NSTXU

TF Coupled Thermal Electromagnetic Diffusion Analysis

(Rev 1)

NSTXU-CALC-132-05-01

Sept 4, 2009

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PPPL Calculation Form

Calculation # **NSTXU-CALC-132-05** Revision # **01** WP #, if any: **1672**
(supersedes NSTXU-CALC-132-01 of April, 2009) (ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)
This current diffusion analysis is performed to calculate the temperature and stresses in the TF inner coils. In the upgrade, the exiting connections between the inner and outer TF coils will be replaced by flags and laminated copper arches. TF current will be promoted to 130KA. Due to the higher current and slew rate, current will distribute non-uniformly, as a function of, coil resistance, inductance and contact pressure between the flag and arch contact joint. This produces localized high temperatures with associated high thermal stress and an increased risk of overheating the coil epoxy. Active water cooling will be added to the inner and outer coils to reduce joule heat. The effect of cooling on thermal stress needs to be investigated. This analysis is based on the previous analysis of Peter Titus.

References (List any source of design information including computer program titles and revision levels.)
(1) E-mail: P. Titus to C. Neumeyer and Phil Heitzenroeder dated April 20, 2009 (attached), "Coupled Electromagnetic-Thermal Analysis - Structural Pass with thermal Stress, Low Flex"
(2) Peter Titus, "Coupled Electromagnetic-Thermal Analysis (04072009)", *NSTX CALC-132-01-00*, 2009.
(3) Peter Titus, "Coupled Electromagnetic-Thermal Analysis (04202009)", NSTX-CALC-132-02-00, 2009.
(4) Charles L. Neumeyer, http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html, dated 7-29-2009.
(5) Tom Willard, "TF Flex Joint and TF Bundle Stub", NSTX-CALC-132-06-00, 2009.
(6) Robert D. Woolley, "TF Joint Pressure VS Temperature In NSTX CSU Upgrade", CSU-CALC-132-090211-RDW-01, 2009.

Assumptions (Identify all assumptions made as part of this calculation.)
1. In the model, the geometry of upper flag, and that of the connector between laminated arch and outer coil are not accurate. Their designs were not totally finalized when building this model.
2. Cooling is first calculated by a separate code especially for beam and then added to the model by specifying the temperature of corresponding nodes.

Calculation (Calculation is either documented here or attached)

See the body of the following document

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

The max temperature for inner coil is 113°C with active cooling, within the temperature allowable of epoxy. It is possible to use high strength copper for the upper flag material, which is only slightly different in temperature. The max temperature in the connectors between laminated arch and outer coil may not be accurate.

Currently the requirement for cooling rate is not yet determined. But to reduce the thermal stress, it is better to cool down slowly. Using thinner tubes, lower coolant speed and different cooling line positions are all possible options to be further evaluated.

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

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Part I

Executive Summary

The objective of this analysis is to calculate the temperature and stresses during TF coil ramp up, flat top and ramp down (Fig. 1). PF field is not considered. This analysis is based on the coupled field electromagnetic and thermal analysis for a simple model by P. Titus [1], [2].

The distribution of current in TF coil depends on the resistance, inductance and contact pressure in the contact area. Coil temperature reaches highest at the end of the pulse, i.e., 10.136s for normal operation. Maximal temperature is 117ºC, at the inner side of arch and inner TF leg. Comparing with C. Neumeyer's result (101 ºC temperature rise [3]) this analysis with current diffusion effect results in a little higher temperature. But within this temperature range, active cooling is not necessary. Max coil temperature is 47 ºC in TF outer coil at the end of pulse. But the temperature at the end of the coil can reach 65 ºC because it connects to the arch which has higher temperature.

In this model, the arch is modeled by two solid pieces. But in reality, they are made of many straps. So the arches in this model have anisotropic material properties (mechanical properties are based on the local structure model results of T. Willard [4]), Current density, magnetic flux density and temperature from this analysis have been provided to T. Willard for his detailed simulation of the joint.

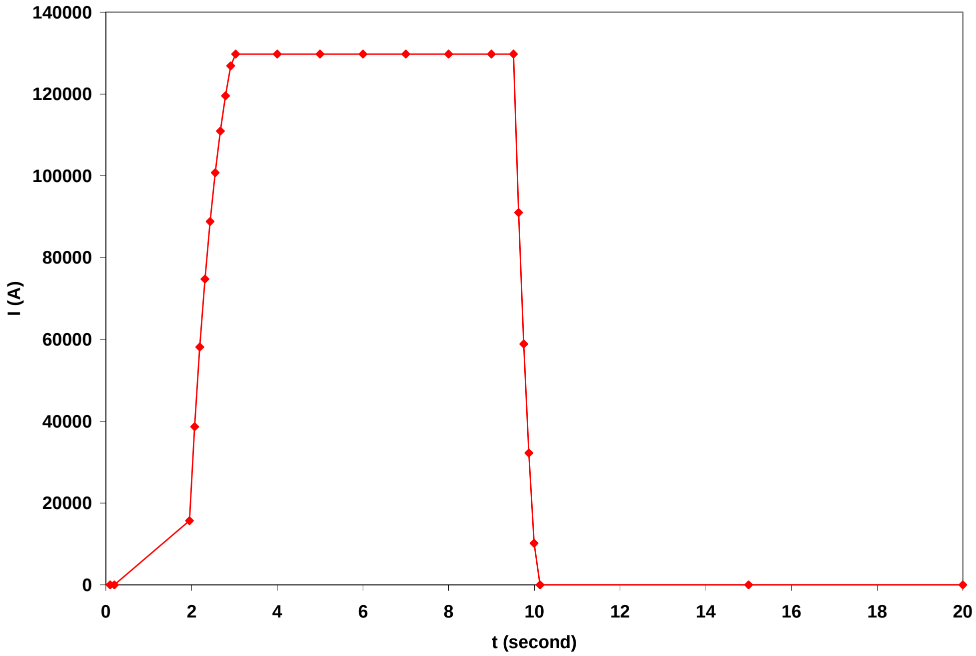
Using high strength copper (80% IACS) in the flag extension increases the temperature only by < 1ºC. Thus high strength copper can be used if required to increase the pressure of joint bolt insert over the capacity of pure copper.

The central beam has maximal hoop tension stress of 72.7MPa at 9.512s (i.e. the end of flat top) and 58.5MPa at 10.136s (i.e. the end of pulse), similar to Titus's result [2]. But there is another even higher hoop stress point of 95.5MPa at 9.512s, at the connection between central beam and flag, which is due to the L-shape connection part between the arch and TF outer leg.

Toroidal field contours have been provided for use in other calculations—in particular the background field in the antenna calculation.

Structure response at the joint has been included for comparison with more detailed modeling of the joint [4].

Figure 1: NSTX normal operation waveform.



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[1] Peter Titus, “Coupled Electromagnetic-Thermal Analysis (04072009)”, *NSTX-CALC-132-01-00*, 2009.

[2] Peter Titus, “Coupled Electromagnetic-Thermal Analysis (04202009)”, NSTX-CALC-132-02-00, 2009.

[3] Charles L. Neumeyer, http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html, dated 7-29-2009.

[4] Tom Willard, “TF Flex Joint and TF Bundle Stub”, NSTX-CALC-132-06-00, 2009.

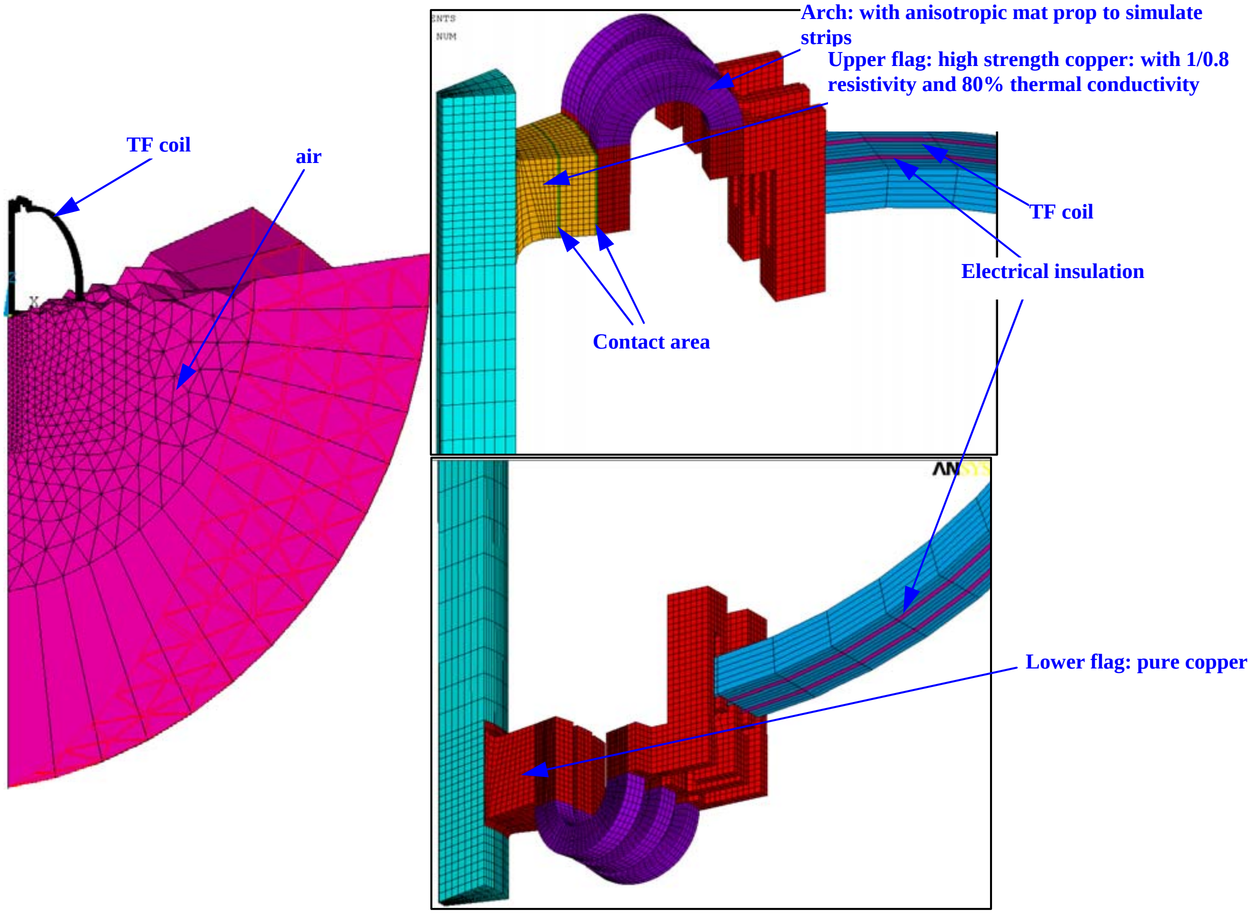
[5] Robert D. Woolley, “TF Joint Pressure VS Temperature In NSTX CSU Upgrade”, CSU-CALC-132-090211-RDW-01, 2009.

Modeling

This is a transient and coupled field analysis. An electromagnetic model (Fig. 2) is used to calculate current diffusion effect and transfer the generated heat and Lorenz force to thermal and structural model. The thermal and structural model calculates the temperature, displacement, thermal stress, contact pressure at contact areas, and then transfer these data back to electromagnetic model. The materials have temperature dependent material properties, including electrical resistivity, thermal conductivity, specific heat, coefficients of thermal expansion. The arches have anisotropic resistivity and thermal conductivity to simulate the straps. Because the arch is made of many straps and not a solid copper, it becomes much more compliant. The modulus of the arch is estimated to be half of that of pure copper. The upper flag uses high strength copper which has 1/0.8 resistivity and 80% thermal conductivity of pure copper. In next section, the results show that using high-strength copper or pure copper doesn't have much difference. The lower flag uses pure copper. In the electromagnetic model, the contact regions have pressure dependent resistivity and the data are from R. Woolley [5] (Table 1).

Figure 2: Electromagnetic model.

A. Model



B. Toroidal field plot

t=8s, flat top, Toroidal field (T)

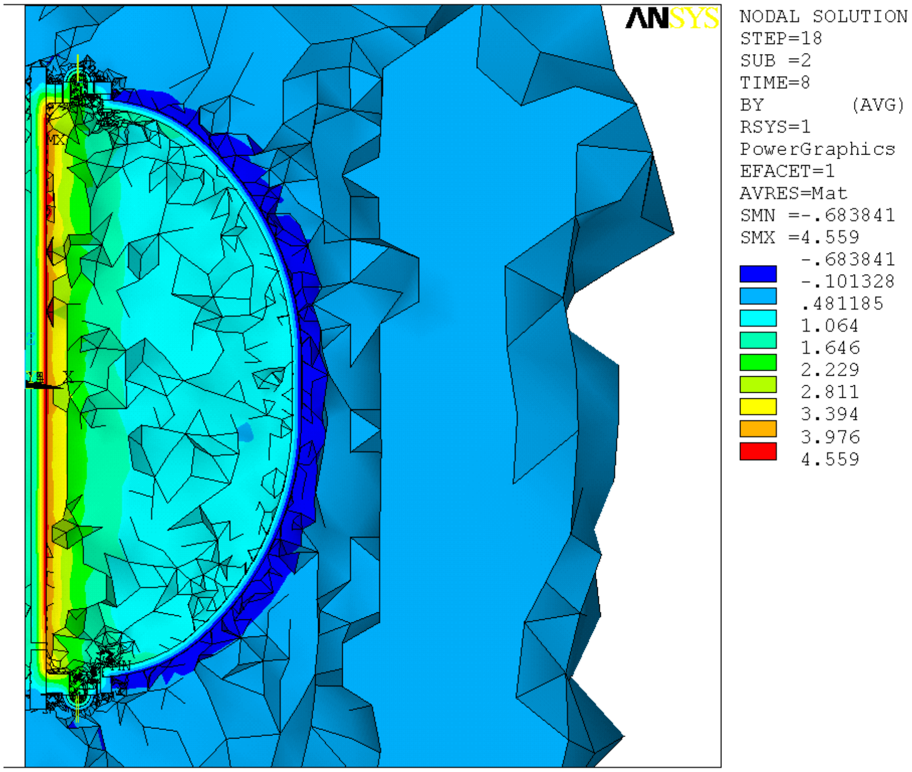


Figure 3: Thermal and structural model.

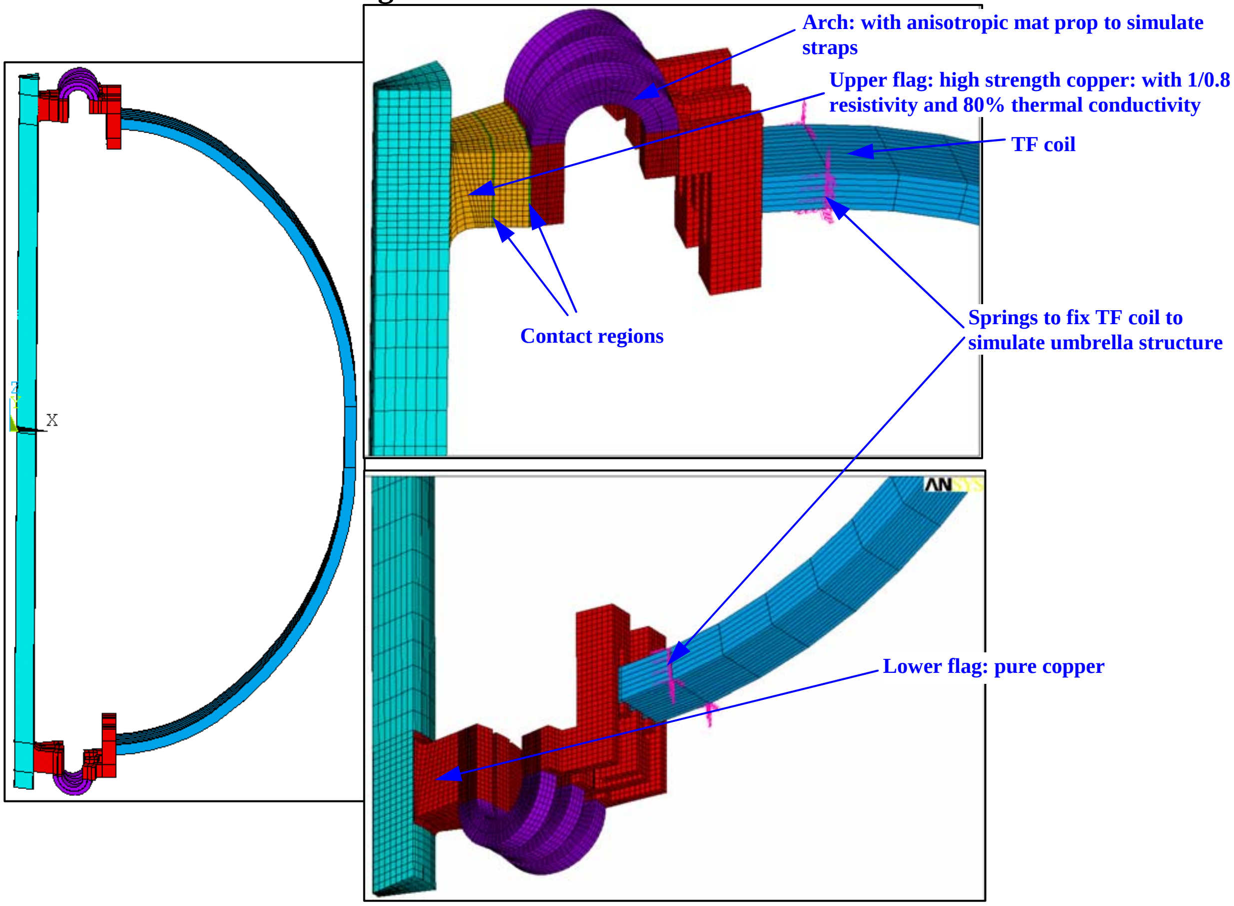
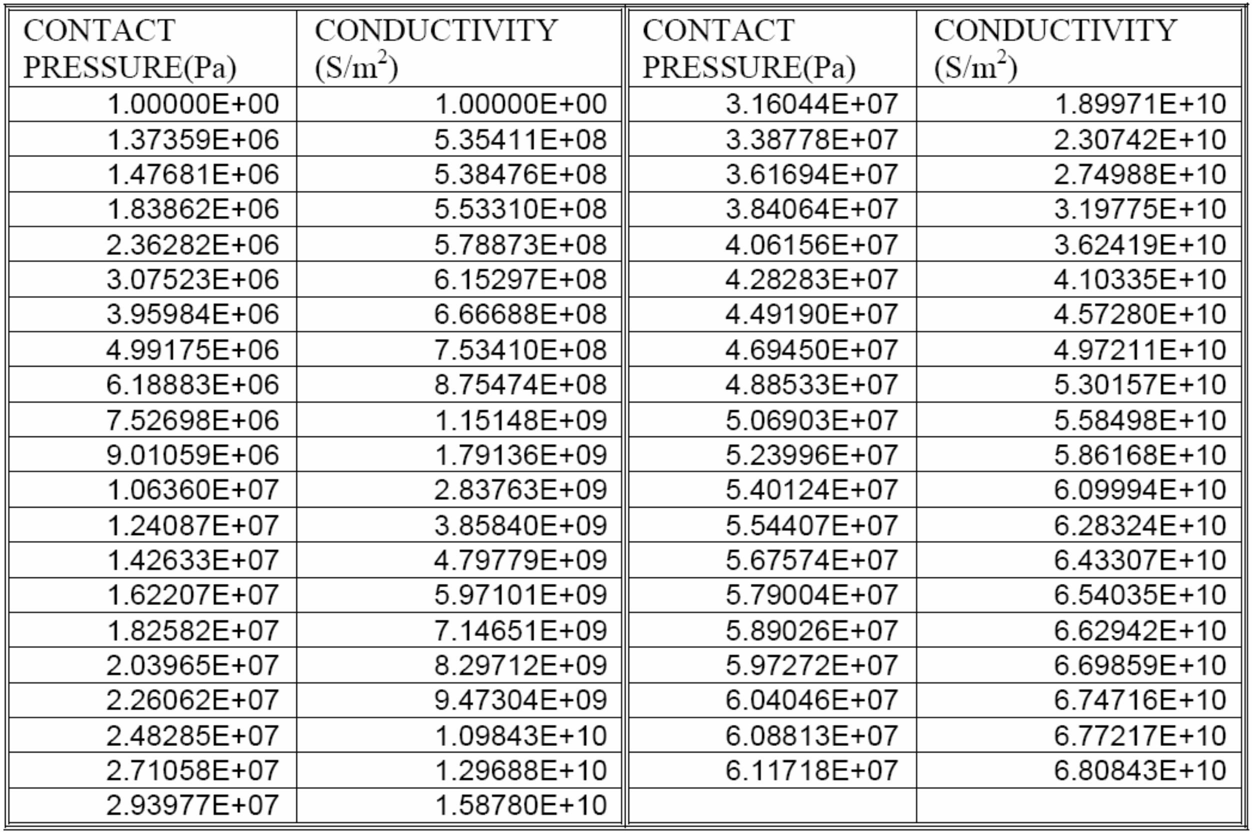


Table 1: Contact resistance data [5].

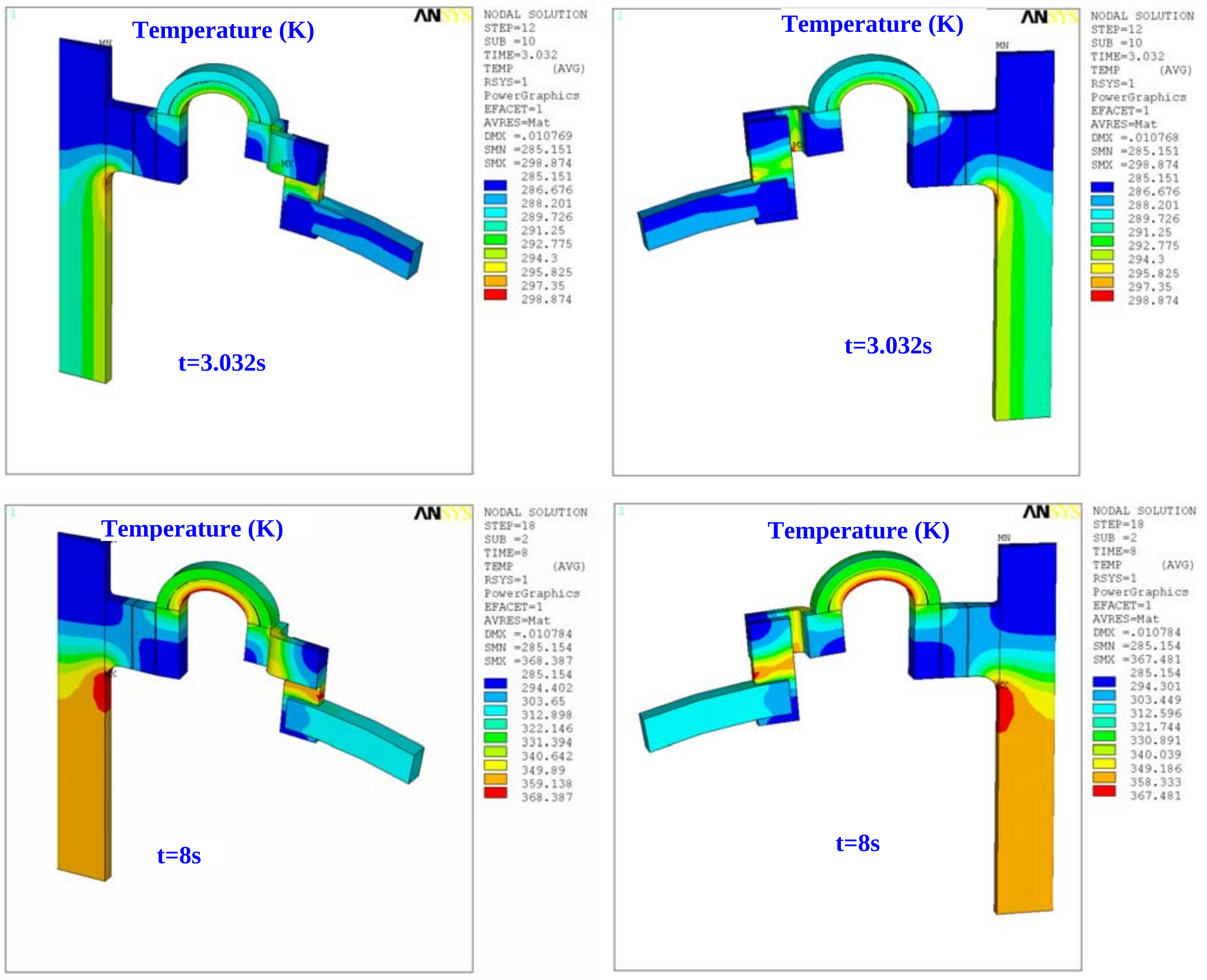


CONTACT PRESSURE(Pa)	CONDUCTIVITY (S/m^2)	CONTACT PRESSURE(Pa)	CONDUCTIVITY (S/m^2)
1.00000E+00	1.00000E+00	3.16044E+07	1.89971E+10
1.37359E+06	5.35411E+08	3.38778E+07	2.30742E+10
1.47681E+06	5.38476E+08	3.61694E+07	2.74988E+10
1.83862E+06	5.53310E+08	3.84064E+07	3.19775E+10
2.36282E+06	5.78873E+08	4.06156E+07	3.62419E+10
3.07523E+06	6.15297E+08	4.28283E+07	4.10335E+10
3.95984E+06	6.66688E+08	4.49190E+07	4.57280E+10
4.99175E+06	7.53410E+08	4.69450E+07	4.97211E+10
6.18883E+06	8.75474E+08	4.88533E+07	5.30157E+10
7.52698E+06	1.15148E+09	5.06903E+07	5.58498E+10
9.01059E+06	1.79136E+09	5.23996E+07	5.86168E+10
1.06360E+07	2.83763E+09	5.40124E+07	6.09994E+10
1.24087E+07	3.85840E+09	5.54407E+07	6.28324E+10
1.42633E+07	4.79779E+09	5.67574E+07	6.43307E+10
1.62207E+07	5.97101E+09	5.79004E+07	6.54035E+10
1.82582E+07	7.14651E+09	5.89026E+07	6.62942E+10
2.03965E+07	8.29712E+09	5.97272E+07	6.69859E+10
2.26062E+07	9.47304E+09	6.04046E+07	6.74716E+10
2.48285E+07	1.09843E+10	6.08813E+07	6.77217E+10
2.71058E+07	1.29688E+10	6.11718E+07	6.80843E+10
2.93977E+07	1.58780E+10		

Comparison of using high strength copper and pure copper

Because the upper flag has two contact regions, using high strength copper as the flag material can help to maintain high and uniform contact pressure and also lower contact resistance. But high strength copper has higher resistance and lower thermal conductivity. The result shows that using high strength copper (1/0.8 resistivity and 80% thermal conductivity) causes temperature rise of less than 1ºC. So there is some margin to change to high strength copper.

Figure 4: Comparison of using pure copper and high strength copper as flag material.
A. Temperature (K).

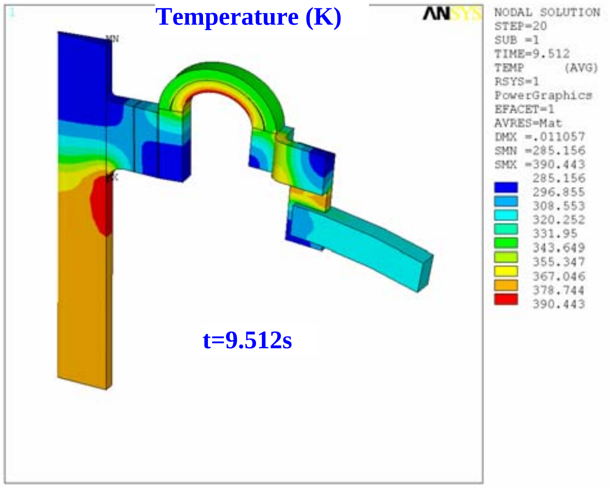


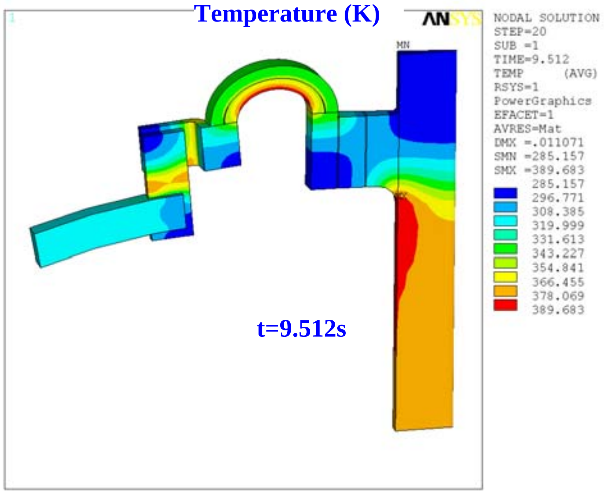
Pure copper

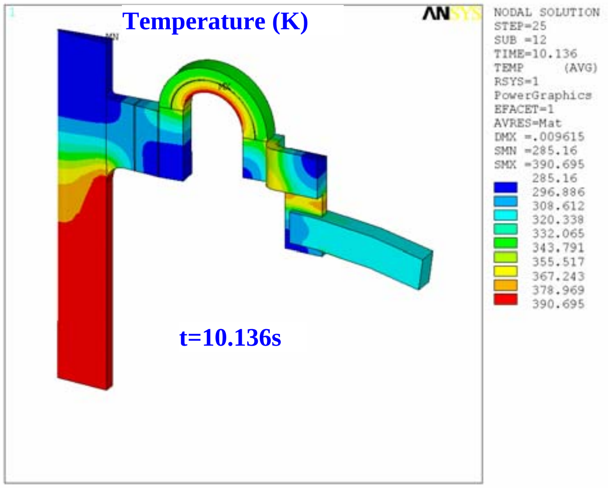
High strength copper

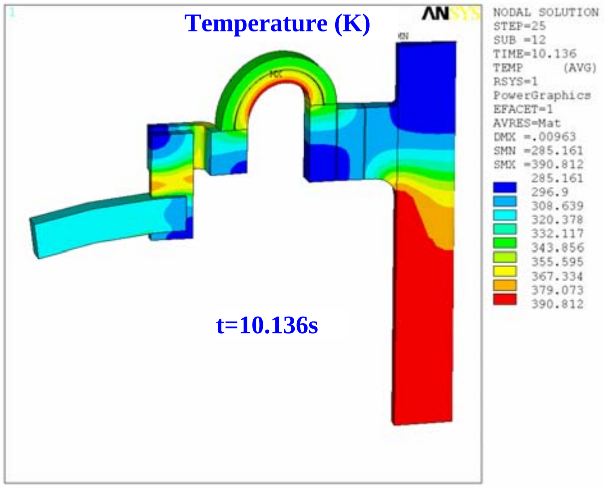
Pure

High strength





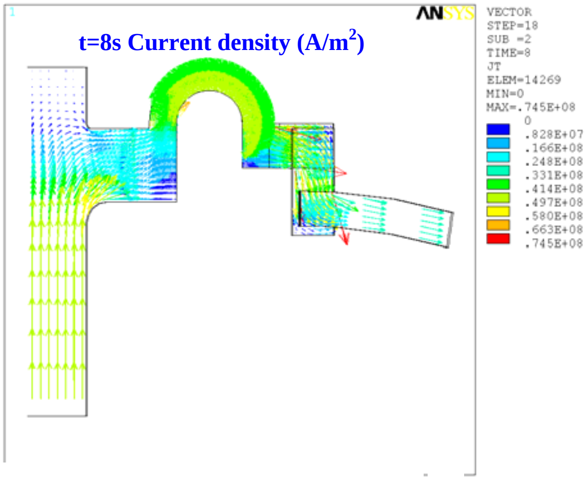


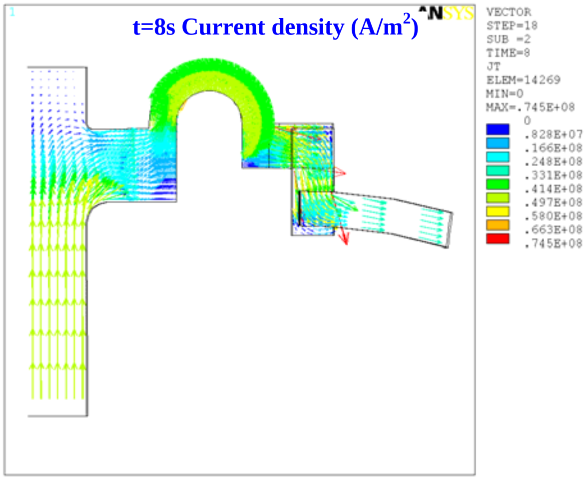


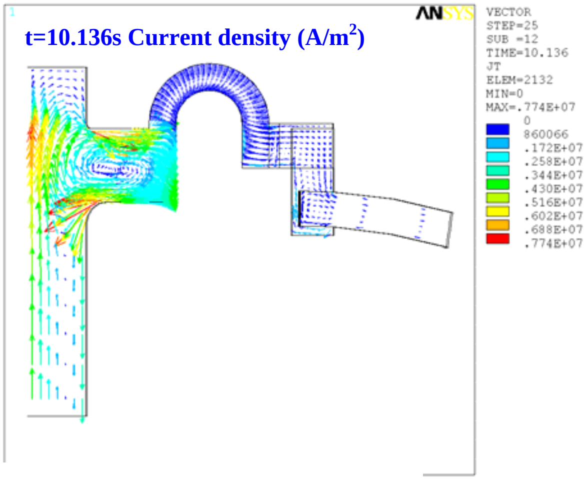
B. Current density (A/m^2).

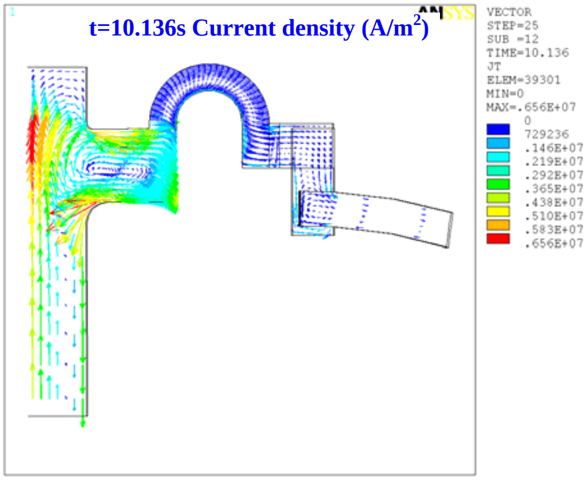
Pure copper

High strength copper


t=8s Current density (A/m^2)


t=8s Current density (A/m^2)


t=10.136s Current density (A/m^2)


t=10.136s Current density (A/m^2)

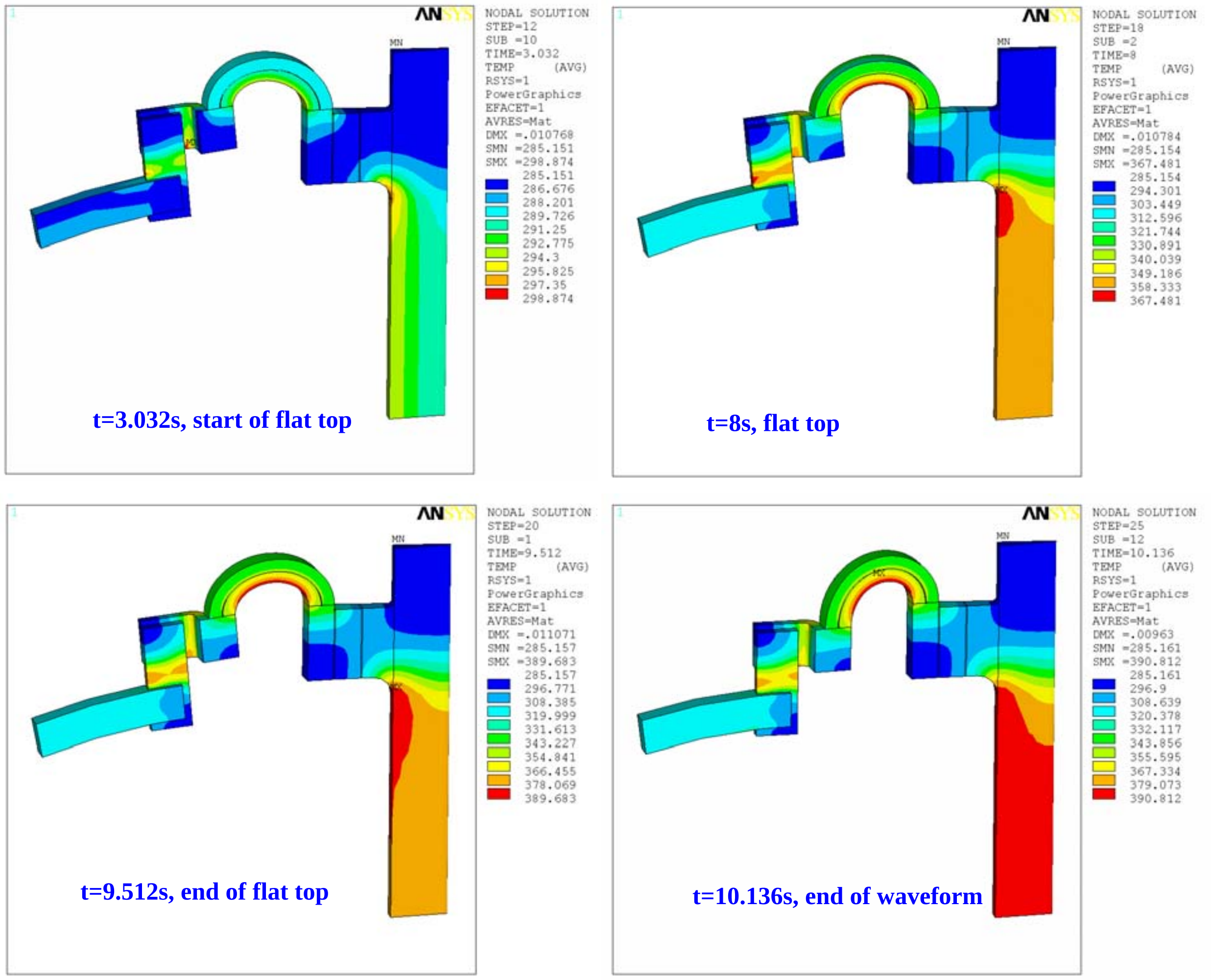
Temperature rise

Fig. 5 shows temperature rise. The maximal temperature is 117ºC at the inside of arch.

Fig. 6 is the time history plot of joint temperature. At the connection plane between central beam and flag, the max temperature difference can reach 103 ºC. Max Von Mises stress is also here (see next sections).

Fig. 7 is the time history plot of coil temperature. Coil temperature reaches highest of 47 ºC at the end of pulse. But the ends can reach 65 ºC and max temperature difference there is 47 ºC because they connected to the joints which have higher temperature and larger temperature difference.

Figure 5: Temperature (K) in the coil.



t=3.032s, start of flat top

t=8s, flat top

t=9.512s, end of flat top

t=10.136s, end of waveform

Figure 6: Time history plot of temperature (K).

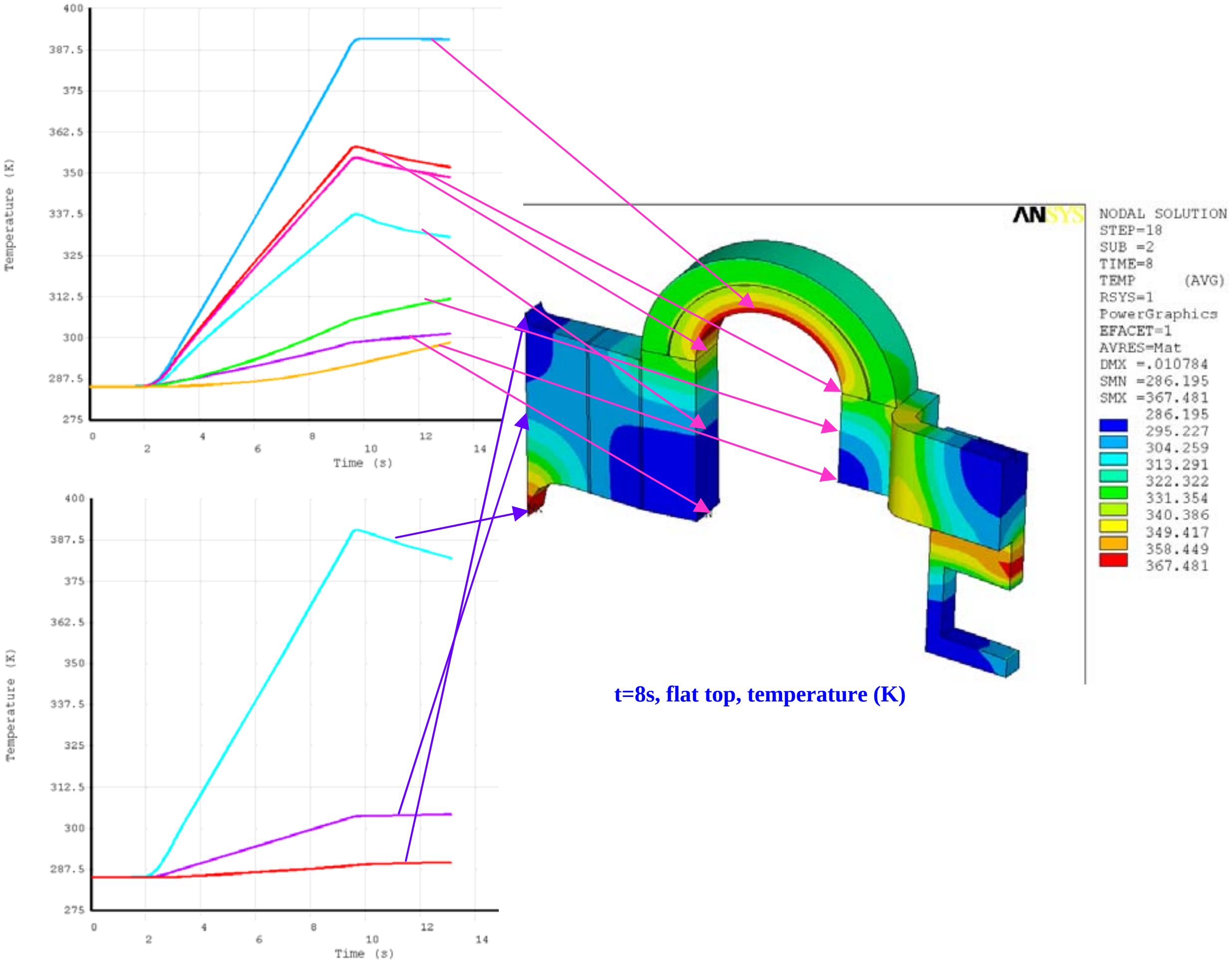
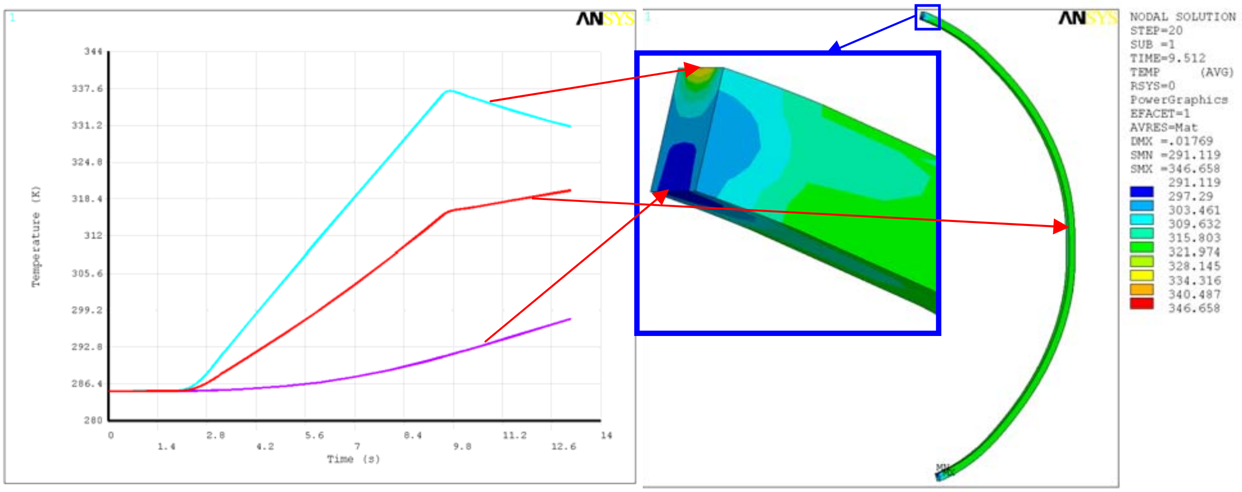


Figure 7: Time history plot of temperature (K).



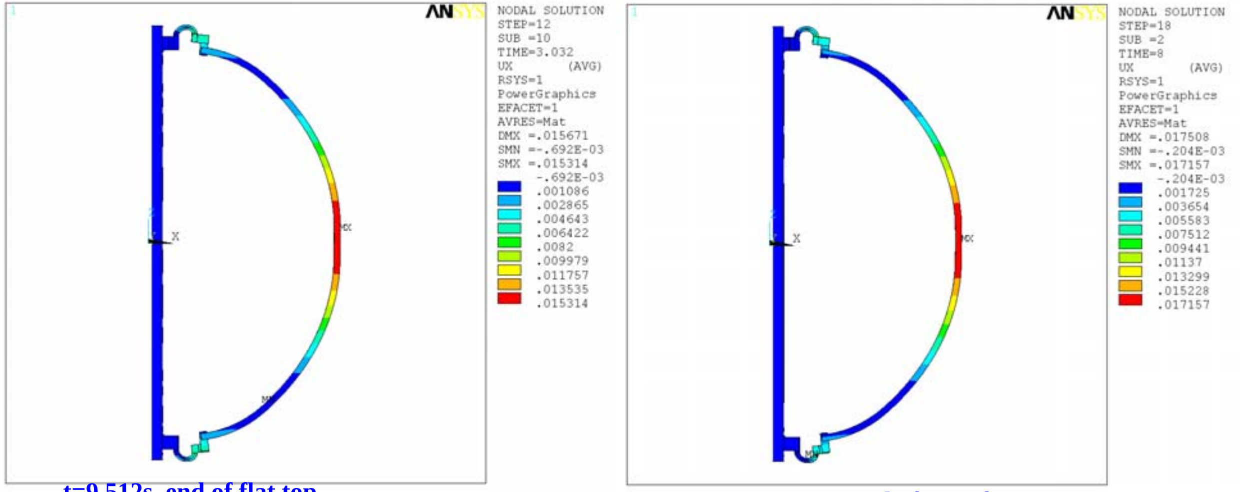
Coil deformation

Fig. 8 shows the deformation of the coil. Maximal radial deformation is 17.4mm (0.685”), theta deformation is <1mm and vertical deformation is 11mm (0.433”). There is no PF coil in this model and thus no out-of-plane force from poroidal field. The connection shape showed in Fig. 9 results in the theta deformation.

Fig. 10 is the time history plot of joint displacement Ux and Uz. The right end of the arch (close to outboard leg) is mainly affected by the magnetic force and thus has a curve shape similar to waveform. The left end and middle point of the arch are mainly affected by the thermal expansion of central beam and thus have a curve shape following temperature rise.

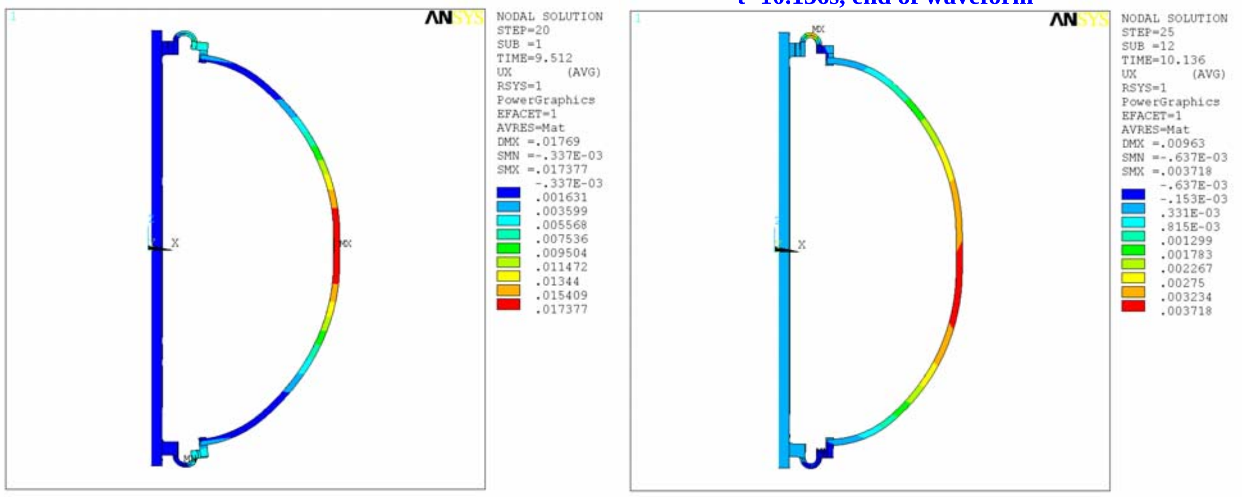
Figure 8: Coil deformation (m).

A. Radial deformation (m).



t=3.032s, start of flat top

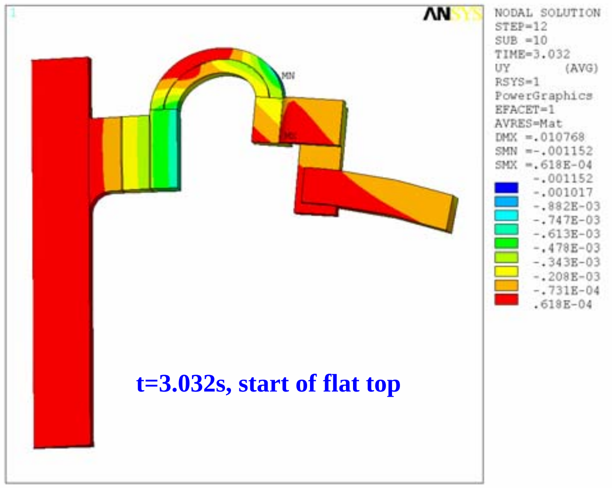
t=8s, flat top



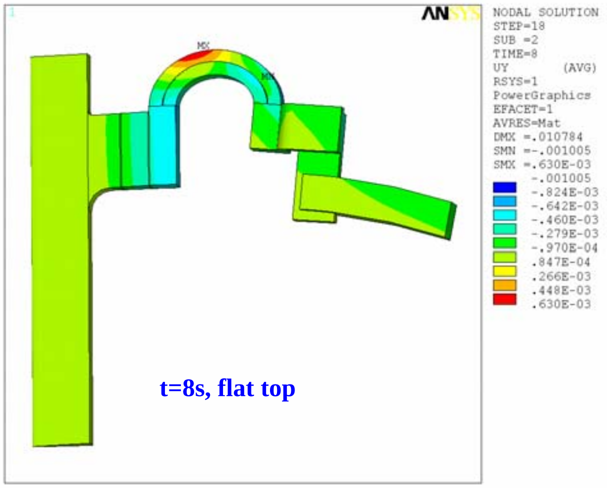
t=9.512s, end of flat top

t=10.136s, end of waveform

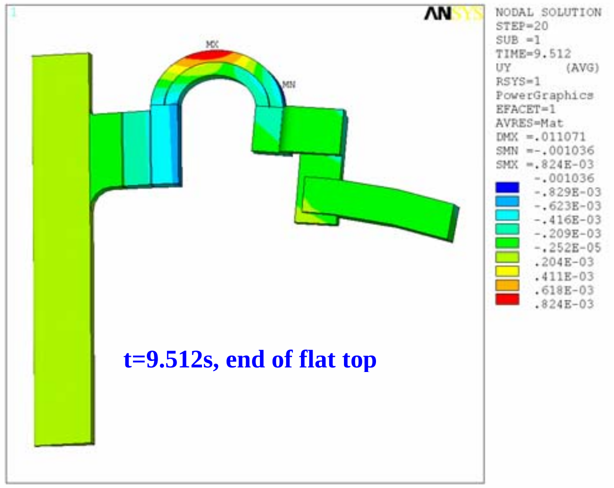
B. Theta deformation (m).



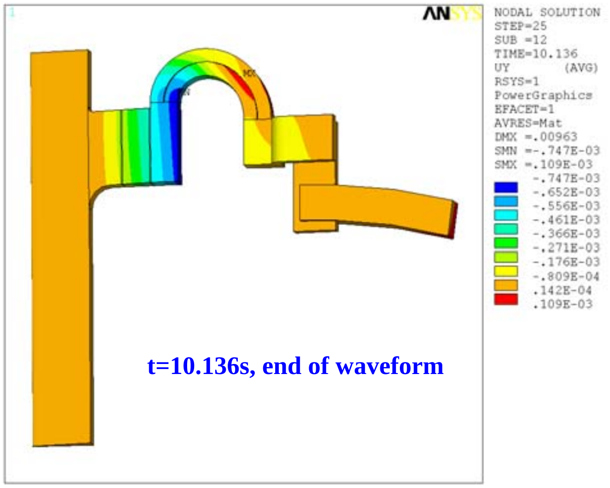
t=3.032s, start of flat top



t=8s, flat top

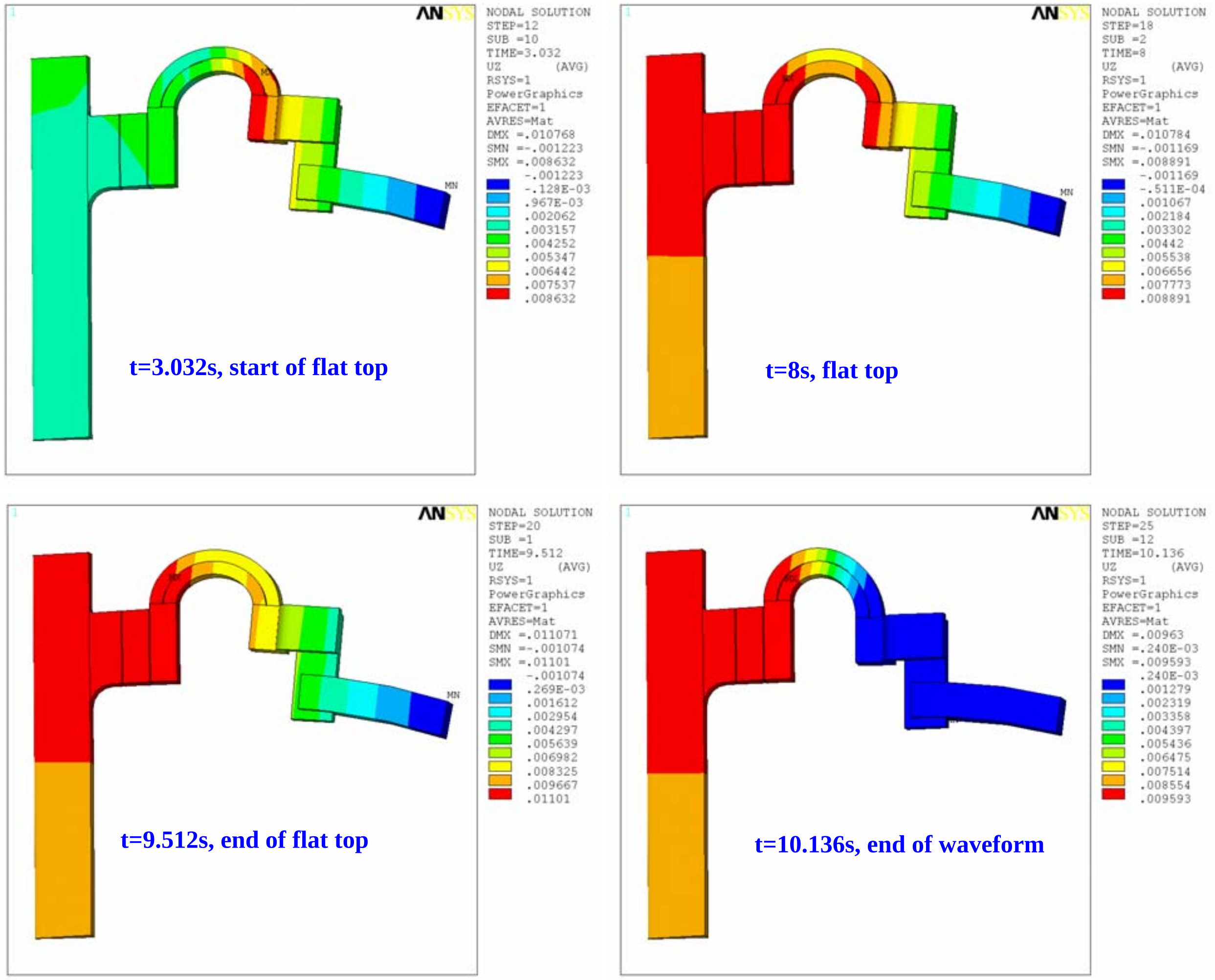


t=9.512s, end of flat top



t=10.136s, end of waveform

C. Vertical deformation (m).



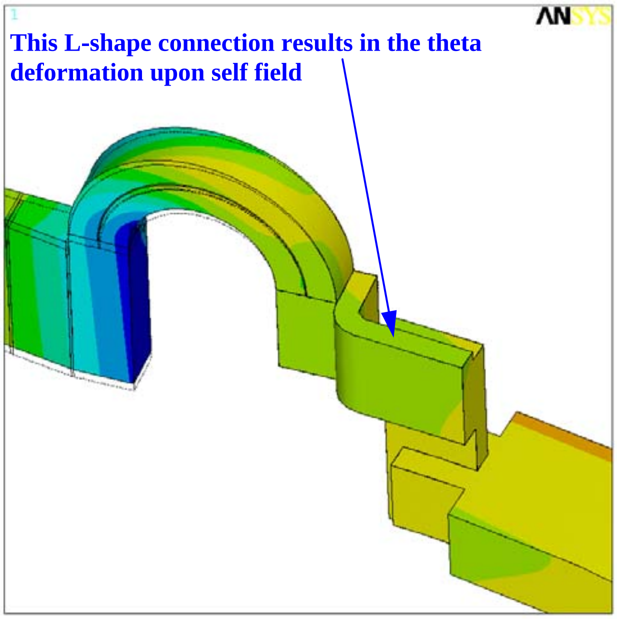
t=3.032s, start of flat top

t=8s, flat top

t=9.512s, end of flat top

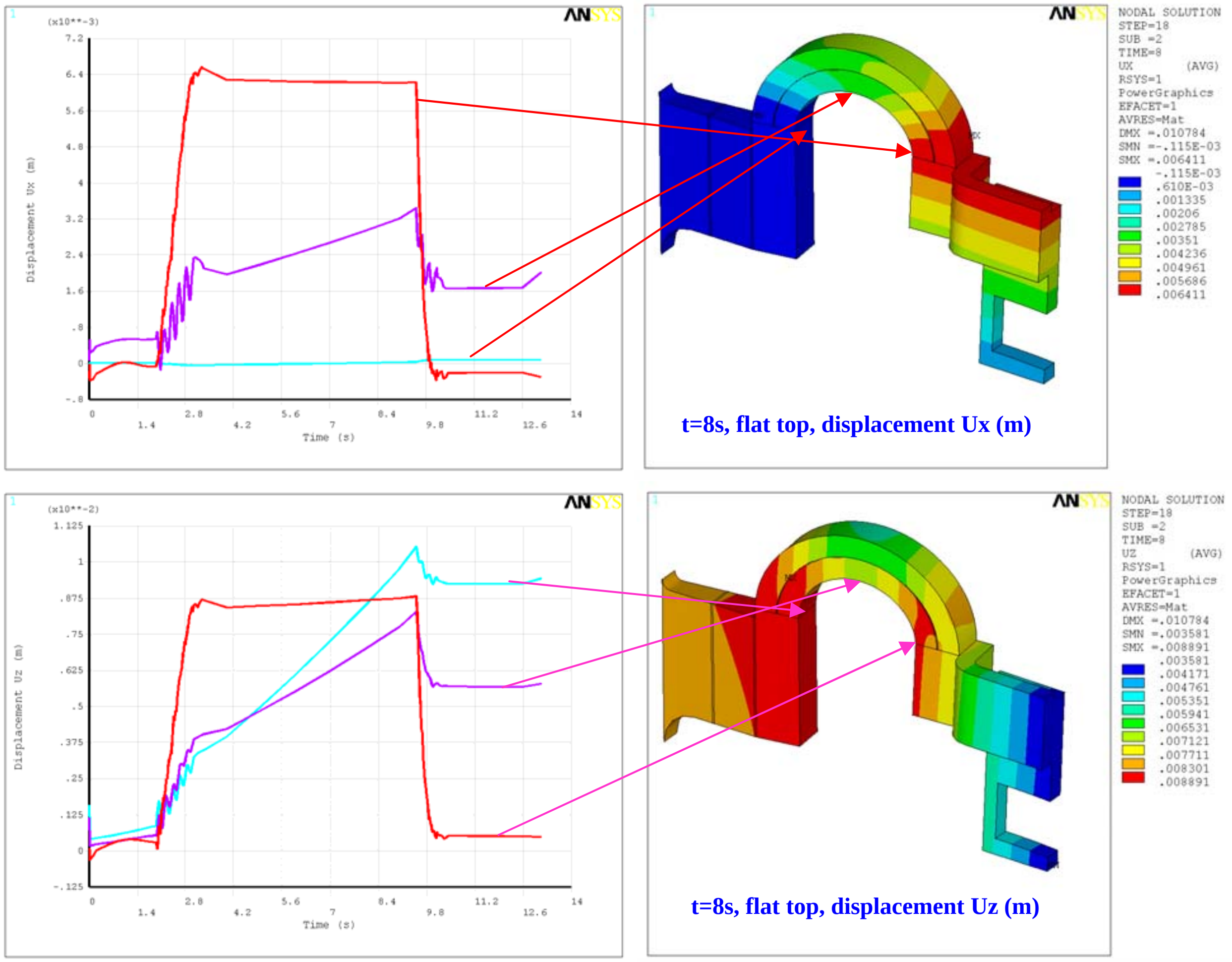
t=10.136s, end of waveform

Figure 9: The L-shape connection results in the theta deformation.



This L-shape connection results in the theta deformation upon self field

Figure 10: Time history plot of joint displacement Ux and Uz (m).



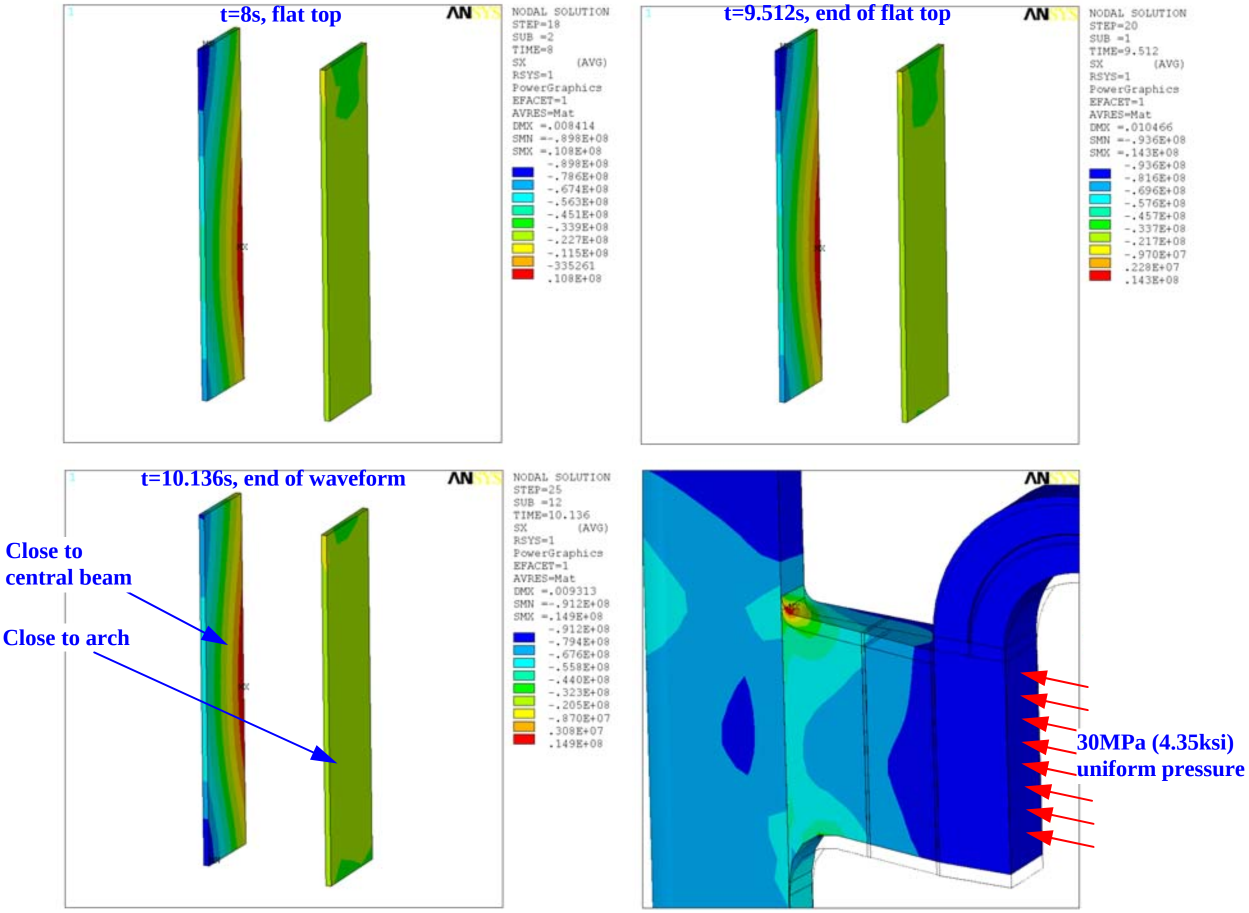
t=8s, flat top, displacement Ux (m)

t=8s, flat top, displacement Uz (m)

Contact pressure

Fig. 11 shows the stress in the contact regions. 30MPa (4.35ksi) pressure is given as shown in Fig. 11 as bolt pressure. The contact region close to arch can maintain adequate and uniform pressure. But the contact close to central beam has separation and requires more bolts pressure to maintain contact.

Figure 11: Stress in contact regions (Pa).



Coil stresses

Fig. 12 shows the Von Mises stress and Fig. 13 is a closer view. Maximal stress is 371 MPa (53.7 ksi). Changing the small fillet into a bigger one or removing the extension of inner leg may help to reduce this stress concentration but this requires further study.

Fig. 14 shows the hoop stress in the upper part.

Figure 12: Coil Von Mises stress (Pa)

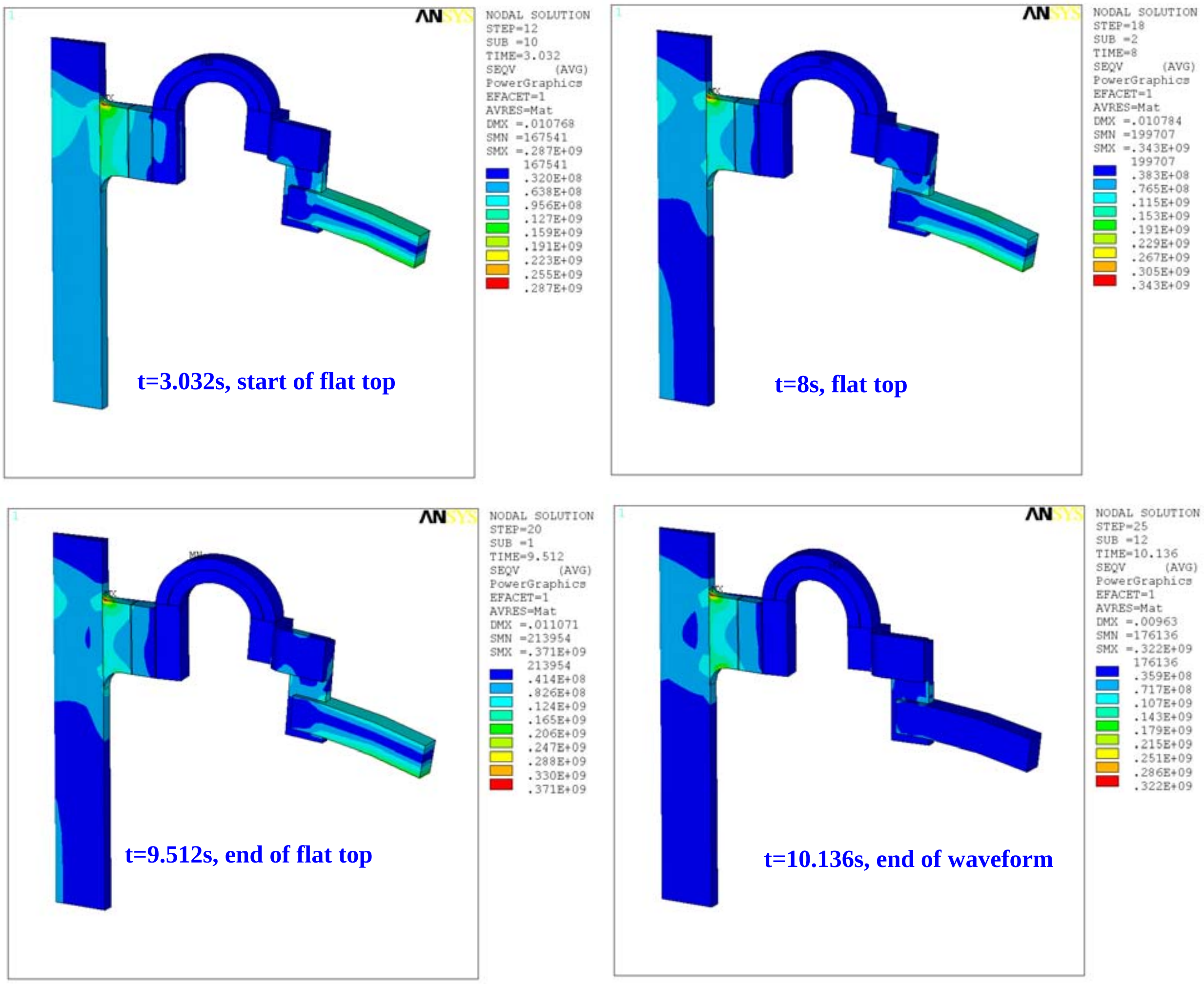
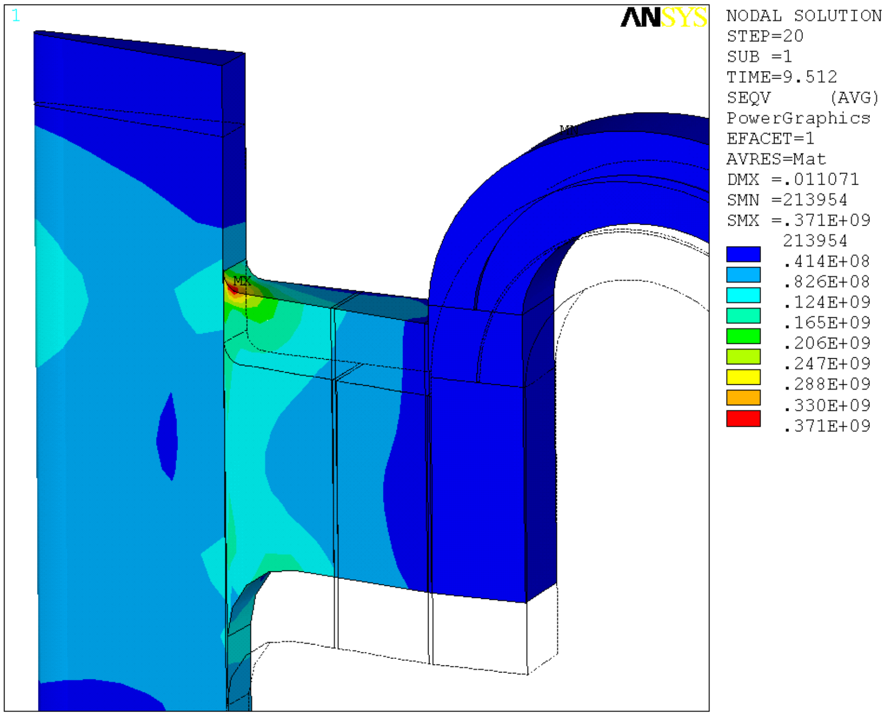


Figure 13: Close view of Von Mises stress (Pa).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ANSYS
MX
MN
NODAL SOLUTION
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SUB =1
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SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.011071
SMN =213954
SMX =.371E+09
213954
.414E+08
.826E+08
.124E+09
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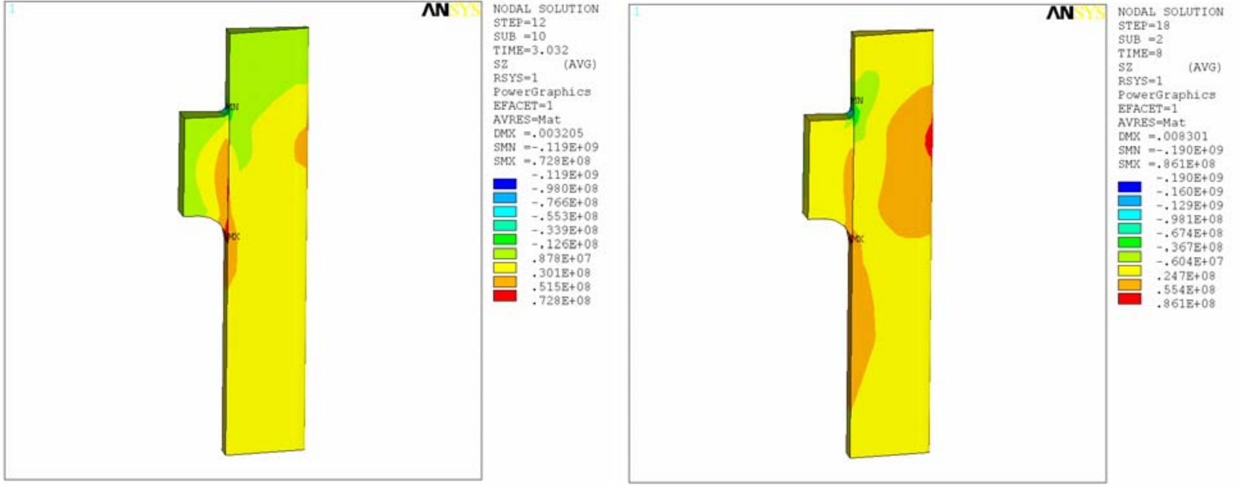
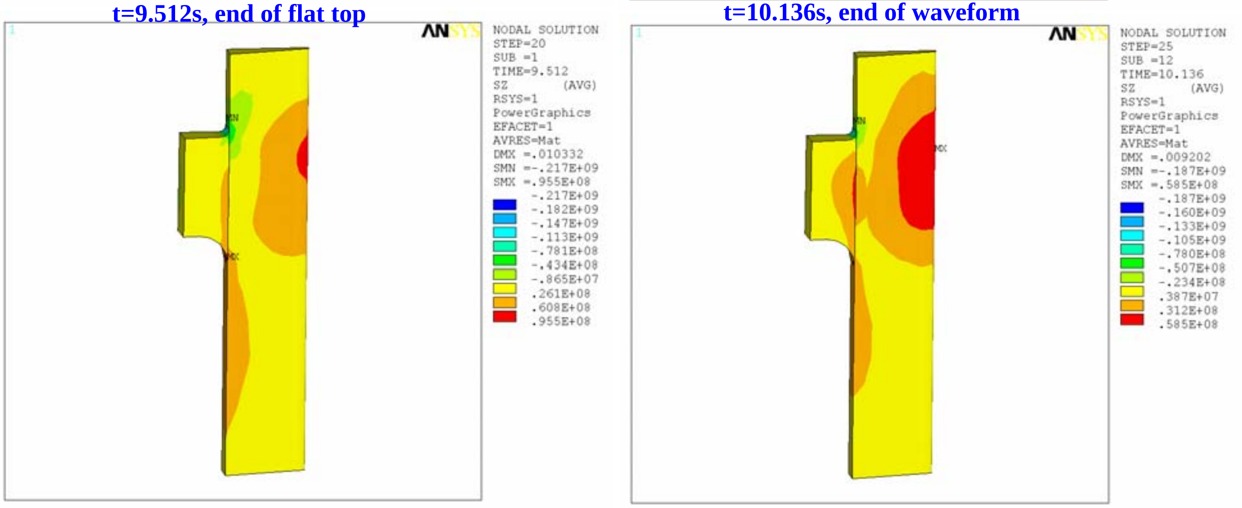
.288E+09
.330E+09
.371E+09

Figure 14: Hoop stress (Pa).



t=3.032s, start of flat top

t=8s, flat top



t=9.512s, end of flat top

t=10.136s, end of waveform

Current density, temperature and toroidal field in the arch area

Each arch is modeled with two solid parts but with anisotropic material properties to simulate the straps. Fig. 15 shows the current density and Fig. 16 shows the temperature in the straps (maximal temperature is 117ºC and maximal temperature difference between inside and outside is 61 ºC).

Fig. 17 shows the estimation of toroidal field in the arch area, which will be useful for the detailed modeling of joint force calculation. Average toroidal field is estimated by reading the radial component of Lorenz force and divided by conductor current and average length. Fig. 17A shows the location for Btheta estimation and B shows the results of radial component of Lorenz force (local coordinate center at the arch center), conductor current, length and the estimated Btheta.

Figure 15: Current density (A/m^2).

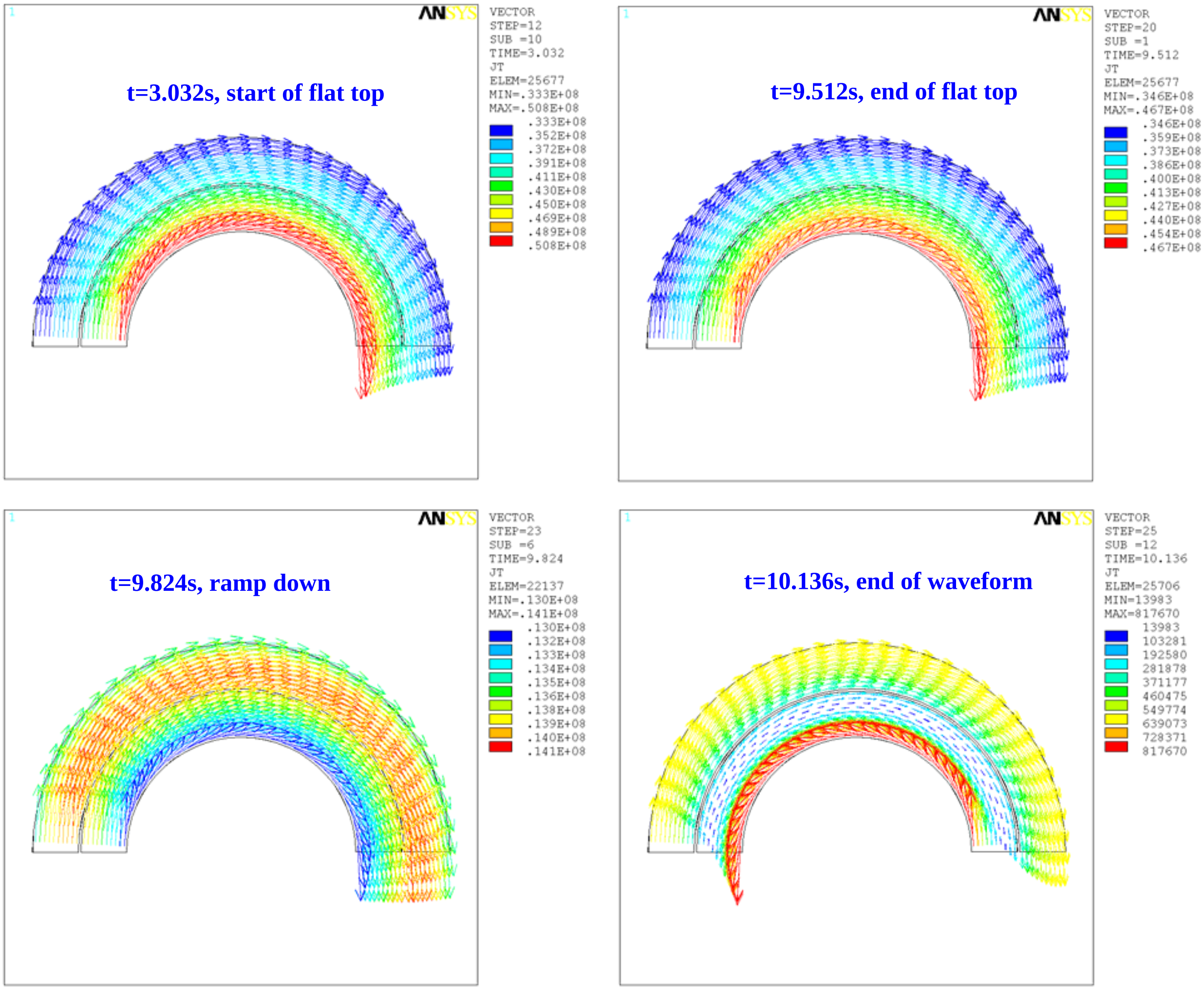


Figure 16: Temperature (K).

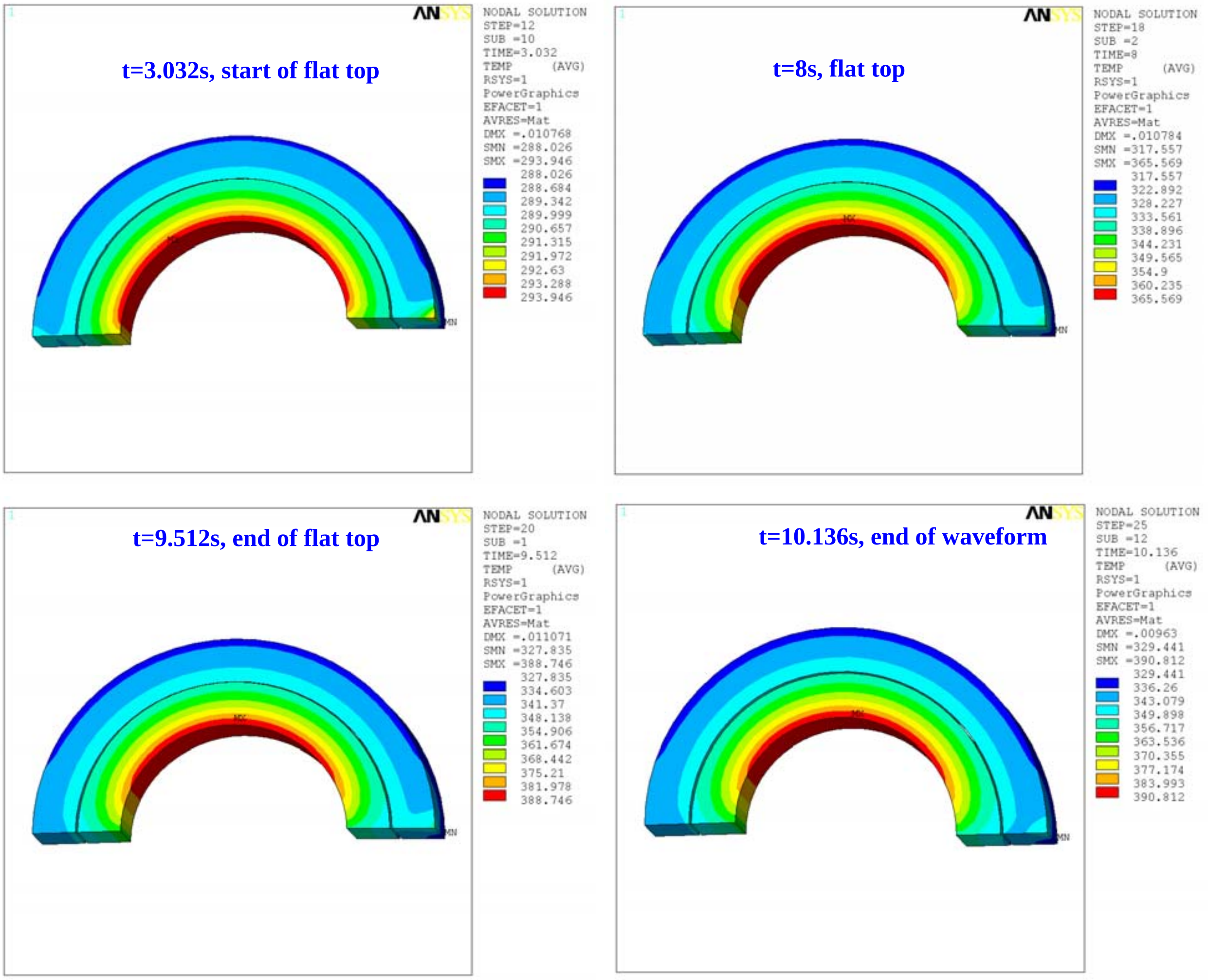
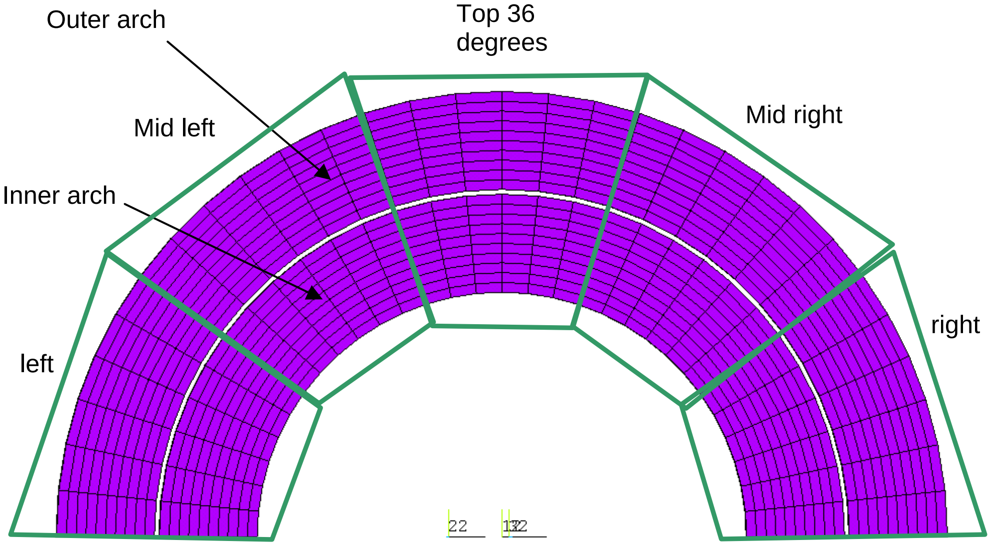


Figure 17: Toroidal field estimation.

A.



B.

	flat top (9s) each section: 36 degree							
	inner arch				**outer arch**			
	total Fmag_rad (N)	**curr (A)**	**length (m)**	**eqv B_theta (T)**	**total Fmag__rad (N)**	**curr (A)**	**length (m)**	**eqv B_theta (T)**
top 36 degree	5595	69465	0.120	**0.673**	1924	59402	0.162	**0.200**
mid left 36 degree	5962	69465	0.120	**0.717**	2038	59402	0.162	**0.212**
left 36 degree	6338	69465	0.120	**0.762**	2303	59402	0.162	**0.240**
mid right 36 degree	5310	69465	0.120	**0.639**	1799	59402	0.162	**0.187**
right 36 degree	4964	69465	0.120	**0.597**	1549	59402	0.162	**0.161**

Appendix

ANSYS code for pulse waveform (from [1])

```
!    NSTX Normal Pulse
NumSteps=29
tfbscale=1.0
t1= .1   $ i1= 0
t2= .2  $ i2= 0
t3= 1.952   $ i3= 15690.906*tfbscale
t4= 2.072   $ i4= 38658.746*tfbscale
t5= 2.192   $ i5= 58169.054*tfbscale
t6= 2.312   $ i6= 74742.32*tfbscale
t7= 2.432   $ i7= 88820.681*tfbscale
t8= 2.552   $ i8= 100779.71*tfbscale
t9= 2.672   $ i9= 110938.46*tfbscale
t10= 2.792   $ i10= 119567.93*tfbscale
t11= 2.912   $ i11= 126898.33*tfbscale
t12= 3.032   $ i12= 129777.84*tfbscale
t13= 4.0   $ i13= 129777.84*tfbscale
t14= 5.0     $ i14= 129777.84*tfbscale
t15= 6.0   $ i15= 129777.84*tfbscale
t16= 7.0   $ i16= 129777.84*tfbscale
t17= 8.0   $ i17= 129777.84*tfbscale
t18= 9.0   $ i18= 129777.84*tfbscale
t19= 9.512   $ i19= 129777.84*tfbscale
t20= 9.632   $ i20= 91022.609*tfbscale
t21= 9.752   $ i21= 58895.183*tfbscale
t22= 9.872   $ i22= 32262.092*tfbscale
```

```
t23= 9.992   $ i23= 10183.711*tfbscale
t24= 10.136   $ i24= 0
t25= 15.0   $ i25= 0
t26= 20.0   $ i26= 0
t27= 30.0   $ i27= 0
t28= 40.0   $ i28= 0
t29= 1200.0   $ i29= 0
```

The batch code for solution

The database models was built from ProE design model and modified in ANSYS. Following is the batch solution code.

```
/clear,start

/filnam,electromag_bc_BeCu
resume,electromag_bc_BeCu,db

/solu
allsel,all
csys,0
antype,trans              ! transient solution

!t_init=1E-10             ! initialize time for static solution

EQSLV,SPARSE

t_init=0.01      ! initialize time for static solution

timestep=0.002
risetime=0.01
timint,ON        ! time-integration effects on for transient solution
time,risetime    ! step down within "risetime"
KBC,1            ! step load KBC,1. ramp load KBC,0
deltim,timestep
outres,,2
allsel,all
csys,0
F,curr_nd1,amps,0
F,curr_nd2,amps,0
F,curr_nd3,amps,0
solve

save
finish


/filnam,thermstress_BeCu
resume,thermstress_BeCu,db
```

```
/solu
allsel,all
csys,0
antype,trans              ! transient solution

!t_init=1E-10             ! initialize time for static solution

EQSLV,SPARSE

t_init=0.01      ! initialize time for static solution

timestep=0.002
risetime=0.01
timint,ON       ! time-integration effects on for transient solution
time,risetime   ! step down within "risetime"
KBC,1           ! step load KBC,1. ramp load KBC,0
deltim,timestep
outres,,2
allsel,all
csys,0
ldread,hgen,last,,,,electromag_bc_BeCu,rst
ldread,forc,last,,,,electromag_bc_BeCu,rst
solve

save
finish

/post1

set,last
allsel,all
csys,1
rsys,1
i=1
*get,cn_pres,node,cn_no(i),s,x
*if,cn_pres,ge,399E6,then
  cn_pres=399E6
*endif

/OUTPUT,contacnd_pres,txt
*VWRITE,(-cn_pres/1E6+400)
(F20.5)
/OUTPUT
*enddo
*do,i,2,cn_n,1
  *get,cn_pres,node,cn_no(i),s,x
  *if,cn_pres,ge,399E6,then
    cn_pres=399E6
```

```
  *endif
  /OUTPUT,contacnd_pres,txt,,APPEND
  *VWRITE,(-cn_pres/1E6+400)
  (F20.5)
  /OUTPUT
*enddo

finish


*create,EM_thermstress         !arg1=timestep,arg2=endtime,arg3=curr,arg4=outres

/filnam,electromag_bc_BeCu
resume,electromag_bc_BeCu,db

/solu
allsel,all
csys,0
antype,trans,rest                    ! transient solution
EQSLV,SPARSE

   timestep=arg1          ! 5 steps.
   risetime=arg2
   timint,ON              ! time-integration effects on for transient solution
   time,risetime! step down within "risetime"
   KBC,0                  ! step load. ramp load KBC,0
   deltim,timestep
   outres,,arg4
   allsel,all
   csys,0
   F,curr_nd1,amps,arg3
   F,curr_nd2,amps,arg3
   F,curr_nd3,amps,arg3
   ldread,temp,last,,,,thermstress_BeCu,rst

! ************************************************************************
! apply contact pressure
! ************************************************************************
*dim,cn_pres,array,cn_n
*VREAD,cn_pres(1),contacnd_pres,txt
(F20.5)
*do,i,1,cn_n,1
  bf,cn_no(i),temp,cn_pres(i)
*enddo

solve

save
finish
```

```
/filnam,thermstress_BeCu
resume,thermstress_BeCu,db

/solu
allsel,all
csys,0
antype,trans,rest                    ! transient solution
EQSLV,SPARSE

   timestep=arg1          ! 5 steps.
   risetime=arg2
   timint,ON              ! time-integration effects on for transient solution
   time,risetime! step down within "risetime"
   KBC,0                  ! step load. ramp load KBC,0
   deltim,timestep
   outres,,arg4
   allsel,all
   csys,0
   ldread,hgen,last,,,,electromag_bc_BeCu,rst
   ldread,forc,last,,,,electromag_bc_BeCu,rst

solve

save
finish

/post1

set,last
allsel,all
csys,1
rsys,1
i=1
*get,cn_pres,node,cn_no(i),s,x
*if,cn_pres,ge,399E6,then
  cn_pres=399E6
*endif
/OUTPUT,contacnd_pres,txt
*VWRITE,(-cn_pres/1E6+400)
(F20.5)
/OUTPUT
*enddo
*do,i,2,cn_n,1
  *get,cn_pres,node,cn_no(i),s,x
  *if,cn_pres,ge,399E6,then
    cn_pres=399E6
  *endif
```

```
  /OUTPUT,contacnd_pres,txt,,APPEND
  *VWRITE,(-cn_pres/1E6+400)
  (F20.5)
  /OUTPUT
*enddo

finish


*end


*use,EM_thermstress,(5e-2),t2,i2,2    !before ramp up.

! ****************************************************************************************
! ramp up
! ****************************************************************************************
*use,EM_thermstress,(0.1),t3,i3,2      !timestep,endtime,curr,outres

*do,loop,4,12,1

*use,EM_thermstress,(0.012),t%loop%,i%loop%,2  !timestep,endtime,curr,outres

*enddo


! ****************************************************************************************
! start of flat top
! ****************************************************************************************
loop=12
*use,EM_thermstress,(0.03),(t%loop%+0.3),i%loop%,2


! ****************************************************************************************
! flat top
! ****************************************************************************************
*do,loop,13,19,1
  *use,EM_thermstress,(0.5),t%loop%,i%loop%,2
*enddo

! ****************************************************************************************
! ramp down
! ****************************************************************************************
*do,loop,20,24,1
  *use,EM_thermstress,(0.012),t%loop%,i%loop%,2
*enddo


! ****************************************************************************************
```

```
! ramp down ends
! ********************************************************************************
loop=24
  *use,EM_thermstress,(0.03),(t%loop%+0.3),i%loop%,2

! ********************************************************************************
! curr=0
! ********************************************************************************
loop=24
  *use,EM_thermstress,(0.5),(t%loop%+3),i%loop%,2
```

Part II

To avoid bending of TF inner leg, some structural supports will be added to the upper flags and the fillet radius of upper flag is modified to be bigger, which will help to reduce the temperature at the corner. Thus the model was modified and ran again to know how much temperature reduction. To avoid the work of re-mesh, only the positions of the nodes at fillet are modified and the radius may not be accurate. Also active water cooling is added with changeable parameters. Current waveform is same as before, normal operation pulse.

Coil temperature reaches maximum at the end of the pulse (Fig. 1), i.e., 10.136 s for normal operation. Without active cooling during the pulse, maximal temperature of the inner coil is 117 ºC, at the inner side of lower flag. Upper flag has more material (Fig. 1) and thus the max temperature is a little lower, 112 ºC. With active water cooling (0.25” diameter tube, 3 m/s coolant velocity and inlet temperature of 12 ºC), the maximal temperature of lower flag drops to 113.4 ºC and that of upper flag becomes 110.8 ºC (Fig. 1).

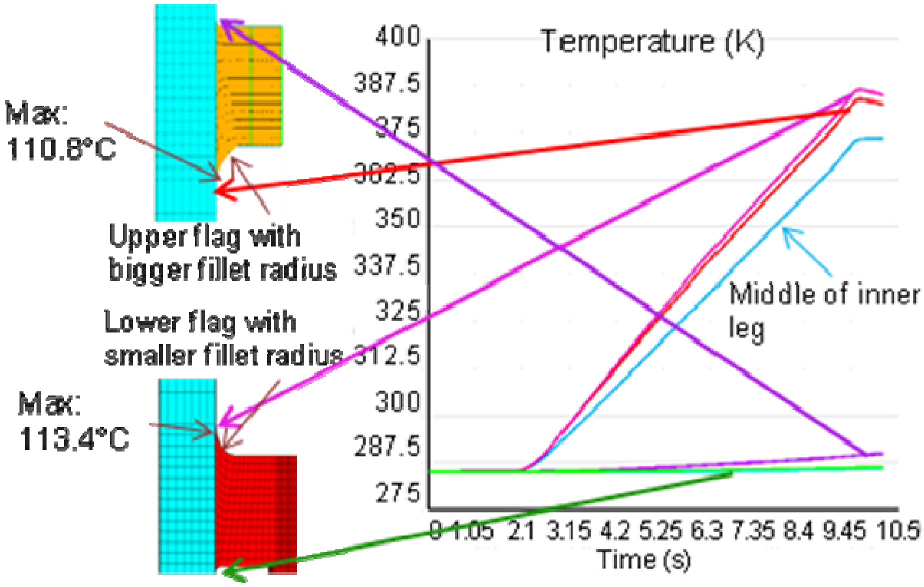


Figure 1: Temperature rise in TF inner coil with water cooling (0.25” diameter tube, 3 m/s coolant velocity and inlet temperature of 12 ºC).

The epoxy to bond TF coils has thermal expansion coefficient of 1.362E-5 /°C. The thermal expansion coefficient of copper is 1.54E-5 /°C at 0 °C and 1.6E-5 /°C at 100 °C. Different thermal expansion between copper and epoxy may cause delamination. Currently there are two ideas to place the cooling line, in the middle or at the side of the coil. Both are evaluated. Fig. 2 shows that putting cooling line at side produces lower Stheta (i.e. stress component that can cause delamination) of 90 MPa than putting cooling lines in the middle, because latter will cool the coil down faster and result in more shrinkage. In these analyses, 0.3” tube is used with 3 m/s velocity and it takes 5 minutes to cool the inner coil down to room temperature. If the cooling process can be slower, for example, by using a 0.25” tube and the same velocity, the stress Stheta can be reduced to 48 MPa (Fig. 3). Total cooling time of using 0.25” tube hasn’t been calculated yet. It is still unknown to us how much stress will cause delamination but we are trying to reduce it as much as possible. To reduce Stheta, it is better to cool down slowly. Using thinner tubes, lower coolant speed and different cooling line positions are all options. Note that the analysis process of Fig. 2 and 3 are different. In Fig. 2, when I run the coupled field (EM and thermal) simulation, there is no cooling during the pulse. Cooling parameters were calculated by Ali Zolfaghari using FCOOL, then transferred the temperature data to me. I directly applied the temperature profile to the cooling line (nodes) in the model and calculated from 10.136 s. Thus the start time point in Fig. 2 is 10.136 s (the end of the pulse). In Fig. 3, I added a cooling calculation in the model (similar to the code of ACOOL) and re-run the coupled field simulation and cooling is added during pulse. Fig. 3 simulates the time period from 0 s to 10.136 s (during the pulse).

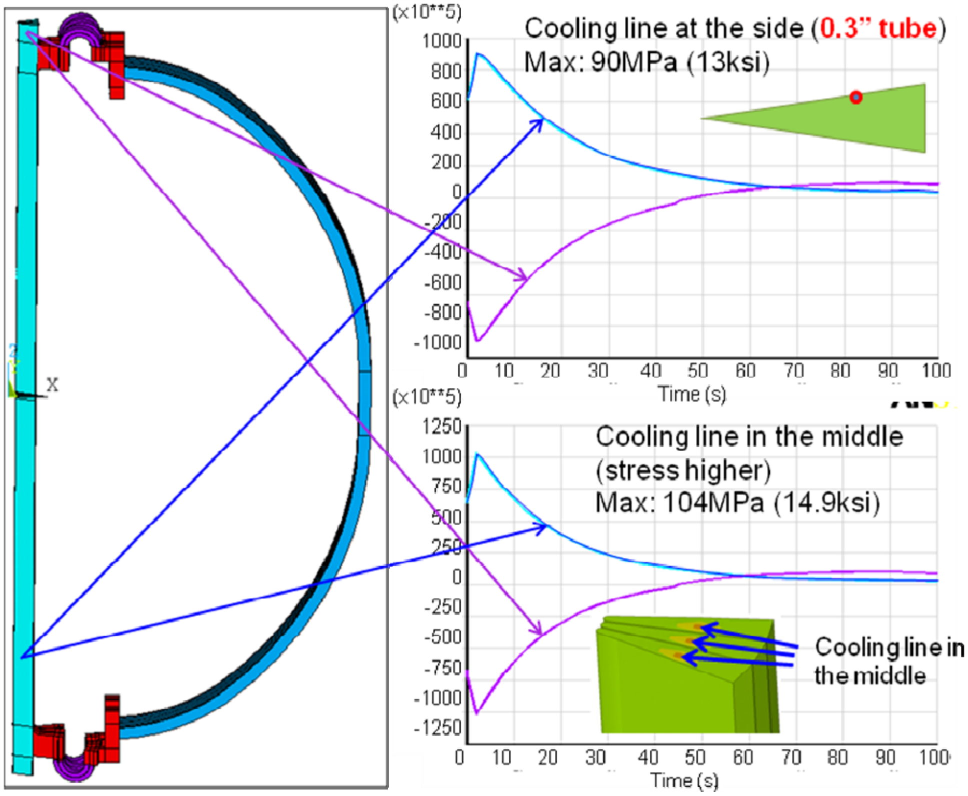


Figure 2: History plot of stress S_{theta} (Pa) in TF coil with water cooling (0.3” tube, 3 m/s).

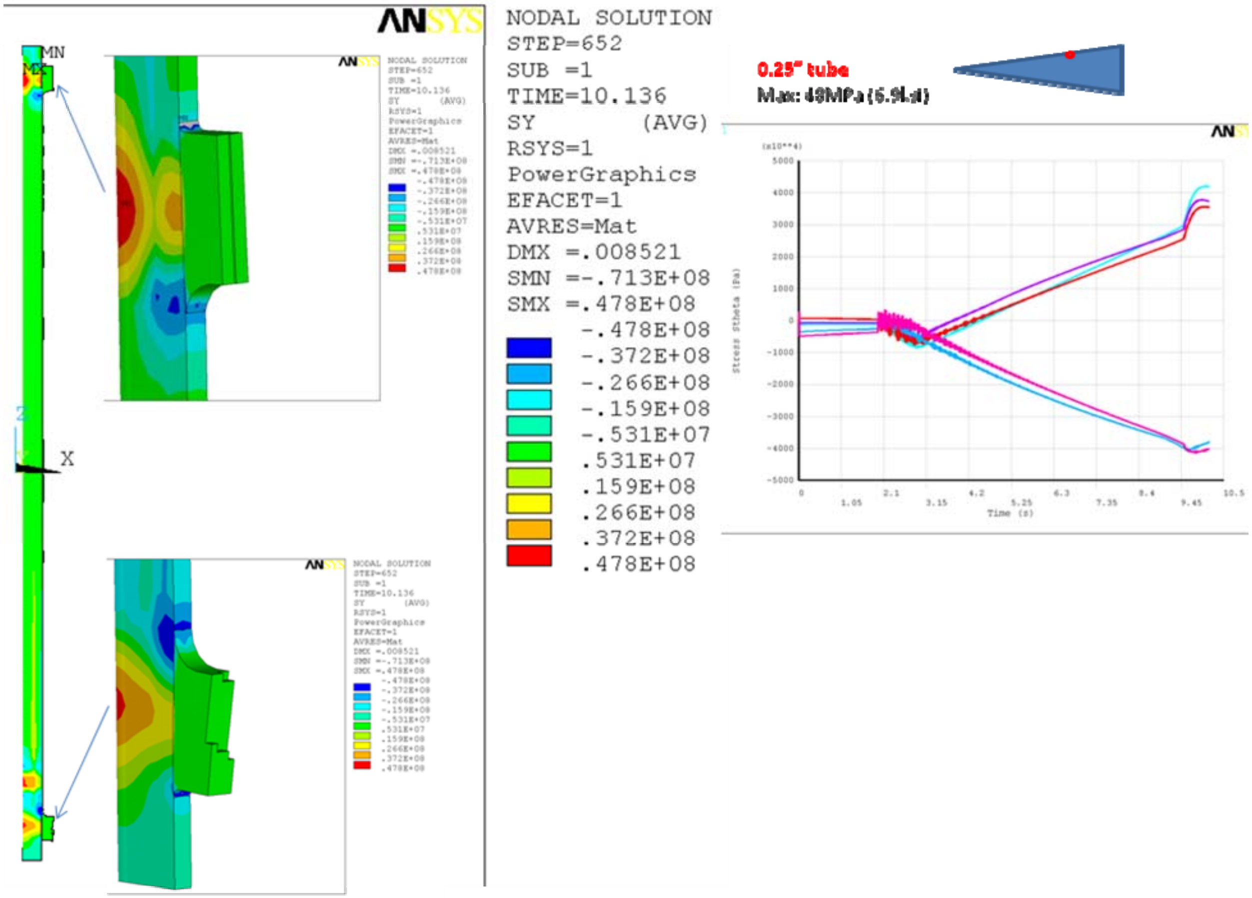


Figure 3: History plot of stress S_{theta} (Pa) in TF coil with water cooling (0.25" tube, 3 m/s, tube at the side).

The max temperature in outer coil reaches only 47 ºC at the end of pulse. But to avoid further temperature rise upon following pulses, active cooling is simulated. With cooling line of 0.5" tube diameter, 3 m/s velocity and tube attached to the surface of outer coil (Fig. 4), the coil can be cooled down to 25 ºC in 5 minutes (Fig. 5, 6).

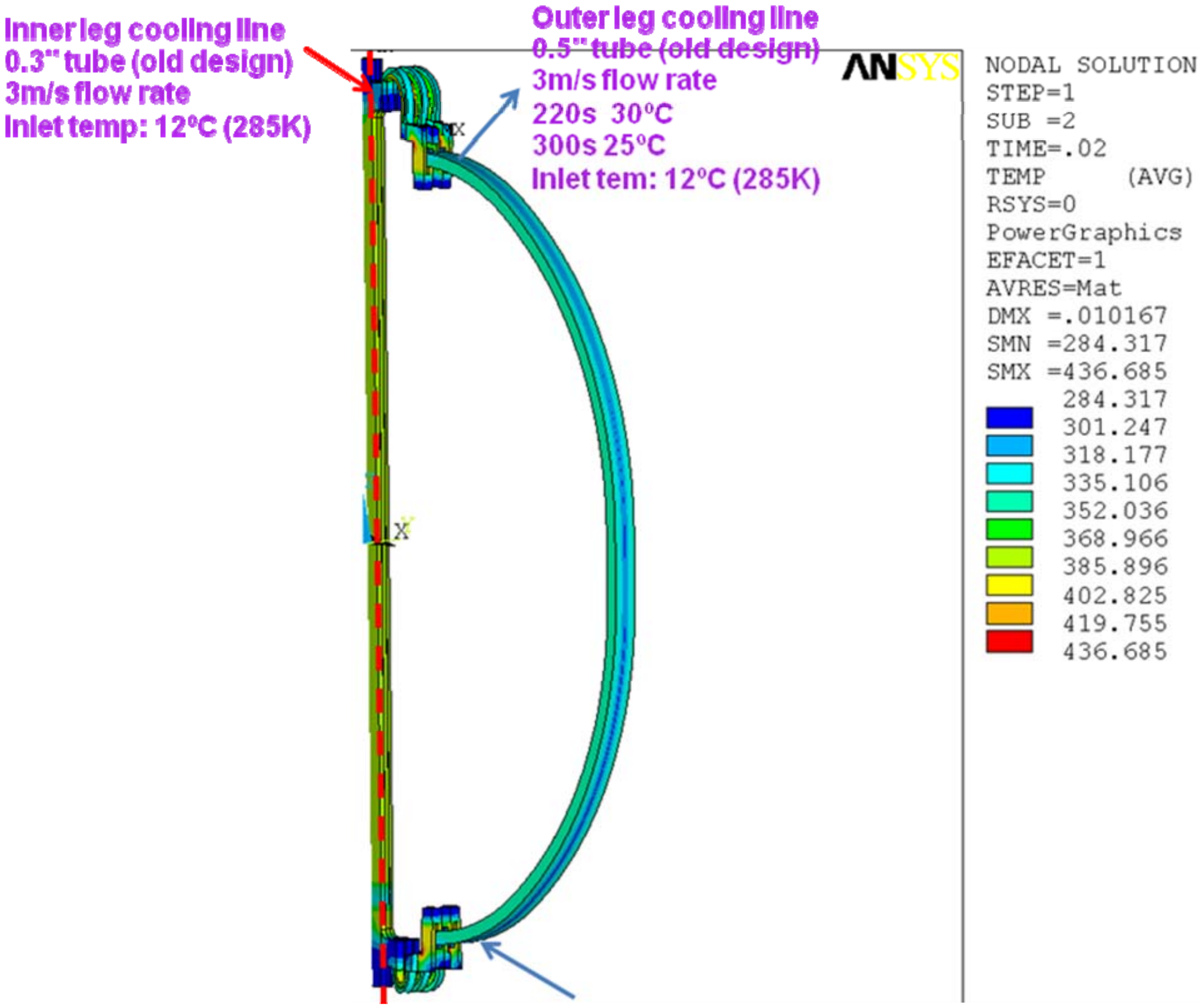


Figure 4: Add cooling line to TF outer coil, attached to the outer surface (0.25” tube, 3 m/s).

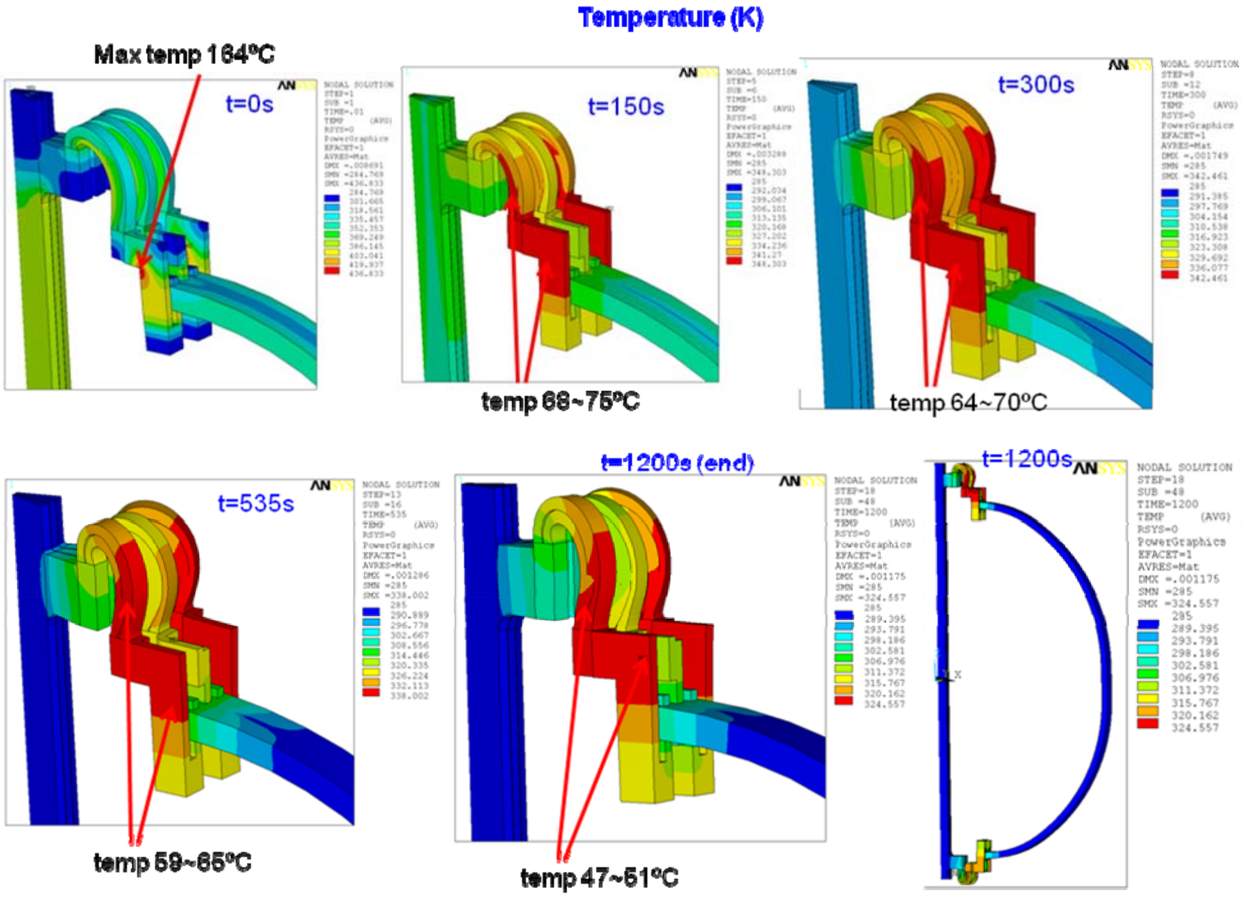


Figure 5: Temperature distribution at different time points, with active cooling in inner and outer coils (parameters shown in Fig. 4).

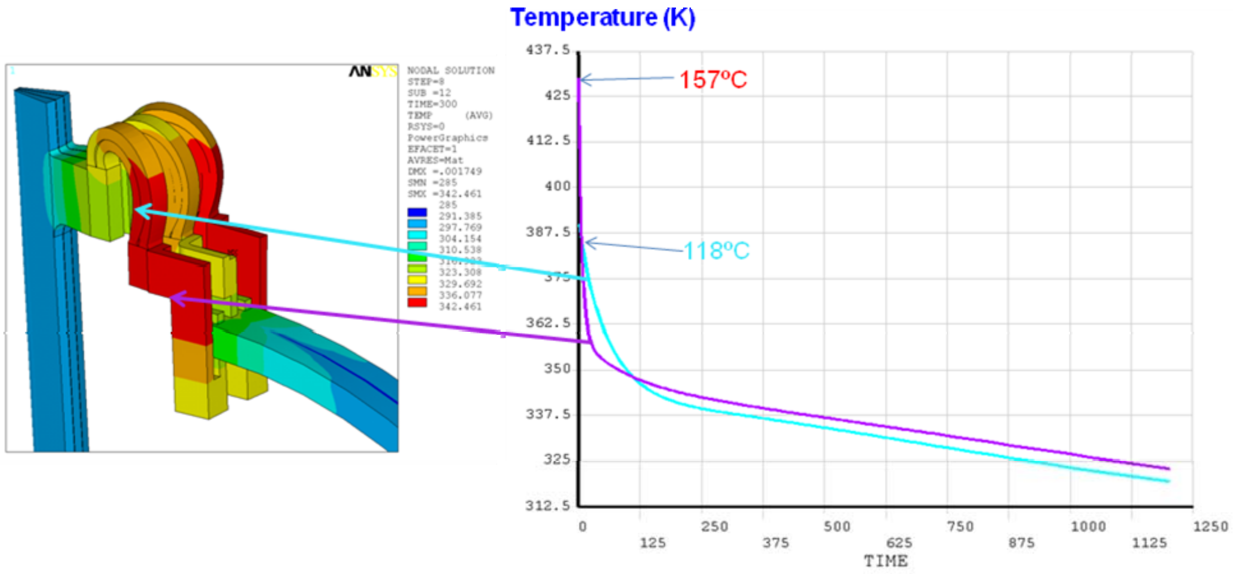


Figure 6: Temperature history plot, with active cooling in inner and outer coils (parameters shown in Fig. 4).

In this model, the flex straps is modeled by two solid pieces. But in reality, they are made of many straps. So the arches in this model have anisotropic material properties. Mechanical properties are based on the local structure model results of Ref. [3]: the force to deflect 31 lamination assembly 0.3" vertically is 76.2 lbf; The flex assembly rotates 2.57 degrees with a torque of 100 in-lbf applied. I converted these data into the modulus of flex straps as follows:

mp,ex,2,0.92e9
mp,ey,2,0.92e9
mp,ez,2,0.92e9
mp,gxy,2,0.08e9
mp,gyz,2,0.08e9
mp,gxz,2,0.35385e9

(x is the arch circumferential direction, y is the arch radial direction and z is the arch central axis). In the Figs. 11 and 12 of Part I, the upper corner of upper flag has a high stress point, which is due to the high modulus used in the previous model. After re-calculate the modulus of flex strap and replot the stress, it is shown in Fig. 7, maximal stress is 124 MPa at 10.136 s.

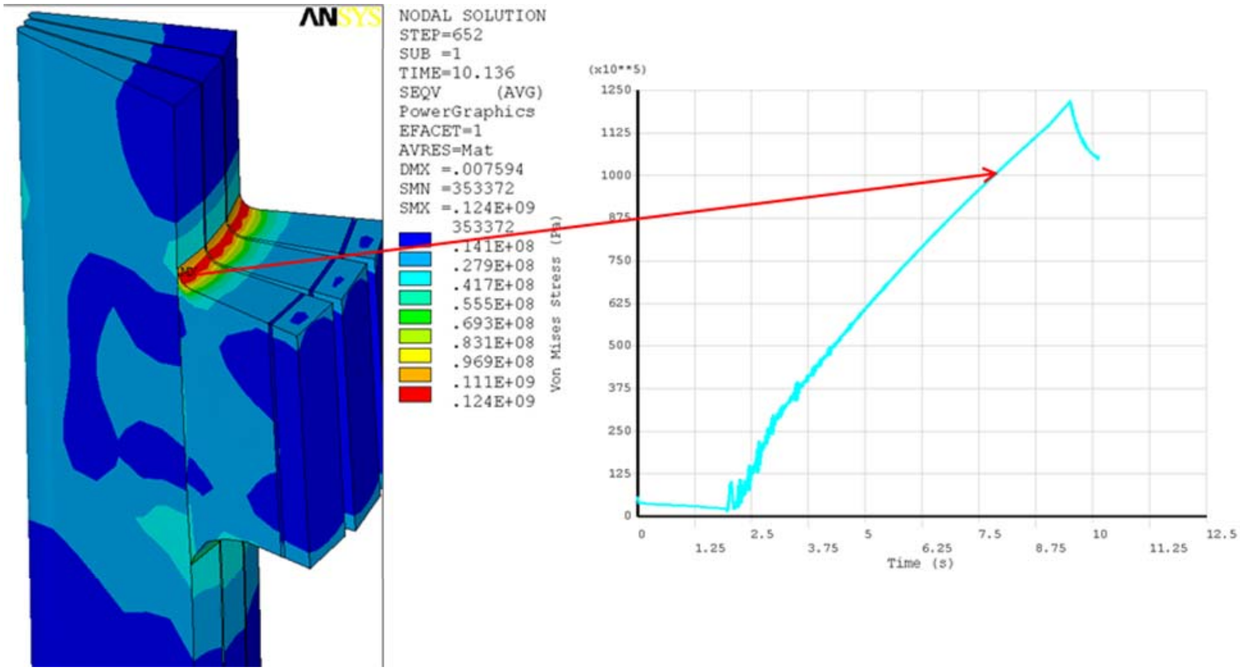


Fig. 7: Von Mises stress in the upper flag (Pa).

Because the upper flag has two contact regions, using high strength copper as the flag material can help to maintain high and uniform contact pressure and also lower contact resistance. But high strength copper has higher resistance and lower thermal conductivity. From the analysis, using high strength copper (1/0.8 resistivity and 80% thermal conductivity) causes temperature difference of less than 1 ºC. Thus high strength copper can be used if required to increase the pressure of joint bolt insert load over the capacity of pure copper.

REFERENCES

1. P. TITUS, “Coupled Electromagnetic-thermal Analysis (04072009)”, *NSTX-CALC-132-01-00*, 2009.

2. P. TITUS, “Coupled Electromagnetic-thermal Analysis (04202009)”, *NSTX-CALC-132-02-00*, 2009.
3. T. WILLARD, “TF Flex Joint and TF Bundle Stub”, *NSTX-CALC-132-06-00*, 2009.

Appendix

The batch code for solution

```
/clear,start
/NERR,,10000000                ! MAX ERROR/WARNING MESSAGE 10,000,000
/CONFIG,NRES,100000
/CONFIG,NBUF,30
/CONFIG,NPROC,2   ! 2 processors

/filnam,electromag_bc
resume,electromag_bc,db

/solu
allsel,all
csys,0
antype,trans              ! transient solution

!t_init=1E-10             ! initialize time for static solution

EQSLV,SPARSE
!EQSLV,PCG,,3
!EQSLV,ICCG,1e-6,2          ! toler=1e-6

t_init=0.01      ! initialize time for static solution

timestep=0.002
risetime=0.01
timint,ON       ! time-integration effects on for transient solution
time,risetime   ! step down within "risetime"
KBC,1           ! step load KBC,1. ramp load KBC,0
deltim,timestep
outres,,2
allsel,all
csys,0
F,curr_nd1,amps,0
F,curr_nd2,amps,0
F,curr_nd3,amps,0
solve

save
finish

!!!============================================
!!!calculate convection heat transfer coefficient
```

```
!!!==============================================
!!read temperature
*create,hcoef
t_avg=arg1
t_coolant=arg2

csys,1
allsel,all
*if,t_avg,ge,273+0,and,t_avg,lt,273+10,then
  PR=13.67
*elseif,t_avg,ge,273+10,and,t_avg,lt,273+20
  PR=9.47        !viscosity: m-Pa-s
*elseif,t_avg,ge,273+20,and,t_avg,le,273+30
  PR=7.01
*elseif,t_avg,ge,273+30,and,t_avg,lt,273+40
  PR=5.43
*elseif,t_avg,ge,273+40,and,t_avg,lt,273+50
  PR=4.34
*elseif,t_avg,ge,273+50,and,t_avg,lt,273+60
  PR=3.56
*elseif,t_avg,ge,273+60,and,t_avg,lt,273+70
  PR=2.99
*elseif,t_avg,ge,273+70,and,t_avg,lt,273+80
  PR=2.56
*elseif,t_avg,ge,273+80,and,t_avg,lt,273+90
  PR=2.23
*elseif,t_avg,ge,273+90,and,t_avg,lt,273+100
  PR=1.96
*elseif,t_avg,ge,273+100,and,t_avg,lt,273+120
  PR=1.75
*elseif,t_avg,ge,273+120,and,t_avg,lt,273+140
  PR=1.45
*elseif,t_avg,ge,273+140,and,t_avg,lt,273+160
  PR=1.25
*endif
visc=2.414E-5*(10**(247.8/(t_avg-140)))
RE=1000*flu_v*DH/visc
*if,t_avg,ge,t_coolant,then
   nnn=0.4
*else
   nnn=0.33
*endif
NU=0.023*(RE**0.8)*(PR**nnn)
h_coef=0.6*NU/DH

*end

!!!==============================================
!!! cooling
```

```
!!!================================================


!!!================================================
!!!end
!!!================================================


/filnam,thermstress
resume,thermstress,db

/solu
allsel,all
csys,0
antype,trans               ! transient solution

!t_init=1E-10              ! initialize time for static solution

EQSLV,SPARSE
!EQSLV,PCG,,3
!EQSLV,ICCG,1e-6,2          ! toler=1e-6

t_init=0.01      ! initialize time for static solution

timestep=0.002
risetime=0.01
timint,ON       ! time-integration effects on for transient solution
time,risetime   ! step down within "risetime"
KBC,1           ! step load KBC,1. ramp load KBC,0
deltim,timestep
outres,,2
allsel,all
csys,0
ldread,hgen,last,,,,electromag_bc,rst
ldread,forc,last,,,,electromag_bc,rst

allsel,all
csys,0
cmsel,s,cooling_line
d,all,temp,12+273
allsel,all

solve

save
finish
```

```
/post1

set,last
allsel,all
csys,1
rsys,1
i=1
*get,cn_pres,node,cn_no(i),s,x
*if,cn_pres,ge,429E6,then
  cn_pres=429E6
*elseif,cn_pres,lt,-30E6
  cn_pres=-30E6
*endif


/OUTPUT,contacnd_pres,txt
*VWRITE,(-cn_pres/1E6+430)
(F20.5)
/OUTPUT

*do,i,2,cn_n,1
  *get,cn_pres,node,cn_no(i),s,x
  *if,cn_pres,ge,429E6,then
    cn_pres=429E6
  *elseif,cn_pres,lt,-30E6
    cn_pres=-30E6
  *endif
  /OUTPUT,contacnd_pres,txt,,APPEND
  *VWRITE,(-cn_pres/1E6+430)
  (F20.5)
  /OUTPUT
*enddo

finish




*create,EM      !arg1=timestep,arg2=endtime,arg3=curr,arg4=outres

parsav,all,parfile,data

/filnam,electromag_bc
resume,electromag_bc,db

/solu
allsel,all
csys,0
antype,trans,rest                    ! transient solution
```

```
EQSLV,SPARSE

   timestep=arg1          ! 5 steps.
   risetime=arg2
   timint,ON              ! time-integration effects on for transient solution
   time,risetime! step down within "risetime"
   KBC,0                  ! step load. ramp load KBC,0
   deltim,timestep
   outres,,arg4
   allsel,all
   csys,0
   F,curr_nd1,amps,arg3
   F,curr_nd2,amps,arg3
   F,curr_nd3,amps,arg3
   ldread,temp,last,,,,thermstress,rst

! ************************************************************************
! apply contact pressure
! ************************************************************************
*dim,cn_pres,array,cn_n
*VREAD,cn_pres(1),contacnd_pres,txt
(F20.5)
*do,i,1,cn_n,1
  bf,cn_no(i),temp,cn_pres(i)
*enddo

solve

save
finish

parres,new,parfile,data

*end


*create,thermstress

parsav,all,parfile,data

/filnam,thermstress
resume,thermstress,db

/solu
allsel,all
csys,0
antype,trans,rest                  ! transient solution
EQSLV,SPARSE
```

```
  timestep=arg1          ! 5 steps.
  risetime=arg2
  curr=arg3
  timint,ON              ! time-integration effects on for transient solution
  time,risetime! step down within "risetime"
  KBC,0                  ! step load. ramp load KBC,0
  deltim,timestep
  outres,,arg4
  allsel,all
  csys,0
  ldread,hgen,last,,,,electromag_bc,rst
  ldread,forc,last,,,,electromag_bc,rst


!!!hcool
tm_step=arg1

allsel,all
csys,1
t2_coolant(1)=12+273
t1_coolant(1)=12+273
z_bottom=NZ(cooling_nd(1))

*do,i,1,83,1
  allsel,all
  esel,s,mat,,1
  nsle,s
  nsel,r,loc,z,NZ(cooling_nd(i))-5e-4,NZ(cooling_nd(i))+5e-4
  n_str=0
  tc_avg=0
  *get,nnum,node,,count
  *do,j,1,nnum,1
    n_nxt=NDNEXT(n_str)
    *get,n_temp,node,n_nxt,temp
    tc_avg=tc_avg+n_temp
  *enddo
  tc_avg=tc_avg/nnum
  *if,i,eq,1,then
      l_elem=(NZ(cooling_nd(i+1))-NZ(cooling_nd(i)))/2
      l_flow=l_elem
  *elseif,i,eq,83
      l_elem=(NZ(cooling_nd(i))-NZ(cooling_nd(i-1)))/2
      l_flow=l_elem
  *else
      l_elem=(NZ(cooling_nd(i+1))-NZ(cooling_nd(i-1)))/2
      l_flow=NZ(cooling_nd(i+1))-NZ(cooling_nd(i))
      *if,l_flow,gt,NZ(cooling_nd(i))-NZ(cooling_nd(i-1)),then
        l_flow=NZ(cooling_nd(i))-NZ(cooling_nd(i-1))
      *endif
```

```
   *endif


      KA_L1=170/0.136525
      a_transf=3.1415926*DH
      *use,hcoef,tc_avg,t2_coolant(NZ(cooling_nd(i)))
      HA2=h_coef*a_transf
      t_wall=(KA_L1*tc_avg+HA2*t2_coolant(NZ(cooling_nd(i))))/(KA_L1+HA2)
      *if,t_wall,ge,(100+273),then
          t_wall=100+273
      *endif
      q_heat=KA_L1*(tc_avg-t_wall)*l_elem
      m_coolant=1000*l_elem*3.1415926*(DH**2)/4
      t1_coolant(i)=t2_coolant(NZ(cooling_nd(i)))+q_heat*tm_step/4186/m_coolant
      *if,t1_coolant(i),ge,(100+273),then
          t1_coolant(i)=100+273
      *endif
      allsel,all
      cmsel,s,cooling_line
      nsel,r,loc,z,NZ(cooling_nd(i))-5e-4,NZ(cooling_nd(i))+5e-4
      d,all,temp,t_wall


*enddo



allsel,all
csys,1
t2_coolant(1)=12+273
z_bottom=NZ(cooling_nd(1))
*do,i,2,83,1
    *if,(NZ(cooling_nd(i))-tm_step*flu_v),gt,z_bottom,then
      t2_coolant(i)=t1_coolant(NZ(cooling_nd(i))-tm_step*flu_v)
    *else
      t2_coolant(i)=12+273
    *endif
    *if,t2_coolant(i),ge,(100+273),then
        t2_coolant(i)=100+273
    *endif
*enddo
t1_coolant(1)=12+273


   allsel,all
   csys,0

!!!==================================
!!! end
```

```
!!!===================================



solve

save
finish

/post1

set,last
allsel,all
csys,1
rsys,1
i=1
*get,cn_pres,node,cn_no(i),s,x
*if,cn_pres,ge,429E6,then
  cn_pres=429E6
*elseif,cn_pres,lt,-30E6
  cn_pres=-30E6
*endif


/OUTPUT,contacnd_pres,txt
*VWRITE,(-cn_pres/1E6+430)
(F20.5)
/OUTPUT

*do,i,2,cn_n,1
  *get,cn_pres,node,cn_no(i),s,x
  *if,cn_pres,ge,429E6,then
    cn_pres=429E6
  *elseif,cn_pres,lt,-30E6
    cn_pres=-30E6
  *endif
  /OUTPUT,contacnd_pres,txt,,APPEND
  *VWRITE,(-cn_pres/1E6+430)
  (F20.5)
  /OUTPUT
*enddo

finish

parres,new,parfile,data

*end
```

```
t_step=5e-2
*use,EM,(5e-2),t2,i2,2           !before ramp up.
*use,thermstress,(5e-2),t2,i2,2           !before ramp up.

! ************************************************************************
! ramp up
! ************************************************************************
*do,step,1,5,1

!  *use,EM_thermstress,(0.1),t3,i3,2  !timestep,endtime,curr,outres
  t_step=(t3-t2)/10
  *use,EM,((t3-t2)/10),(t2+(t3-t2)/5*step),(i2+(i3-i2)/5*step),2
  *use,thermstress,((t3-t2)/10),(t2+(t3-t2)/5*step),(i2+(i3-i2)/5*step),2
!timestep,endtime,curr,outres
*enddo

loopp=4
  *do,step,1,5,1
    t_step=(t4-t3)/10
    i_step=(i4-i3)/10
    *use,EM,t_step,(t3+t_step*2*step),(i3+i_step*2*step),2
    *use,thermstress,t_step,(t3+t_step*2*step-t_step),(i3+i_step*2*step-i_step),1
    *use,thermstress,t_step,(t3+t_step*2*step),(i3+i_step*2*step),1
    !!timestep,endtime,curr,outres
  *enddo

loopp=5
  *do,step,1,5,1
    t_step=(t5-t4)/10
    i_step=(i5-i4)/10
    *use,EM,t_step,(t4+t_step*2*step),(i4+i_step*2*step),2
    t_step=(t5-t4)/10
    i_step=(i5-i4)/10
    *use,thermstress,t_step,(t4+t_step*2*step-t_step),(i4+i_step*2*step-i_step),1
    t_step=(t5-t4)/10
    i_step=(i5-i4)/10
    *use,thermstress,t_step,(t4+t_step*2*step),(i4+i_step*2*step),1
    !!timestep,endtime,curr,outres
  *enddo

loopp=6
  *do,step,1,5,1
    t_step=(t6-t5)/10
    i_step=(i6-i5)/10
    *use,EM,t_step,(t5+t_step*2*step),(i5+i_step*2*step),2
    *use,thermstress,t_step,(t5+t_step*2*step-t_step),(i5+i_step*2*step-i_step),1
    *use,thermstress,t_step,(t5+t_step*2*step),(i5+i_step*2*step),1
```

```
    !timestep,endtime,curr,outres
  *enddo

loopp=7
  *do,step,1,5,1
    t_step=(t7-t6)/10
    i_step=(i7-i6)/10
    *use,EM,t_step,(t6+t_step*2*step),(i6+i_step*2*step),2
    *use,thermstress,t_step,(t6+t_step*2*step-t_step),(i6+i_step*2*step-i_step),1
    *use,thermstress,t_step,(t6+t_step*2*step),(i6+i_step*2*step),1
    !timestep,endtime,curr,outres
  *enddo

loopp=8
  *do,step,1,5,1
    t_step=(t8-t7)/10
    i_step=(i8-i7)/10
    *use,EM,t_step,(t7+t_step*2*step),(i7+i_step*2*step),2
    *use,thermstress,t_step,(t7+t_step*2*step-t_step),(i7+i_step*2*step-i_step),1
    *use,thermstress,t_step,(t7+t_step*2*step),(i7+i_step*2*step),1
    !timestep,endtime,curr,outres
  *enddo

loopp=9
  *do,step,1,5,1
    t_step=(t9-t8)/10
    i_step=(i9-i8)/10
    *use,EM,t_step,(t8+t_step*2*step),(i8+i_step*2*step),2
    t_step=(t9-t8)/10
    i_step=(i9-i8)/10
    *use,thermstress,t_step,(t8+t_step*2*step-t_step),(i8+i_step*2*step-i_step),1
    t_step=(t9-t8)/10
    i_step=(i9-i8)/10
    *use,thermstress,t_step,(t8+t_step*2*step),(i8+i_step*2*step),1
    !timestep,endtime,curr,outres
  *enddo

loopp=10
  *do,step,1,5,1
    t_step=(t10-t9)/10
    i_step=(i10-i9)/10
    *use,EM,t_step,(t9+t_step*2*step),(i9+i_step*2*step),2
    t_step=(t10-t9)/10
    i_step=(i10-i9)/10
    *use,thermstress,t_step,(t9+t_step*2*step-t_step),(i9+i_step*2*step-i_step),1
    t_step=(t10-t9)/10
    i_step=(i10-i9)/10
    *use,thermstress,t_step,(t9+t_step*2*step),(i9+i_step*2*step),1
    !timestep,endtime,curr,outres
```

```
  *enddo

loopp=11
  *do,step,1,5,1
    t_step=(t11-t10)/10
    i_step=(i11-i10)/10
    *use,EM,t_step,(t10+t_step*2*step),(i10+i_step*2*step),2
    t_step=(t11-t10)/10
    i_step=(i11-i10)/10
    *use,thermstress,t_step,(t10+t_step*2*step-t_step),(i10+i_step*2*step-t_step),1
    t_step=(t11-t10)/10
    i_step=(i11-i10)/10
    *use,thermstress,t_step,(t10+t_step*2*step),(i10+i_step*2*step),1
    !timestep,endtime,curr,outres
  *enddo

loopp=12
  *do,step,1,5,1
    t_step=(t12-t11)/10
    i_step=(i12-i11)/10
    *use,EM,t_step,(t11+t_step*2*step),(i11+i_step*2*step),2
    t_step=(t12-t11)/10
    i_step=(i12-i11)/10
    *use,thermstress,t_step,(t11+t_step*2*step-t_step),(i11+i_step*2*step-t_step),1
    t_step=(t12-t11)/10
    i_step=(i12-i11)/10
    *use,thermstress,t_step,(t11+t_step*2*step),(i11+i_step*2*step),1
    !timestep,endtime,curr,outres
  *enddo

! *************************************************************************
! start of flat top
! *************************************************************************
!loop=12
!*use,EM_thermstress,(0.03),(t%looprrr%+0.3),i%looprrr%,2
  *do,step,1,5,1
    t_step=0.03
    *use,EM,(0.03),(t12+0.3/10*2*step),(i12),2          !timestep,endtime,curr,outres
    t_step=0.02
    *use,thermstress,(0.02),(t12+0.3/10*2*step-0.04),(i12),1 !timestep,endtime,curr,outres
    t_step=0.02
    *use,thermstress,(0.02),(t12+0.3/10*2*step-0.02),(i12),1 !timestep,endtime,curr,outres
    t_step=0.02
    *use,thermstress,(0.02),(t12+0.3/10*2*step),(i12),1         !timestep,endtime,curr,outres
  *enddo


  *do,step,1,2,1
    t_step=(t13-t12-0.3)/4
```

```
    *use,EM,((t13-t12-0.3)/4),(t12+0.3+(t13-t12-0.3)/2*step),(i13),2
!timestep,endtime,curr,outres
  *enddo

  *do,step,1,50,1
    t_step=(t13-t12-0.3)/50
    *use,thermstress,((t13-t12-0.3)/50),(t12+0.3+(t13-t12-0.3)/50*step),(i13),1
!timestep,endtime,curr,outres
  *enddo


! ************************************************************************
! flat top
! ************************************************************************
!*do,loopp,14,19,1
loopp=14
*do,step,1,5,1
t_step=((t18-t13)/5)
*use,EM,((t18-t13)/5),(t13+(t18-t13)/5*step),i14,1
*enddo


*do,step,1,400,1
t_step=((t18-t13)/400)
*use,thermstress,((t18-t13)/400),(t13+(t18-t13)/400*step),i14,1
*enddo

loopp=19
t_step=((t19-t18)/2)
*use,EM,((t19-t18)/4),(t18+(t19-t18)/2),i19,2
*use,EM,((t19-t18)/4),(t19),i19,2

*do,step,1,40,1
t_step=((t19-t18)/40)
*use,thermstress,((t19-t18)/40),(t18+(t19-t18)/40*step),i14,1
*enddo




! ************************************************************************
! ramp down
! ************************************************************************
!*do,loopp,20,24,1
  loopp=20
  *do,step,1,5,1
    t_step=(t20-t19)/10
    i_step=(i20-i19)/10
    *use,EM,t_step,(t19+t_step*2*step),(i19+i_step*2*step),2
```

```
    t_step=(t20-t19)/10
    i_step=(i20-i19)/10
    *use,thermstress,t_step,(t19+t_step*2*step-t_step),(i19+i_step*2*step-i_step),1
    t_step=(t20-t19)/10
    i_step=(i20-i19)/10
    *use,thermstress,t_step,(t19+t_step*2*step),(i19+i_step*2*step),1
!timestep,endtime,curr,outres
  *enddo
!*enddo

!*do,loopp,20,24,1
  loopp=21
  *do,step,1,5,1
    t_step=(t21-t20)/10
    i_step=(i21-i20)/10
    *use,EM,t_step,(t20+t_step*2*step),(i20+i_step*2*step),2
    t_step=(t21-t20)/10
    i_step=(i21-i20)/10
    *use,thermstress,t_step,(t20+t_step*2*step-t_step),(i20+i_step*2*step-i_step),1
    t_step=(t21-t20)/10
    i_step=(i21-i20)/10
    *use,thermstress,t_step,(t20+t_step*2*step),(i20+i_step*2*step),1
!timestep,endtime,curr,outres
  *enddo
!*enddo

!*do,loopp,20,24,1
  loopp=22
  *do,step,1,5,1
    t_step=(t22-t21)/10
    i_step=(i22-i21)/10
    *use,EM,t_step,(t21+t_step*2*step),(i21+i_step*2*step),2
    t_step=(t22-t21)/10
    i_step=(i22-i21)/10
    *use,thermstress,t_step,(t21+t_step*2*step-t_step),(i21+i_step*2*step-i_step),1
    t_step=(t22-t21)/10
    i_step=(i22-i21)/10
    *use,thermstress,t_step,(t21+t_step*2*step),(i21+i_step*2*step),1
!timestep,endtime,curr,outres
  *enddo
!*enddo

!*do,loopp,20,24,1
  loopp=23
  *do,step,1,5,1
    t_step=(t23-t22)/10
    i_step=(i23-i22)/10
    *use,EM,t_step,(t22+t_step*2*step),(i22+i_step*2*step),2
    t_step=(t23-t22)/10
```

```
    i_step=(i23-i22)/10
    *use,thermstress,t_step,(t22+t_step*2*step-t_step),(i22+i_step*2*step-i_step),1
    t_step=(t23-t22)/10
    i_step=(i23-i22)/10
    *use,thermstress,t_step,(t22+t_step*2*step),(i22+i_step*2*step),1
!timestep,endtime,curr,outres
  *enddo
!*enddo

!*do,loopp,20,24,1
  loopp=24
  *do,step,1,5,1
    t_step=(t24-t23)/10
    i_step=(i24-i23)/10
    *use,EM,t_step,(t23+t_step*2*step),(i23+i_step*2*step),2
    t_step=(t24-t23)/10
    i_step=(i24-i23)/10
    *use,thermstress,t_step,(t23+t_step*2*step-t_step),(i23+i_step*2*step-i_step),1
    t_step=(t24-t23)/10
    i_step=(i24-i23)/10
    *use,thermstress,t_step,(t23+t_step*2*step),(i23+i_step*2*step),1
!timestep,endtime,curr,outres
  *enddo
!*enddo

! ************************************************************************
! ramp down ends
! ************************************************************************
```