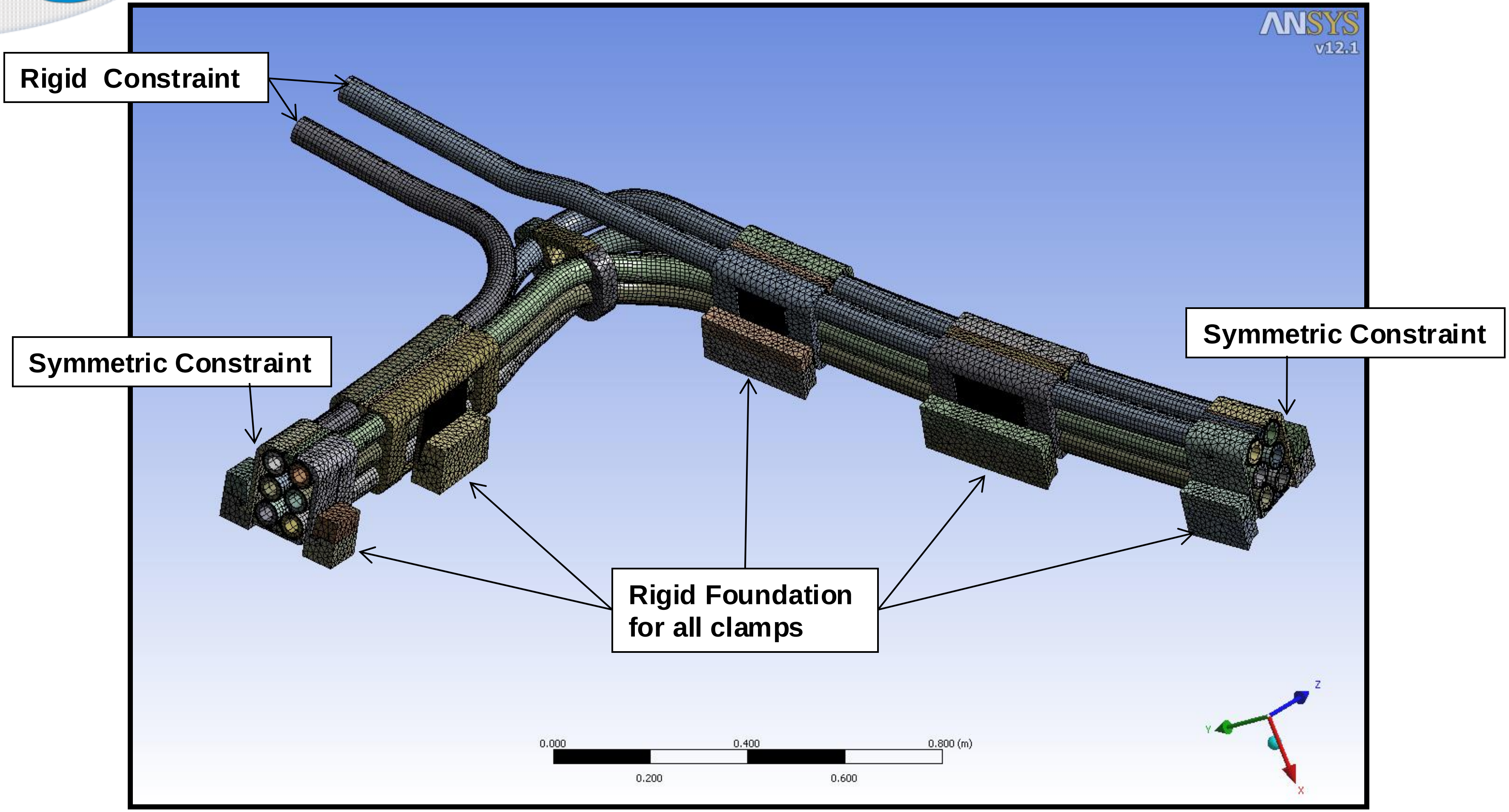
Comparing the two designs, second one is more difficult for fabrication.

Next step:
1.non-linear buckling with non-linear mat property will be done. Also displacement boundary conditions (2mm axial, 1mm transverse) will be added.
2.Fatigue life will be evaluated.

CROSSOVER DESIGN

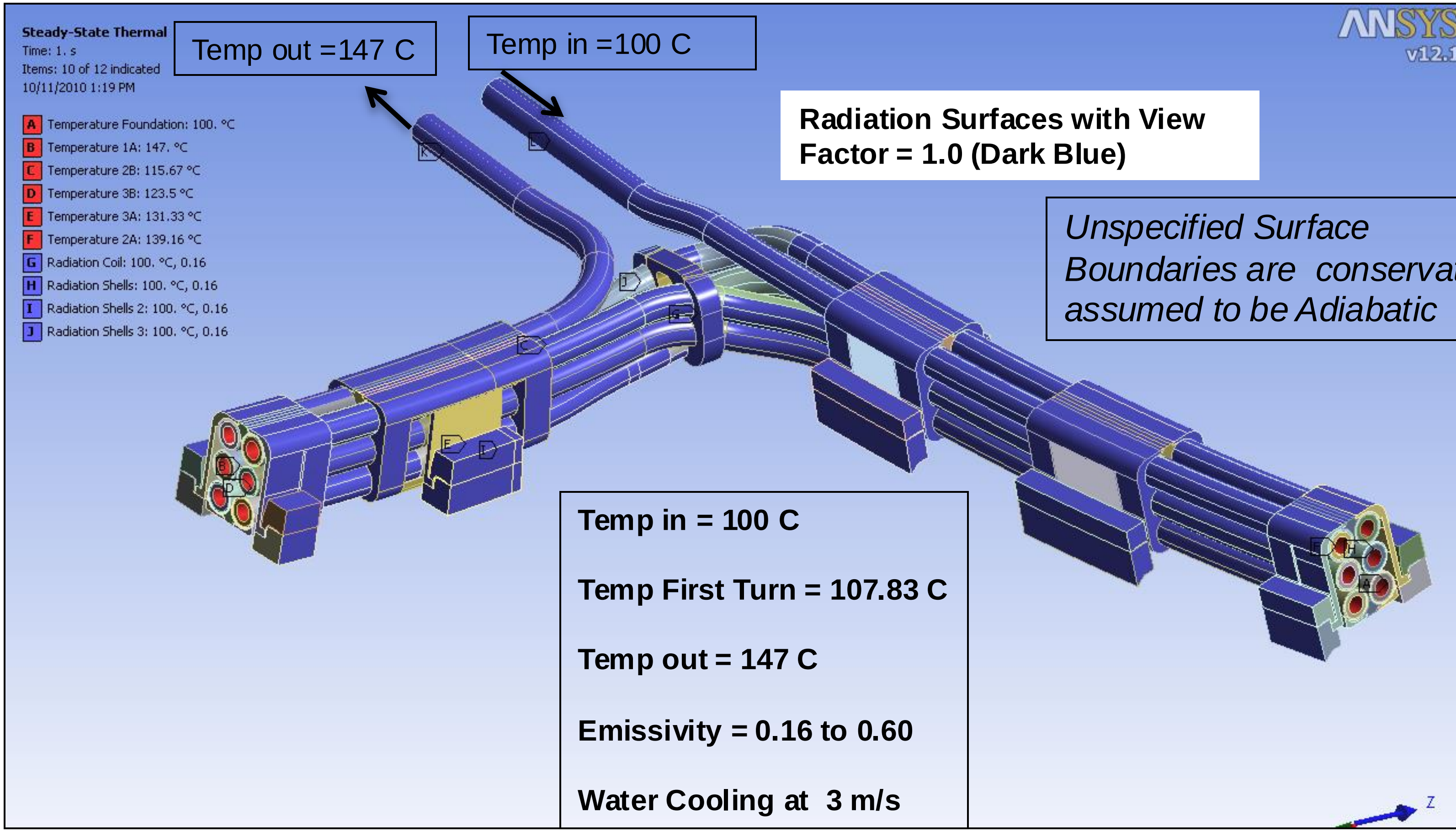
Opposite Corner Of ELM

ELM – CROSSOVER MESH



The New Sandwich Design Box 59 mm Cross-Over Support is Meshed with Hexahedral Elements On the Coil Components

THERMAL BOUNDARY CONDITIONS



Temp out =147 C

Temp in =100 C

Radiation Surfaces with View Factor = 1.0 (Dark Blue)

Unspecified Surface Boundaries are conservatively assumed to be Adiabatic

Temp in = 100 C

Temp First Turn = 107.83 C

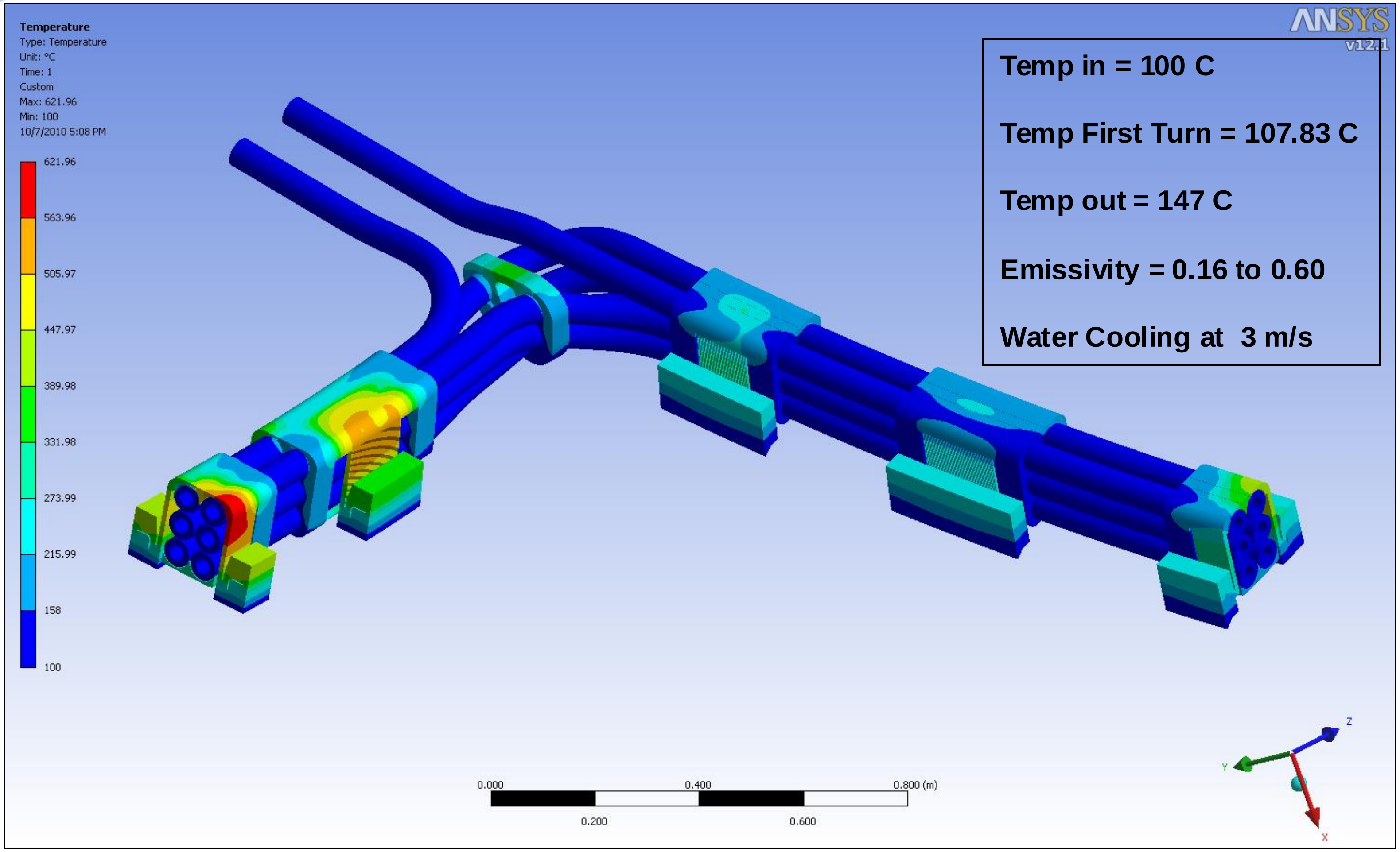
Temp out = 147 C

Emissivity = 0.16 to 0.60

Water Cooling at 3 m/s

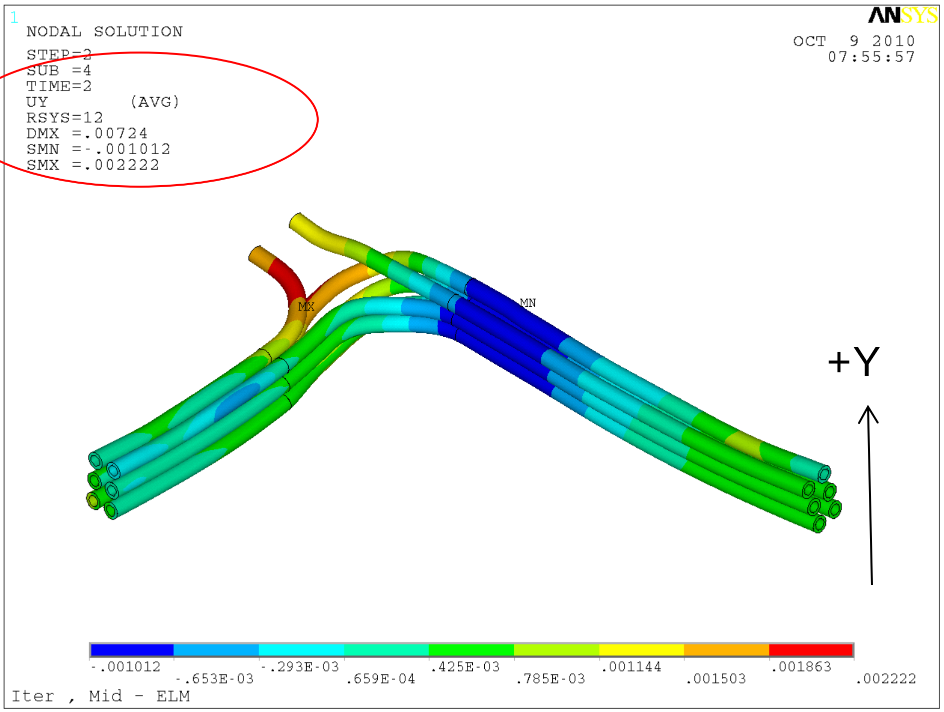
The Cross Over Model Thermal Boundary Conditions are Defined

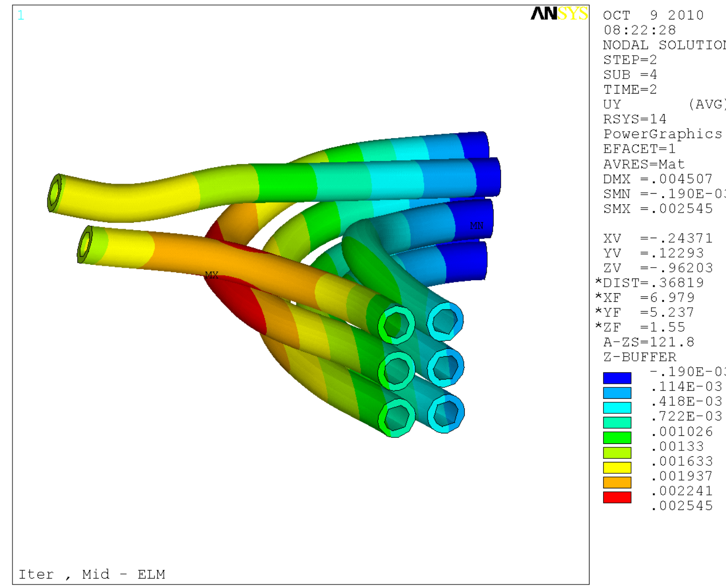
Steady State Temperatures



Preliminary Temperatures for Cross Over Model are Defined

Steady State
Pressure + Thermal + Lorentz Load
Displacements

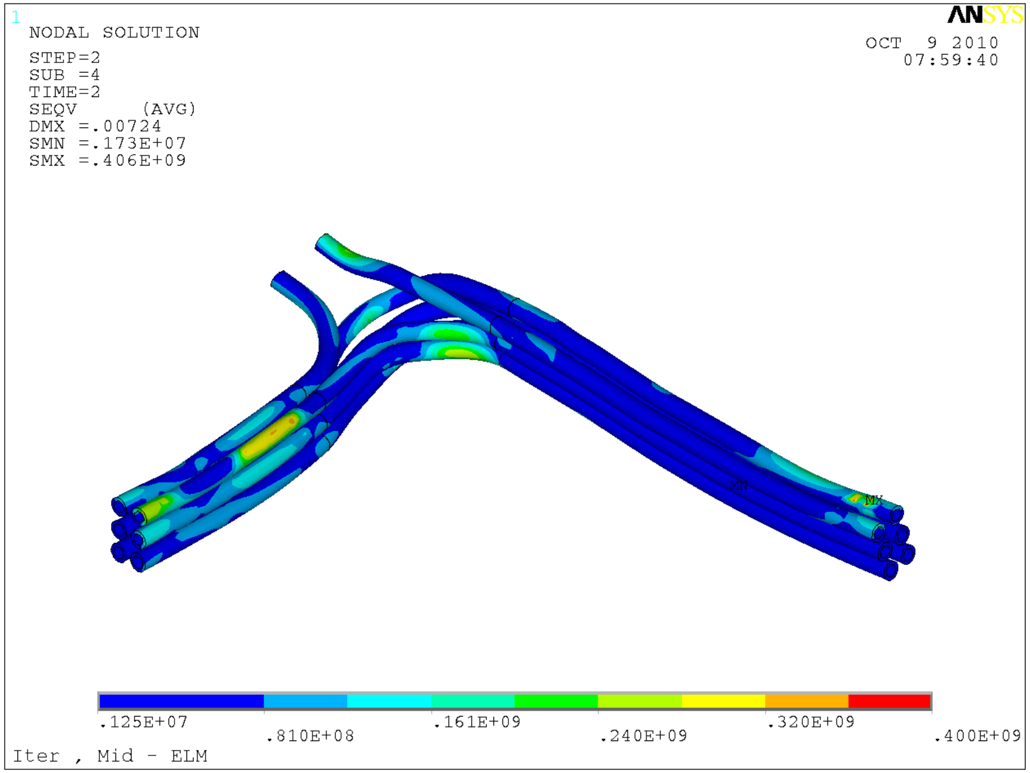


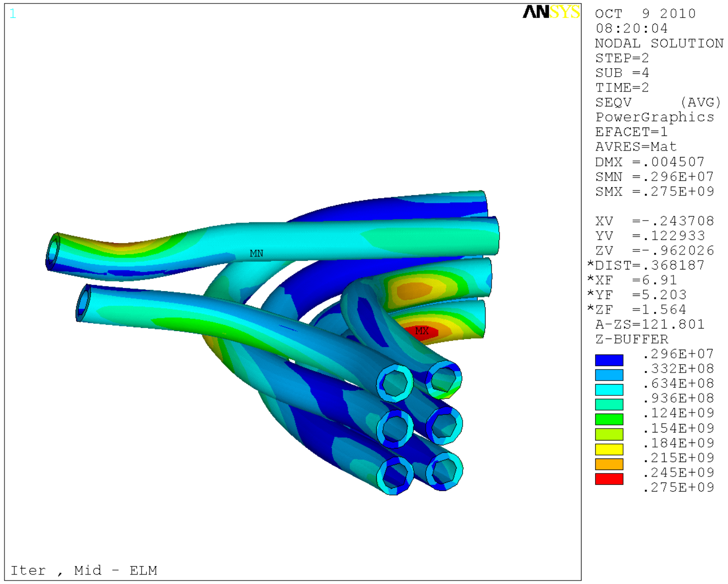


Note: Local Y displacement is approximately a global radial

The Displacements are Reasonable for the Specified Boundary Conditions
Lorentz Loads Acting Down Toward The Reactor

Steady State
Pressure + Thermal + Lorentz Load Stress





A Preliminary Cross-over Model is complete
von Mises Stresses are Concentrated on the lower coil turns as expected

Conclusions

- The Copper Coil will meet Static & fatigue initiation life based on the NSTX equivalent stress with a few local modifications in the constraints.
- The Copper Coil Fracture Fatigue life criteria is not satisfied and is specifically limited by the Lorentz Peak Stress for loading into the reactor wall
- Reducing the mean stress through thermal load reduction will reduce the alternating stress in direct proportion to this reduced mean stress fraction.
- The Lorentz Load into the reactor wall is a much larger contributor to the stress amplitude. Reduction in the design support stiffness will be required in order to meet fracture life.
- The Stainless Steel will meet Static and fatigue initiation life based on the NSTX equivalent stress with a few local modifications in the constraints.

Conclusions

- The Coil temperatures are conservatively based on the worst case Nuclear Heating although this max case is only applied on one side of the coil dependent on maintaining emissivity's of 0.60
- The Coil will survive a Fault Temperature (without water cooling) although with additional copper cladding, temperatures are expected to drop further.
- The modal analysis shows the lowest frequency of 83 hz is the lowest frequency at operating temperatures. Pre-stressing is expected to increase the modes.
- Fault temperatures significantly increase reaction loads. This will need to be evaluated on the foot, sandwich supports and reactor rail design
- The Bracket Support Optimization for stress and buckling has defined the current design using 718 Inconel and several alternative beam designs to increase buckling.
- The first runs of the Cross-over model are complete with temperatures and stresses. A similar methodology will be applied to this model to resolve the stress and displacement issues.

Issues and Resolution Plan

Issue	Resolution	Pre/Post TA
Design Foundation Stiffness is to large to allow fracture life criteria to be satisfied	Reduce the foundation stiffness with innovative methods without allowing the frequencies to approach 5 HZ	Pre
Alternating stress is too high. Additional temperature reductions by increasing flow rates (targeted for the Feeders) are not incorporated into analysis	Obtain new predicted temperature boundary conditions to reduce the mean stress which reduces (proportionate by alternating to mean stress ratio) the alternating stress.	Pre
Temperatures need to be controlled along the top of the brackets.	Copper cladding to be designed into brackets to allow good uniform thermal contact without need of uniform mechanical constraint	Pre
718 Inconel Material Properties to be used in place of 316 Stainless on the brackets	Obtain ITER material data for 718 Inconel and implement into analysis.	Pre
The Bracket Optimization will need to be updated as the foundation stiffness is reduced.	Determine the required foundation stiffness changes and evaluate impact on the bracket optimization.	Pre
The Cross-over ELM model needs to be developed with insights from ELM. Similarly for the Upper & Lower ELMS	Develop Crossover ELM Model with new constraints and boundary conditions.	Pre

Issues and Resolution Plan

Issue	Resolution	Pre/Post TA
ELM and Crossover Models require evaluation for other Power levels and for Transient Operation	Implement Boundary Conditions and re-evaluate as the design matures.	Pre
Nuclear Heat for the corner of the ELM is expected to be updated by the University of Wisconsin Neutronics team	Contact Wisconsin Team to obtain a projected update	Pre
Material Properties for MGO from R& D program to be improved.	Completed R& D Testing and calibrate analysis with results	Pre
Load Transfer between the MGO and Jacket Boundary Conditions to be improved over current assumption of bonding.	Test out material models that provide a match to the experimental data.	Pre
A reference temperature of 100 C was included to represent the reactor to support displacement which introduced some errors.	Adjust foundation displacements with an APDL script to incorporate accurate thermal and any other reactor displacements and return all reference temperatures to 22 C	Pre