National Spherical Torus eXperiment - Upgrade

NSTX-U

PF Coil Cooldown and Thermal Stresses

NSTXU-CALC-131-07-00

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NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	01/12/18	Initial Release	

NSTX-U Calculation Form

Purpose of Calculation: Evaluate Cooldown time and Thermal Stresses of PF Coils

References: See References section in body of report

Assumptions: See Assumptions section in body of report

Calculation: See body of report

Conclusion: See body of report

PF Coil Cooldown Thermal Stresses

Executive Summary

This report presents documents the Thermal Stresses calculated in the PF coils during cooldown. Based on a common linear analysis (ie assuming coil fully bonded and freely supported 2D analysis) it identified the PF1a coils as by far the highest stressed coil. Further detailed 3D analysis of the PF1a coil was carried out by P. Titus. The satisfactory results of that analysis which capture the effects of turn transitions and lead were used to argue that the other coils were acceptable as well.

Introduction

The PF coils have been previously analyzed (ref 1) for normal operation with the 96 scenario identified in the design point spread sheet (ref 2). The results demonstrated their adequacy for EM loading and end of pulse thermal conditions.

More recently it was identified that while the end of pulse thermal condition has the highest temperature and bulk thermal expansion the thermal gradients turn to turn and layer to layer are much higher during cooldown. The stresses induced can exceed those from EM loads. During a pulse the coil heats up fairly adiabatically. Following a pulse, cold water enters thru one lead and begins to cool it down until it equilibrates with the conductor over some flow length. A cooling wave gradually marches thru the coil turn by turn. For coils that are cooled from the OD, the cooled turn develops hoop tension since they are constrained by the warm turns. The strain in the copper, given by alp*dT is 16e-6*88=.14%. While this is less than .2% - the value normally associated with yield – it is above the elastic limit for annealed copper. Based on E.alp.dT the hoop stress would be 125e9*16e-6*88=176 MPa for exceeding the annealed copper .2% yield strength of ~75 MPa. This leads to strain hardening of the copper. When the coil fully cools, the outer turn wants to pull away from the bundle putting normal strain on the turn insulation. This can potentially cause delamination of the insulation.

The purpose of this analysis is not to present final stress numbers for the coils but to provide a relative ranking of the coils. A detailed 3D analysis of the highest stressed coil found will be documented separately.

Results of previous testing of the conductor and insulation are included in Appendix I and II to support some of the assumptions (ie linear behavior over the stain range expected for the copper and strain limits for insulation).

Assumptions

- Flow rates are based on available pressure drop:
  - 400 psi for PF1a, b & c
  - 100 psi for PF2, 3, 4 & 5
- Flow varies with temperature due to large variation in viscosity
- Pump assumed to be able to deliver constant pressure, not limited by flow

PF Coil Cooldown Thermal Stresses

- PF5 modified to reflect two cooling channels.
- Coefficient of thermal expansion for Copper is 16e-6 m/m-C
- Insulation bonded (ie not delaminated)
- Assumes linear behavior for Copper (ie no yielding)

Method of Analysis

ANSYS 2D axisymmetric parametric models (see Appendices III-IX) was developed for a turn wound and a layer wound coils. The coil cooling was modeled with fluid116 elements with properties based on a 3D winding.

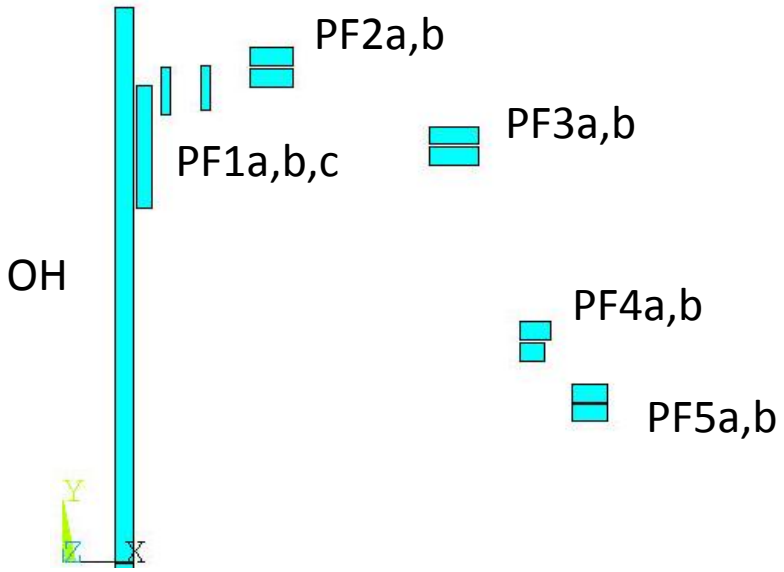
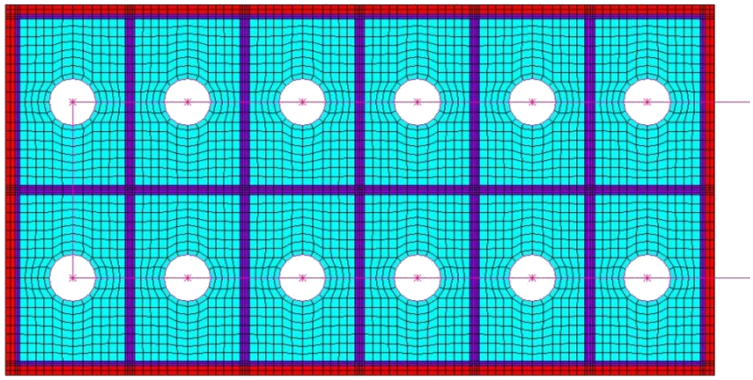


Figure-1 PF and OH Geometry



PF Coil Cooldown Thermal Stresses

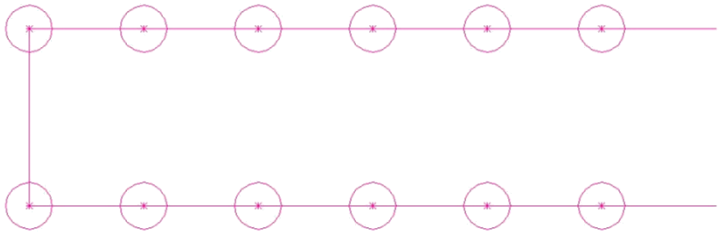


Figure-2 Typical Mesh with Fluid116 & Surf151

Coil	R0	Z0	Nr	Nz	Cond W	Cond H	Hole D	Turn Ins	GW	Vel	dP, psi	Cur	esw
PF1a	0.3246	1.5906	4	16	0.0143	0.0276	0.0052	0.0007	0.0022	2.72	400	19000	5.5
PF1b	0.4003	1.8042	2	16	0.0161	0.0100	0.0032	0.0007	0.0028	2.50	400	8050	2.109
PF1c	0.5504	1.8136	2	10	0.0179	0.0153	0.0032	0.0007	0.0018	2.73	400	14129	4.289
PF2a	0.8000	1.9335	7	2	0.0204	0.0323	0.0090	0.0017	0.0048	2.60	100	15000	5.5
PF2b	0.8000	1.8526	7	2	0.0204	0.0323	0.0090	0.0017	0.0048	2.60	100	15000	5.5
PF3a	1.4945	1.6335	7.5	2	0.0204	0.0323	0.0090	0.0017	0.0048	1.75	100	16000	5.5
PF3b	1.4945	1.5526	7.5	2	0.0204	0.0323	0.0090	0.0017	0.0048	1.75	100	16000	5.5
PF4b	1.7946	0.8072	4.5	2	0.0204	0.0323	0.0090	0.0017	0.0048	2.11	100	16000	5.5
PF4c	1.8065	0.8881	4.5	2	0.0204	0.0323	0.0090	0.0017	0.0048	2.10	100	16000	5.5
PF5a	2.0128	0.6521	6	2	0.0204	0.0323	0.0090	0.0009	0.0018	2.50	100	31847	5.5
PF5b	2.0128	0.5780	6	2	0.0204	0.0323	0.0090	0.0009	0.0018	2.50	100	31847	5.5

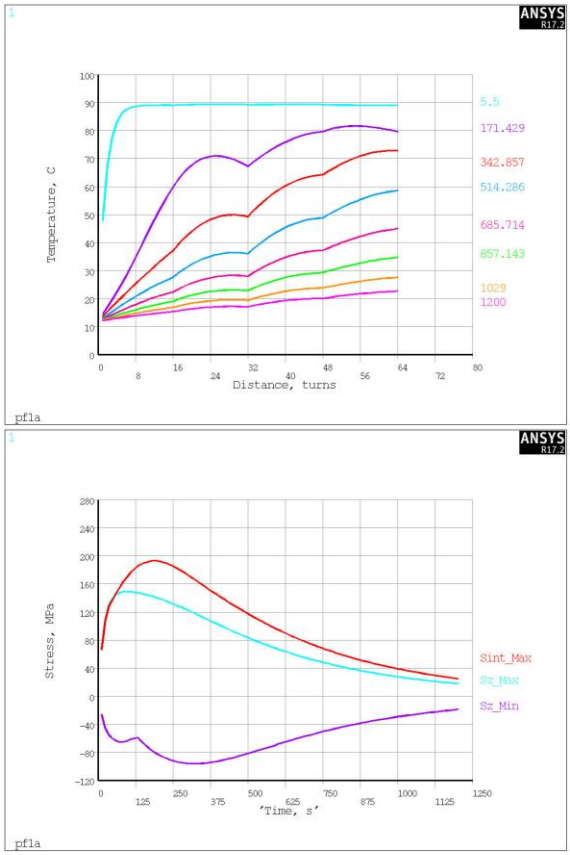
Figure-3 Data from Design Point Spreadsheet with Pressure and Velocity modified

Results

The results of this analysis are shown below for each of the coils. Three plots are given for each coil: 1) The temperature along the unwound length of the conductor for several times during the cooldown; 2) The peak copper stresses vs time and 3) a contour plot of hoop stress shortly after the end of pulse.

PF Coil Cooldown Thermal Stresses

Figure 4



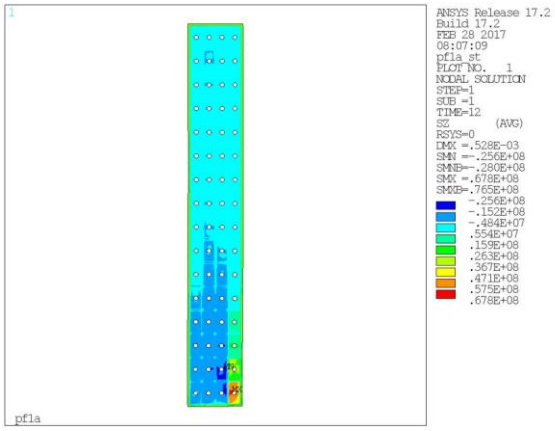
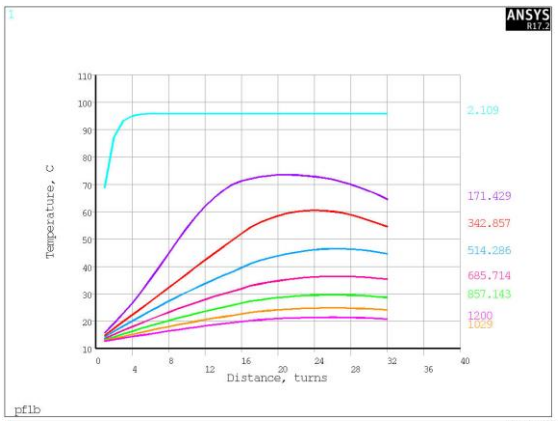
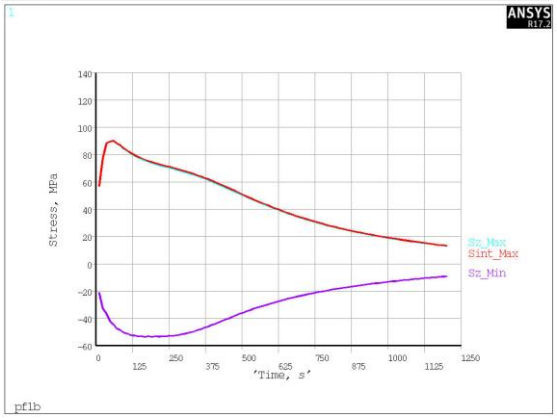


Figure 5 PF1a

PF Coil Cooldown Thermal Stresses





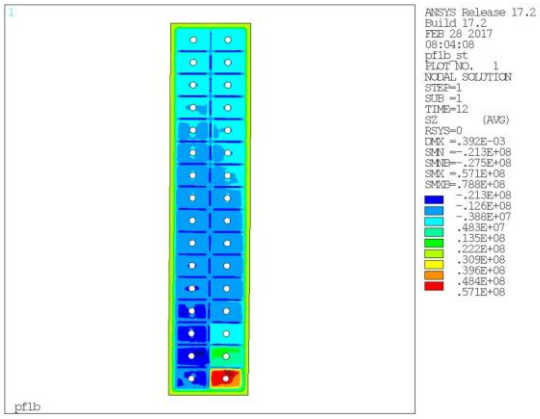
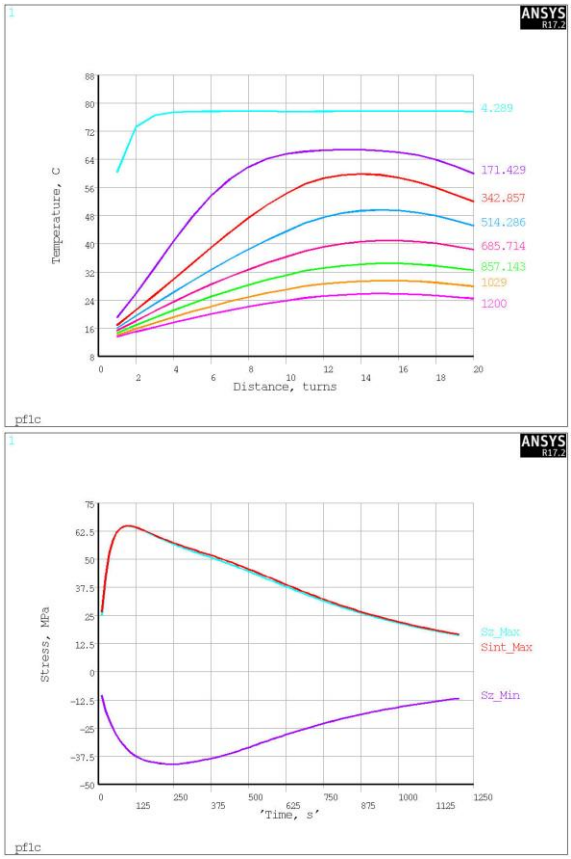


Figure 6 PF1b

PF Coil Cooldown Thermal Stresses



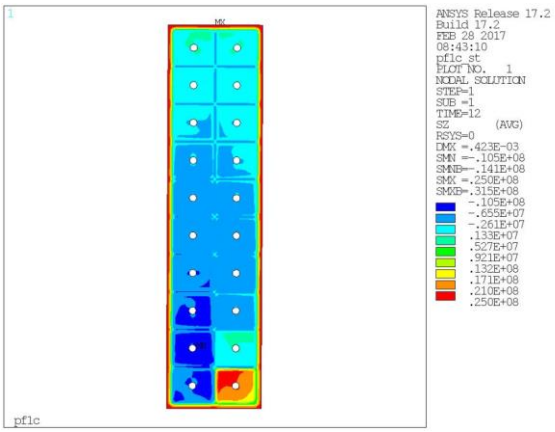
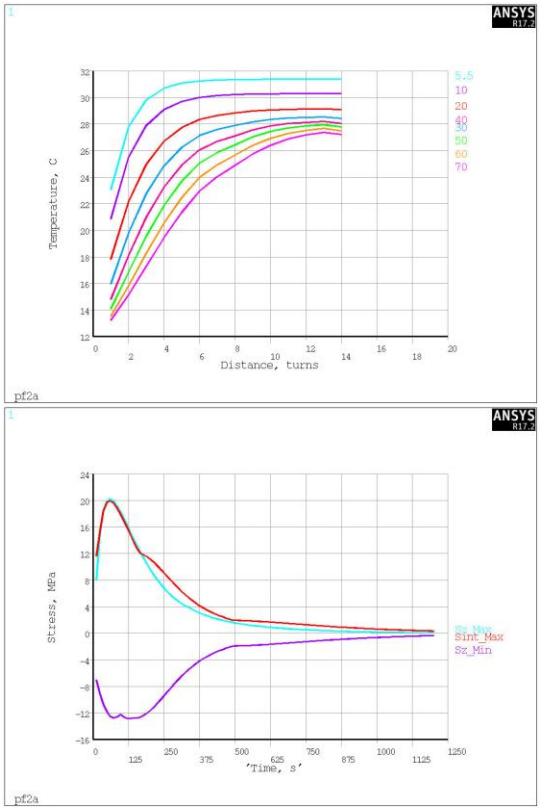


Figure 7 PF1c

PF Coil Cooldown Thermal Stresses



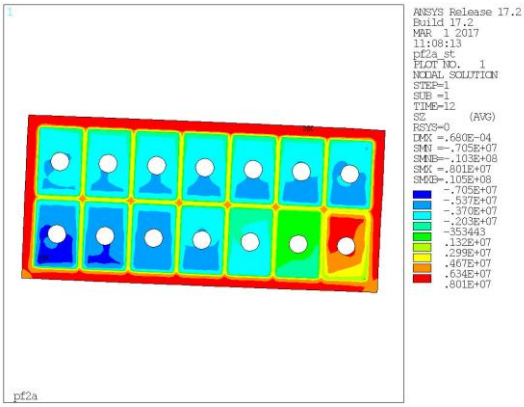
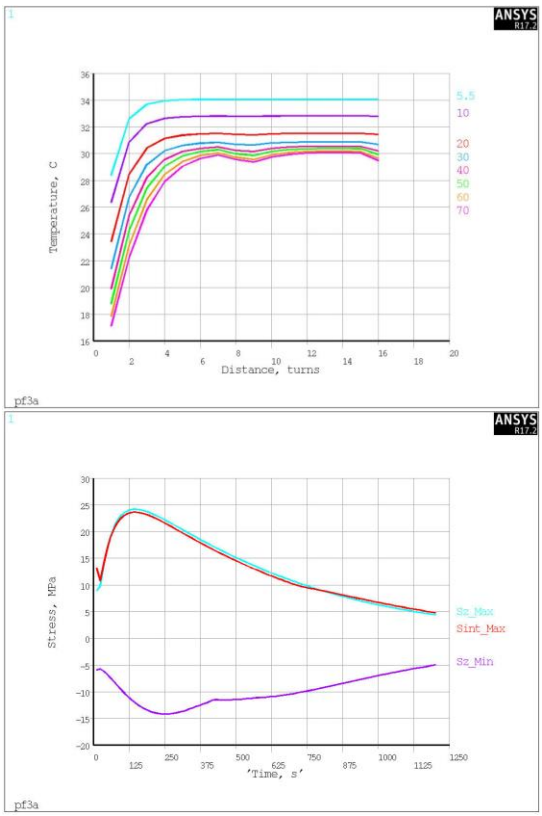


Figure 8 PF2a,b

PF Coil Cooldown Thermal Stresses



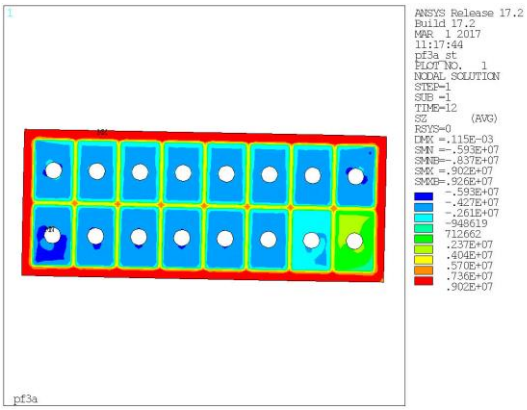
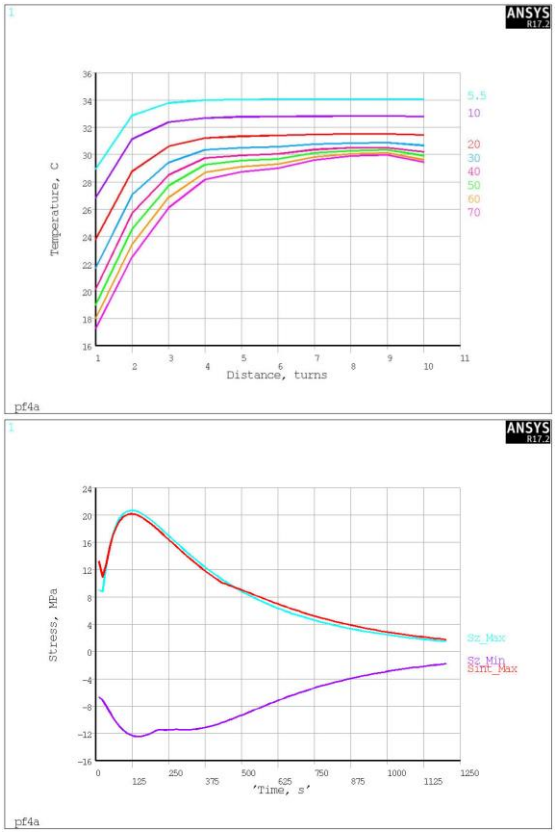


Figure 9 PF3a, b

PF Coil Cooldown Thermal Stresses



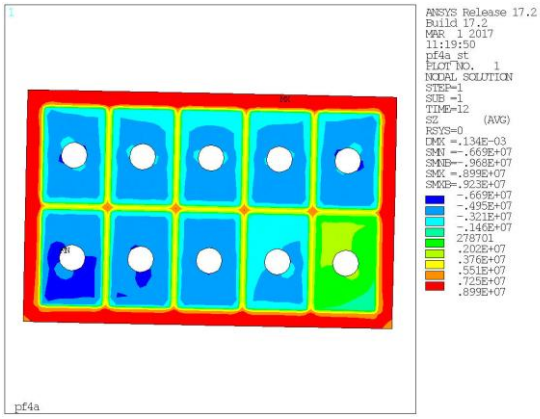
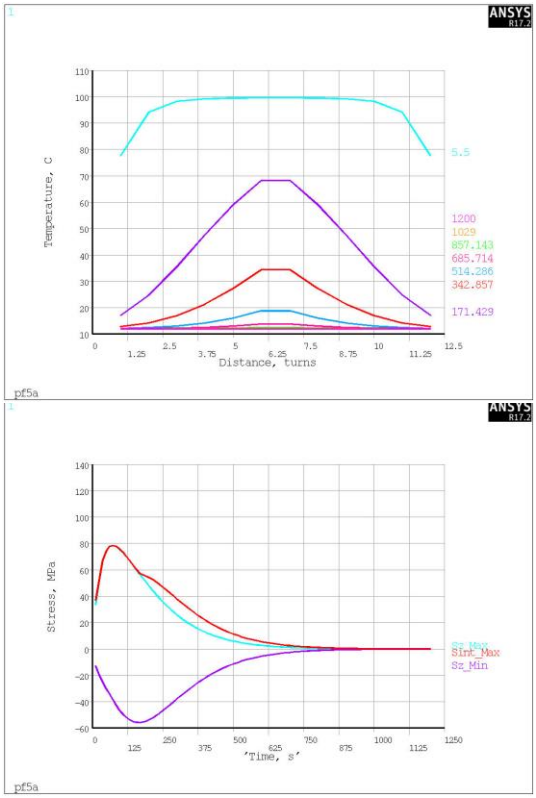


Figure 10 PF4a,b

PF Coil Cooldown Thermal Stresses



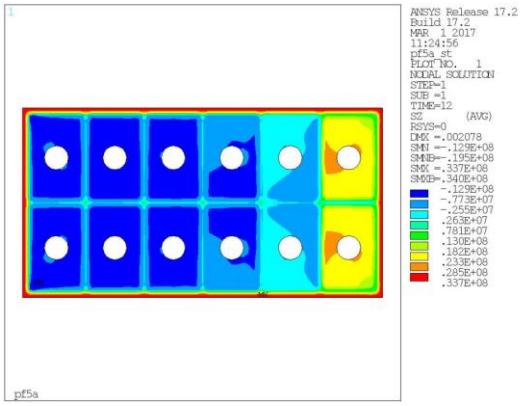


Figure 11PF5a, b

The turn insulation strain for each of the coils is given below. The peak epelx typically occurs in the layer to layer insulation while the epely occurs in he turn to turn insulation.

PF Coil Cooldown Thermal Stresses

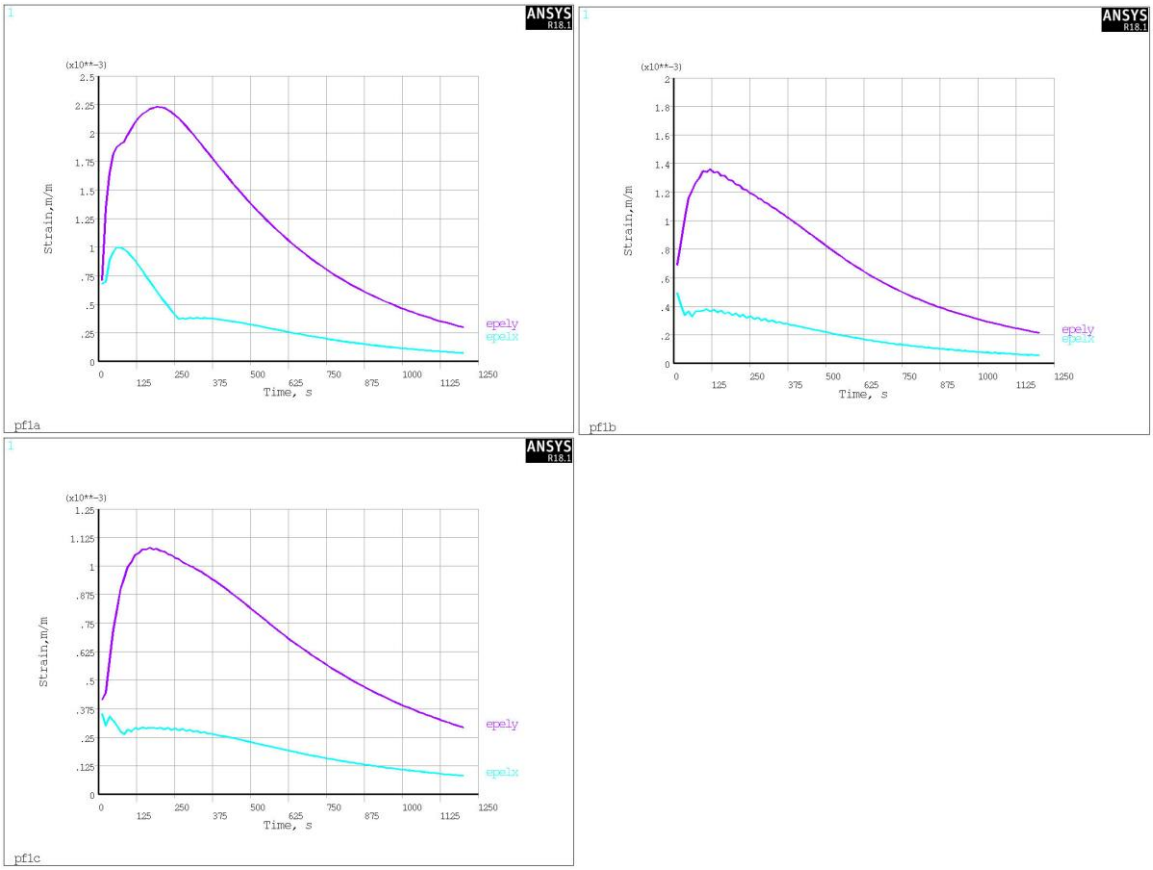


Figure 12 PF1a, b & c Insulation Strain vs Time during Cooldown

PF Coil Cooldown Thermal Stresses

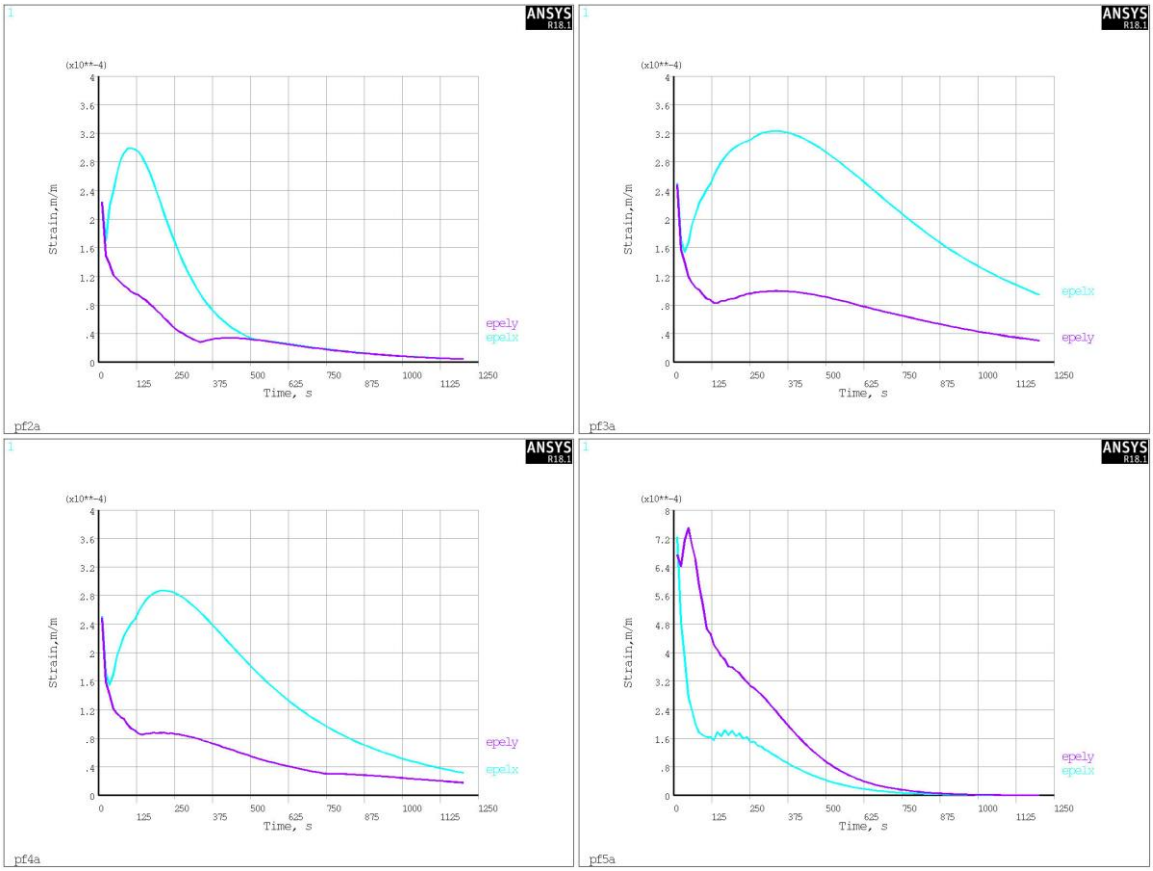


Figure 13 PF2, 3, 4 & 5 Insulation Strain vs Time during Cooldown

PF Coil Cooldown Thermal Stresses

Summary

The table below summarizes the resultant Peak Temeratures, Cooldown time, Max Stress and Turn Insulation Strain for each of the coils. As can be seen the PF1a is by far the highest stressed.

Coil	Tmax, C	tcool*, s	#flow paths	Smax, MPa	Radial Turn Ins Strain**, m/m	Vertical Turn Ins Strain**, m/m
PF1a	90	>1200 (T=22.9 C at EOC)	1	195	.0010	.0023
PF1b	96	>1200 (T=21.4 C at EOC)	1	90	.0005	.0014
PF1c	77	>1200 (T=25.9 C at EOC)	1	65	.0004	.0011
PF2a	32	636	1	20	.0003	.0003
PF3a	34	>1200 (T=17.0 C at EOC)	1	24	.0004	.0004
PF4a	34	~1200 (T=13.8 C at EOC)	1	20	.0003	.0003
PF5a	99	800	2	79	.0007	.0007

PF Coil Cooldown Thermal Stresses

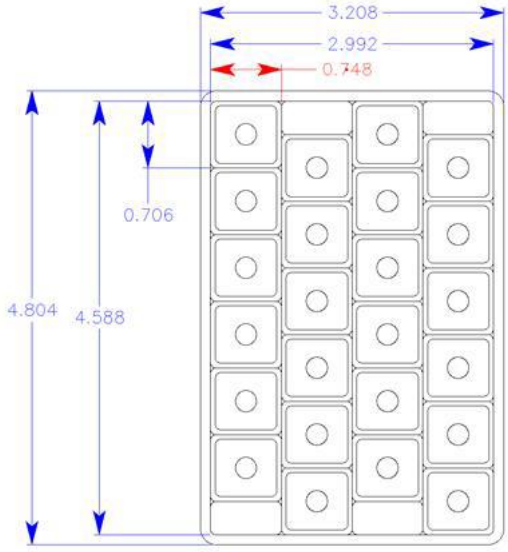
References

1) NSTXU-CALC-133-01-01 “Stress Analysis of Inner PF Coils (1a, 1b & 1c), Center Stack Upgrade”, by L Myatt, dated April 2, 2012
2) NSTXU Design Point Spreadsheet “NSTX_CS_Upgrade_120409.xls” by C. Neumeyer, dated April 12, 2012

PF Coil Cooldown Thermal Stresses

Appendix I
Test Results for CTD Misaligned Specimen

CTD Misaligned Specimen



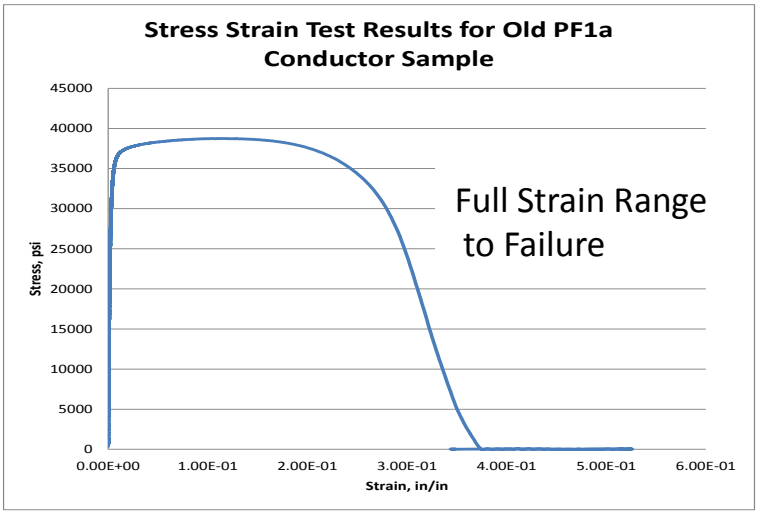
Preliminary Sample Dimensions. Note that the sample was reduced in size to a 3 by 4 array to save costs

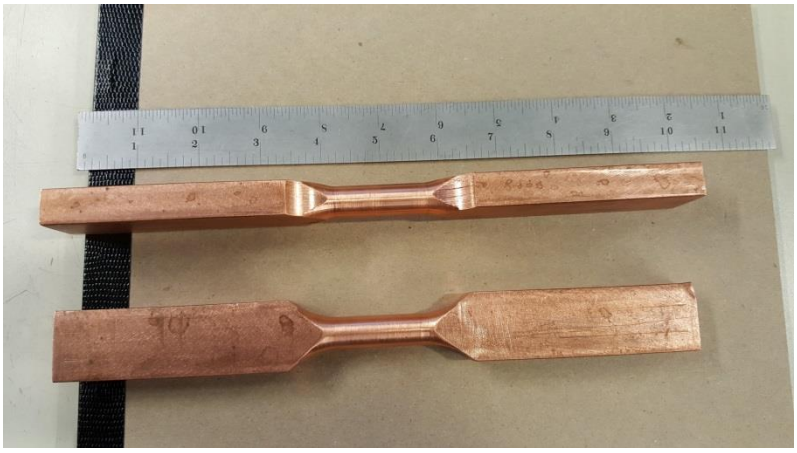
Imposed strain during the test was 4e-4 as a requirement. The actual test imposed 6e-4. Based on the sample in the figure above, the displacement of the insulation system would be 6e-4*4.804 inches = .00288 inches. 6 layers or .00048 inches per insulation layer.

This equates to 0.6% strain thru the .080" insulation thickness

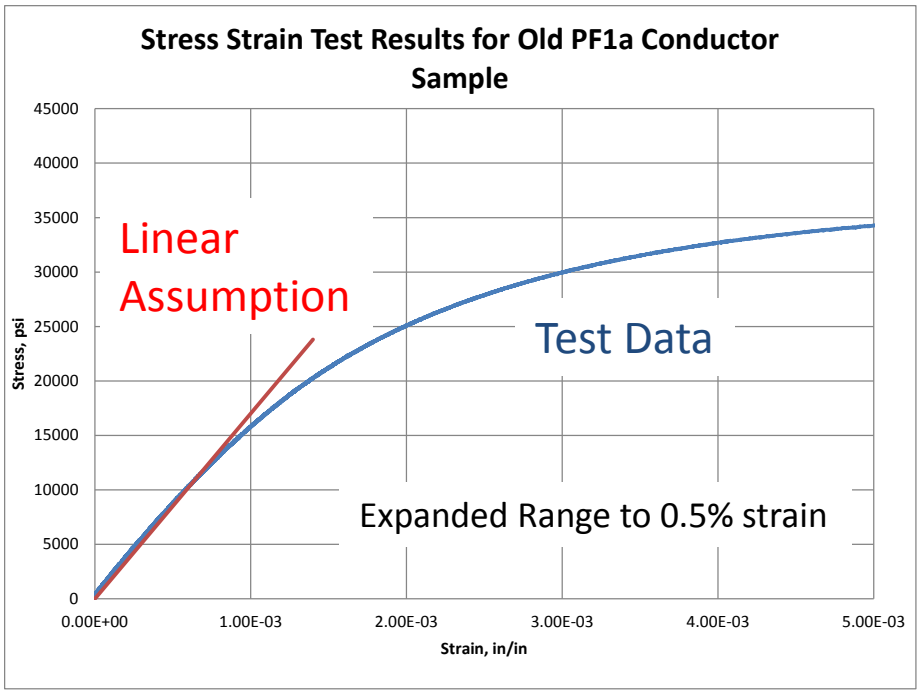
PF Coil Cooldown Thermal Stresses

Appendix II
PF1a Conductor Stress Strain Test Results





PF Coil Cooldown Thermal Stresses



A sample was taken from the old PF1a coil and a stress strain test was performed. The material showed a yield stress of 25 ksi at 0.2% strain and 35 ksi at 0.5 % strain.

At .14% expected thermal strain linear assumption is conservative on stress

PF Coil Cooldown Thermal Stresses

Appendix III
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF1a

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ----------

coil='pf1a'
r0=0.324561
z0=1.590600
nr=4
nz=16
w=0.014326
h=0.027584
d=0.005207
t=0.000737
g=0.002184
v=2.715
cur=19000
esw=5.500
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,5,w/2,h/2
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
```

PF Coil Cooldown Thermal Stresses

```
arsym,x,all

!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
```

PF Coil Cooldown Thermal Stresses

```
dens_cu=8854          ! conductor density

Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
```

PF Coil Cooldown Thermal Stresses

```
r,2
r,3,Dhyd, Aflow
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nz,1,nmax+1,nmax+1,1,,dz
ngen,nr,nz,nmax+1,nmax+nz,1,-dr

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nz-1,1,emax+1
engen,nz,nr,nz,emax+1,emax+nz-1,1

! add inlet, crossovers and outlets
```

PF Coil Cooldown Thermal Stresses

```
*get,nmax2,node,,num,maxd

csys,14
!

n,nmax2+1,,-dz
n,nmax2+2,-3*dr,-dz

*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1        ! outer layer 1 lead
en,emax2+2,nmax+nz,nmax+2*nz     ! layer 1 to layer 2 crossover
en,emax2+3,nmax+nz+1,nmax+2*nz+1     ! layer 2 to layer 3 crossover
en,emax2+4,nmax+3*nz,nmax+4*nz     ! layer 3 to layer 4 crossover
en,emax2+5,nmax+3*nz+1,nmax2+2     ! inner layer 4 lead

! identify flow direction by inlet/outlet/recirculation nodes
nin=nmax2+1
nout=nmax2+2
!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+3*nz


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt
```

PF Coil Cooldown Thermal Stresses

```
!cur=19000.
tpulse=esw
trep=1200
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout,pres,50*7000 ! .35e6
d,nin,temp,12

!f,nin,flow,mdot
d,nin,pres,450*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
```

PF Coil Cooldown Thermal Stresses

```
allsel

time,1e-6
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=trep/(ntim-1)
Tw=
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
```

PF Coil Cooldown Thermal Stresses

```
set,,,,,tim
iwind=-1

ii=0
*do,ir,1,nr ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nz1=1
  nz2=nz
*else
  nz1=nz
  nz2=1
*endif

*do,iz,nz1,nz2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+iz+(ir-1)*nz
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9
```

PF Coil Cooldown Thermal Stresses

```
/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim

ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
```

PF Coil Cooldown Thermal Stresses

```
/post1
allsel
smxmn=
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo




/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'




*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0
```

PF Coil Cooldown Thermal Stresses

```
/show,close
/show,term

fini
*endif

/exit,all
```

PF Coil Cooldown Thermal Stresses

Appendix IV
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF1b

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ------------------

coil='pf1b'
r0=0.400253
z0=1.804200
nr=2
nz=16
w=0.016078
h=0.009957
d=0.003200
t=0.000737
g=0.002794
v=2.50
cur=13000
esw=2.109
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
k,5,w/2,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
arsym,x,all
```

PF Coil Cooldown Thermal Stresses

```
!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
dens_cu=8854          ! conductor density
```

PF Coil Cooldown Thermal Stresses

```
Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
r,2
```

PF Coil Cooldown Thermal Stresses

```
r,3,Dhyd, Aflow
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nz,1,nmax+1,nmax+1,1,,dz
ngen,nr,nz,nmax+1,nmax+nz,1,-dr

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nz-1,1,emax+1
engen,nz,nr,nz,emax+1,emax+nz-1,1

! add inlet, crossovers and outlets

*get,nmax2,node,,num,maxd
```

PF Coil Cooldown Thermal Stresses

```
csys,14
!

n,nmax2+1,,-dz
n,nmax2+2,-dr,-dz

*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1        ! outer layer 1 lead
en,emax2+2,nmax+nz,nmax+2*nz     ! layer 1 to layer 2 crossover
en,emax2+3,nmax+nz+1,nmax2+2    ! inner layer 2 lead

! identify flow direction by inlet/outlet/recirculation nodes
nin=nmax2+1
nout=nmax2+2
!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+nz


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt


!cur=19000.
tpulse=esw
trep=1200
```

PF Coil Cooldown Thermal Stresses

```
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout,pres,50*7000 ! .35e6
d,nin,temp,12

!f,nin,flow,mdot
d,nin,pres,450*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
allsel

time,1e-6
```

PF Coil Cooldown Thermal Stresses

```
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=trep/(ntim-1)
Tw=
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
set,,,,,tim
iwind=-1
```

PF Coil Cooldown Thermal Stresses

```
ii=0
*do,ir,1,nr ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nz1=1
  nz2=nz
*else
  nz1=nz
  nz2=1
*endif

*do,iz,nz1,nz2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+iz+(ir-1)*nz
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0
```

PF Coil Cooldown Thermal Stresses

```
/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim

ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
/post1
allsel
smxmn=
```

PF Coil Cooldown Thermal Stresses

```
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo




/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'



*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term
```

```
fini
*endif

/exit,all
```

PF Coil Cooldown Thermal Stresses

Appendix V
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF1c

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ------------------

coil='pf1c'
r0=0.550393
z0=1.813600
nr=2
nz=10
w=0.017907
h=0.015316
d=0.003200
t=0.000737
g=0.001829
v=2.73
cur=14129
esw=4.289
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
k,5,w/2,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
arsym,x,all
```

PF Coil Cooldown Thermal Stresses

```
!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
dens_cu=8854          ! conductor density
```

PF Coil Cooldown Thermal Stresses

```
Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
r,2
```

PF Coil Cooldown Thermal Stresses

```
r,3,Dhyd, Aflow
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nz,1,nmax+1,nmax+1,1,,dz
ngen,nr,nz,nmax+1,nmax+nz,1,-dr

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nz-1,1,emax+1
engen,nz,nr,nz,emax+1,emax+nz-1,1

! add inlet, crossovers and outlets

*get,nmax2,node,,num,maxd
```

PF Coil Cooldown Thermal Stresses

```
csys,14
!

n,nmax2+1,,-dz
n,nmax2+2,-dr,-dz

*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1        ! outer layer 1 lead
en,emax2+2,nmax+nz,nmax+2*nz     ! layer 1 to layer 2 crossover
en,emax2+3,nmax+nz+1,nmax2+2    ! inner layer 2 lead

! identify flow direction by inlet/outlet/recirculation nodes
nin=nmax2+1
nout=nmax2+2
!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+nz


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt


!cur=19000.
tpulse=esw
trep=1200
```

PF Coil Cooldown Thermal Stresses

```
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout,pres,50*7000 ! .35e6
d,nin,temp,12

!f,nin,flow,mdot
d,nin,pres,450*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
allsel

time,1e-6
```

PF Coil Cooldown Thermal Stresses

```
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=trep/(ntim-1)
Tw=
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
set,,,,,tim
iwind=-1
```

PF Coil Cooldown Thermal Stresses

```
ii=0
*do,ir,1,nr ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nz1=1
  nz2=nz
*else
  nz1=nz
  nz2=1
*endif

*do,iz,nz1,nz2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+iz+(ir-1)*nz
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0
```

PF Coil Cooldown Thermal Stresses

```
/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim

ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
/post1
allsel
smxmn=
```

PF Coil Cooldown Thermal Stresses

```
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo




/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'



*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term
```

```
fini
*endif

/exit,all
```

PF Coil Cooldown Thermal Stresses

Appendix VI
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF2a

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ------------------
coil='pf2a'
r0=0.799998
z0=1.933473
nr=7
nz=2
w= 0.020371
h=0.032309
d=0.009042
t=0.001676
g=0.004775
v=2.60
cur=15000
esw=5.500
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
k,5,w/2,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
arsym,x,all
```

PF Coil Cooldown Thermal Stresses

```
!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
dens_cu=8854          ! conductor density
```

PF Coil Cooldown Thermal Stresses

```
Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
r,2
```

PF Coil Cooldown Thermal Stresses

```
r,3,Dhyd, Aflow,,,,,
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nr,1,nmax+1,nmax+1,1,-dr
ngen,nz,nr,nmax+1,nmax+nr,1,,dz

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nr-1,1,emax+1
engen,nr,nz,nr,emax+1,emax+nr-1,1

! add inlet, crossovers and outlets

*get,nmax2,node,,num,maxd
```

PF Coil Cooldown Thermal Stresses

```
csys,14
!


n,nmax2+1,dr
n,nmax2+2,dr,dz

*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1        ! bottom layer 1 lead
en,emax2+2,nmax+nr,nmax+2*nr     ! layer 1 to layer 2 crossover
en,emax2+3,nmax+nr+1,nmax2+2   ! top layer 2 lead

! identify flow direction by inlet/outlet/recirculation nodes
nin=nmax2+1
nout=nmax2+2
!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+nr


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt


!cur=19000.
tpulse=esw
```

PF Coil Cooldown Thermal Stresses

```
trep=1200
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout,pres,50*7000 ! .35e6
d,nin,temp,12

!f,nin,flow,mdot
d,nin,pres,150*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
allsel
```

PF Coil Cooldown Thermal Stresses

```
time,1e-6
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=10 ! trep/(ntim-1)
Tw=
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
set,,,,,tim
iwind=-1
```

PF Coil Cooldown Thermal Stresses

```
ii=0
*do,iz,1,nz ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nr1=1
  nr2=nr
*else
  nr1=nr
  nr2=1
*endif

*do,ir,nr1,nr2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+ir+(iz-1)*nr
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0
```

PF Coil Cooldown Thermal Stresses

```
/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim

ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
/post1
allsel
```

PF Coil Cooldown Thermal Stresses

```
smxmn=
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo




/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'



*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term
```

```
fini
*endif

/exit,all
```

PF Coil Cooldown Thermal Stresses

Appendix VII
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF3a

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ------------------
      3.54     16000     5.500
coil='pf3a'
r0=1.494460
z0=1.633474
nr=8
nz=2
w=0.020371
h=0.032309
d=0.009042
t=0.001676
g=0.004775
v=1.75
cur=16000
esw=5.500
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,5,w/2,h/2
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
```

PF Coil Cooldown Thermal Stresses

```
arsym,x,all

!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
```

PF Coil Cooldown Thermal Stresses

```
dens_cu=8854          ! conductor density

Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
```

PF Coil Cooldown Thermal Stresses

```
r,2
r,3,Dhyd, Aflow
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nr,1,nmax+1,nmax+1,1,-dr
ngen,nz,nr,nmax+1,nmax+nr,1,,dz

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nr-1,1,emax+1
engen,nr,nz,nr,emax+1,emax+nr-1,1

! add inlet, crossovers and outlets
```

PF Coil Cooldown Thermal Stresses

```
*get,nmax2,node,,num,maxd

csys,14
!


n,nmax2+1,dr
n,nmax2+2,dr,dz

*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1        ! bottom layer 1 lead
en,emax2+2,nmax+nr,nmax+2*nr     ! layer 1 to layer 2 crossover
en,emax2+3,nmax+nr+1,nmax2+2    ! top layer 2 lead

! identify flow direction by inlet/outlet/recirculation nodes
nin=nmax2+1
nout=nmax2+2
!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+nr


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt


!cur=19000.
```

PF Coil Cooldown Thermal Stresses

```
tpulse=esw
trep=1200
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout,pres,50*7000 ! .35e6
d,nin,temp,12

!f,nin,flow,mdot
d,nin,pres,150*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
allsel
```

PF Coil Cooldown Thermal Stresses

```
time,1e-6
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=10 ! trep/(ntim-1)
Tw=
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
set,,,,,tim
```

PF Coil Cooldown Thermal Stresses

```
iwind=-1

ii=0
*do,iz,1,nz ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nr1=1
  nr2=nr
*else
  nr1=nr
  nr2=1
*endif

*do,ir,nr1,nr2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+ir+(iz-1)*nr
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9

/RGB,INDEX,100,100,100,15
```

PF Coil Cooldown Thermal Stresses

```
/RGB,INDEX,0,0,0,0

/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim

ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
/post1
```

PF Coil Cooldown Thermal Stresses

```
allsel
smxmn=
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo



/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'



*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
```

PF Coil Cooldown Thermal Stresses

/show,term

fini
*endif

/exit,all

PF Coil Cooldown Thermal Stresses

Appendix VIII
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF4a

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ------------------

coil='pf4a'
r0=1.806473
z0=0.888086
nr=5
nz=2
w=0.020371
h=0.032309
d=0.009042
t=0.001676
g=0.004775
v=2.10
cur=16000
esw=5.500
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
k,5,w/2,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
arsym,x,all
```

PF Coil Cooldown Thermal Stresses

```
!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
dens_cu=8854         ! conductor density
```

PF Coil Cooldown Thermal Stresses

```
Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
r,2
```

PF Coil Cooldown Thermal Stresses

```
r,3,Dhyd, Aflow
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nr,1,nmax+1,nmax+1,1,-dr
ngen,nz,nr,nmax+1,nmax+nr,1,,dz

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nr-1,1,emax+1
engen,nr,nz,nr,emax+1,emax+nr-1,1

! add inlet, crossovers and outlets

*get,nmax2,node,,num,maxd
```

PF Coil Cooldown Thermal Stresses

```
csys,14
!


n,nmax2+1,dr
n,nmax2+2,dr,dz

*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1        ! bottom layer 1 lead
en,emax2+2,nmax+nr,nmax+2*nr     ! layer 1 to layer 2 crossover
en,emax2+3,nmax+nr+1,nmax2+2    ! top layer 2 lead

! identify flow direction by inlet/outlet/recirculation nodes
nin=nmax2+1
nout=nmax2+2
!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+nr


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt


!cur=19000.
tpulse=esw
```

PF Coil Cooldown Thermal Stresses

```
trep=1200
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout,pres,50*7000 ! .35e6
d,nin,temp,12

!f,nin,flow,mdot
d,nin,pres,150*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
allsel
```

PF Coil Cooldown Thermal Stresses

```
time,1e-6
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=10 ! trep/(ntim-1)
Tw=
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
set,,,,,tim
iwind=-1
```

PF Coil Cooldown Thermal Stresses

```
ii=0
*do,iz,1,nz ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nr1=1
  nr2=nr
*else
  nr1=nr
  nr2=1
*endif

*do,ir,nr1,nr2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+ir+(iz-1)*nr
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0
```

PF Coil Cooldown Thermal Stresses

```
/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim

ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
/post1
allsel
```

PF Coil Cooldown Thermal Stresses

```
smxmn=
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo




/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'



*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term
```

```
fini
*endif

/exit,all
```

PF Coil Cooldown Thermal Stresses

Appendix IX
Sample ANSYS APDL Script for Thermal/Hydraulic/Structural Analysis of PF5a

```
/batch ! fini $ /clear


*get,jobid,active,,jobnam
/prep7

! coil data ------------------

coil='pf5a'
r0=2.012798
z0=0.652069
nr=6
nz=2
w=0.020371
h=0.032309
d=0.009042
t=0.000914
g=0.001829
v=2.50
cur=31847
esw=5.500
!-----------------------------

! center of lower left turn offset from corner
rc=g+t+w/2
zc=g+t+h/2
dr=w+2*t
dz=h+2*t

! bundle size
wb=2*g+nr*(w+2*t)
hb=2*g+nz*(h+2*t)

rin=r0-wb/2
rout=r0+wb/2
zbot=z0-hb/2
ztop=z0+hb/2

d2=.001
```

PF Coil Cooldown Thermal Stresses

```
et,1,Plane77,,,1 ! 55==4 node, 77==8 node
!et,1,223,11,0,1 ! temp,ux,uy; weakly couple; axisymmetric

! Copper

mp,kxx,1,400
mp,c,1,383
mp,dens,1,8900
mp,ex,1,125e9
mp,nuxy,1,.31
mp,alpx,1,16e-6
mp,reft,1,27

! G10

mp,kxx,2,.3
mp,c,2,1600
mp,dens,2,1850
mp,ex,2,25e9
mp,nuxy,2,.13
mp,alpx,2,16e-6
mp,reft,2,27

mpcopy,,2,3

wpcsys,1,0
wpoff,rin+rc,zbot+zc

local,11,0,rin+rc,zbot+zc
clocal,12,1

k,1,d/2
k,2,d/2,45
k,3,d/2,90

k,9,d/2+d2
k,10,d/2+d2,45
k,11,d/2+d2,90
l,1,2
l,2,3
l,9,10
l,10,11
csys,11
k,4,0,h/2
k,5,w/2,h/2
```

PF Coil Cooldown Thermal Stresses

```
k,6,w/2,0
k,7,w/2,ky(10)
k,8,kx(10),h/2

allsel
a,1,2,10,9
a,10,8,5,7
a,2,3,11,10
a,10,11,4,8
a,9,10,7,6
aatt,1

csys,12
lsel,s,loc,x,d/2+d2/2
lesize,all,,,1
csys,11

asel,none

rect,w/2,w/2+t,0,ky(10)
rect,w/2,w/2+t,ky(10),h/2
rect,w/2,w/2+t,h/2,h/2+t
rect,0,kx(10),h/2,h/2+t
rect,kx(10),w/2,h/2,h/2+t
aatt,2

allsel

nummrg,kp
type,1
esize,es
mshape,0
mshkey,1
amesh,all

csys,11
arsym,y,all
arsym,x,all


csys,11
agen,nr,all,,,dr
agen,nz,all,,,,dz

! groundwrap
```

PF Coil Cooldown Thermal Stresses

```
wpcsys,1,0
wpoff,rin+rc,zbot+zc
csys,11

*get,amax,area,,num,max
numstr,area,amax+1

asel,none
rect,-w/2-t-g,-w/2-t,-h/2-t-g,-h/2-t  ! corner
rect,-w/2-t,-w/2,-h/2-t-g,-h/2-t      ! base
rect,-w/2,-kx(10),-h/2-t-g,-h/2-t
rect,-kx(10),0,-h/2-t-g,-h/2-t
rect,-w/2-t-g,-w/2-t,-h/2-t,-h/2  ! id
rect,-w/2-t-g,-w/2-t,-h/2,-ky(10)
rect,-w/2-t-g,-w/2-t,-ky(10),0
aatt,3

allsel
nummrg,kp
asel,s,mat,,3
amesh,all

! cs in middle of bundle


local,13,0,r0,z0

asel,s,area,,amax+1
arsym,x,all
arsym,y,all

asel,s,area,,amax+2,amax+4
csys,11
arsym,x,all
csys,13
agen,nr,all,,,dr
arsym,y,all

asel,s,area,,amax+5,amax+7

csys,11
arsym,y,all
csys,13
agen,nz,all,,,,dz
asel,u,mat,,4
arsym,x,all
```

PF Coil Cooldown Thermal Stresses

```
!asel,s,area,,amax+6
!arsym,y,all



/pnum,mat,1
/num,1
/auto
aplot

nummrg,node
nummrg,kp
numcmp,node
numcmp,elem

allsel
eplot


fini
!/exit,all

save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!! fluid116_pf1a.txt
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Model Parameters
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pi=3.14159

Dhyd = d  ! Flow diameter, m
Acu =w*h-3.14159/4*d*d
Aflow = pi*Dhyd**2/4       ! flow area, m2

Len =2*pi*r0*nz*nr     ! Length of Conductor, m (OH outer turn)
Asurf=pi*Dhyd*Len          ! Surface area for convection


!Cur=19000.     ! conductorCurrent, amps
res = 1.724e-8         ! Condcutor Resistivity, ohm-m
alp = .0041          ! resistivity temperature coeff
tref=20             ! ref temp
dens_cu=8854         ! conductor density
```

PF Coil Cooldown Thermal Stresses

```
Tin=12     ! Inlet Water Temperature, C
Pout=0.5e6    ! Outlet Pressure, Pa
!v=2.13         ! water velocity, m/s

! Water Properties
dvisc=.001        ! dynamic viscosity, kg/m-s
dens=1000.        ! density, kg/m3
kvisc=dvisc/dens  ! kinematic viscosity, m2/s
kxx=.6            ! thermal conductivity, w/m-C
Cp=4186           ! capacitance, J/kg-C



j=Cur/Acu                ! current density, a/m2
hgen = res*j**2   ! heat generation,w/m3 at RT


Re=v*Dhyd/kvisc        ! Reynolds number
Pr=Cp*dvisc/kxx        ! Prandlt Number
Nu=.023*Re**.8*Pr**.3  ! Nusselt number using McAdams

hfilm=Nu*kxx/Dhyd         ! film coefficient
mdot=v*Aflow*dens      ! mass flow in

Qtot=hgen*Len*Acu      ! total heat input
dTflow=Qtot/mdot/Cp    ! fluid temperature rise
Tout=Tin+dTflow        ! Outlet fluid temperature
dTfilm=Qtot/hfilm/asurf  ! temperature drop across film
Tsurf=Tout+dTfilm        ! inner surface temperature at outlet

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

!et,1,Plane77,,,1 ! 55==4 node, 77==8 node
et,2,Surf151
  keyopt,2,3,1 ! axisymmetric
  keyopt,2,4,1 ! no midside nodes
  keyopt,2,5,1 ! 2 fluid nodes for convection to fluid116 elemens
  keyopt,2,8,2 ! Evaluate film coefficient hf (if any) at average film temperature, (TS
+TB)/2
et,3,Fluid116,0 ! temp and pres dof
  keyopt,3,2,1    ! 2 nodes and convection information passed to SURF151/SURF152


r,1
r,2
```

PF Coil Cooldown Thermal Stresses

```
r,3,Dhyd, Aflow
rmore,,,,,,,
rmore,,2*pi*r0



! Cu
mp,kxx,1,400
mp,dens,1,dens_cu
mp,c,1,383
mp,rsvx,1,res

! Water
mp,dens,5,dens
mp,kxx,5,kxx
mp,C,5,Cp
mp,mu,1,.02 ! initial guess
!mp,visc,5,dvisc ! dynamic viscosity
mptemp,1,0,5,10,20,30,40
mptemp,7,50,60,70,80,90,100
mpdata,visc,5,1,1.787e-3,1.519e-3,1.307e-3,1.002e-3,0.798e-3,0.653e-3
mpdata,visc,5,7,0.547e-3,0.467e-3,0.404e-3,0.355e-3,0.315e-3,0.282e-3
mptemp
fini
save
!
!!!!!!!!!!!!!! generate fluid elements
!
/prep7
*get,nmax,node,,num,maxd
local,14,0,rout-rc,zbot+zc
n,nmax+1,0,0
ngen,nr,1,nmax+1,nmax+1,1,-dr
ngen,nz,nr,nmax+1,nmax+nr,1,,dz

type,3 $ mat,5 $ real,3


*get,emax,elem,,num,maxd
en,emax+1,nmax+1,nmax+2
engen,1,nr-1,1,emax+1
engen,nr,nz,nr,emax+1,emax+nr-1,1

! add inlet, crossovers and outlets

*get,nmax2,node,,num,maxd
```

PF Coil Cooldown Thermal Stresses

```
csys,14
!


n,nmax2+1,dr
n,nmax2+2,dr,dz

csys,11

n,nmax2+3,-dr
n,nmax2+4,-dr,dz


*get,emax2,elem,,num,maxd
en,emax2+1,nmax2+1,nmax+1      ! bottom layer 1 inlet
en,emax2+2,nmax+nr,nmax2+3     ! bottom layer outlet
en,emax2+3,nmax+nr+1,nmax2+2   ! top layer 2 inlet
en,emax2+4,nmax+nr*2,nmax2+4   ! bottom layer outlet

! identify flow direction by inlet/outlet/recirculation nodes
nin1=nmax2+1
nout1=nmax2+3
nin2=nmax2+2
nout2=nmax2+4

!nrecirc=nmax2+3
ninner=nmax+1
nouter=nmax+1+nr


asel,none $ lsel,none $ ksel,none $ gplot

! generate surface elements for convection

type,2 $ real,2
*do,ir,1,nr
*do,iz,1,nz
local,21,1,rin+rc+(ir-1)*dr,zbot+zc+(iz-1)*dz
nsel,s,loc,x,0
*get,n2,node,,num,min
n1=n2-1
nsel,s,loc,x,d/2
esln
esurf,n2
*enddo
```

PF Coil Cooldown Thermal Stresses

```
*enddo

allsel
save

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!solu_pf1a.txt


!cur=19000.
tpulse=esw
trep=1200
npulse=1

acu=w*h-3.14159/4*d*d
curden=cur/acu
Tavg=56  ! guestimate
Tin=12
res_tavg=1.724e-8*(1+alp*(tavg-12))
hgen=res_tavg*curden**2

/solu

allsel
lsclear,all
ddel,all
fdel,all

antype,trans,new

outres,all,all

monitor,1,ninner,temp
monitor,2,nouter,temp
monitor,3,nout,temp

esel,s,type,,1
nsle
csys,0
!d,node(0,-10,0),uy,0.
allsel

tunif,12
d,nout1,pres,50*7000 ! .35e6
d,nout2,pres,50*7000 ! .35e6
d,nin1,temp,12
d,nin2,temp,12
```

PF Coil Cooldown Thermal Stresses

```
!f,nin1,flow,mdot
!f,nin2,flow,mdot
d,nin1,pres,150*7000
d,nin2,pres,150*7000
esel,s,type,,2
nsle
sfe,all,,conv,,hfilm

esel,s,mat,,1
esel,r,type,,1
bfe,all,hgen,,hgen
allsel

time,1e-6
nsubst,10
solve

time,tpulse
nsubst,10
solve

esel,s,mat,,1
esel,r,type,,1
bfedel,all,hgen
allsel

time,tpulse+1e-6
nsubst,1
solve

*do,istep,1,100
time,trep*istep/100
nsubst,1
solve
*enddo

fini
save
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1

! Plot Water Temp vs Length

ntim=8
dtim=trep/(ntim-1)
Tw=
```

PF Coil Cooldown Thermal Stresses

```
Lw=
*dim,Tw,table,nr*nz,ntim
*dim,Lw,table,nr*nz

*do,itim,0,ntim-1

*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
set,,,,,tim
iwind=-1

ii=0
*do,iz,1,nz ! reverse flow layer by layer

iwind=-iwind
*if,iwind,eq,1,then
  nr1=1
  nr2=nr
*else
  nr1=nr
  nr2=1
*endif

*do,ir,nr1,nr2,iwind
ii=ii+1
Lw(ii)=ii
nw=nmax+ir+(iz-1)*nr
Tw(ii,itim+1)=TEMP(nw)
*enddo ! ir
*enddo ! iz

*enddo ! itim


/titl, %coil%
/axlab,x,Distance, turns
/axlab,y,Temperature, C
*do,itim,0,ntim-1
*if,itim,eq,0,then
  tim=tpulse
*else
  tim=itim*dtim
*endif
```

PF Coil Cooldown Thermal Stresses

```
/gcolu,itim+1,chrval(tim)
*enddo

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*vplot,Lw(1),Tw(1,1),2,3,4,5,6,7,8,9

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term

fini
*if,1,eq,1,then
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!STRUCTURAL
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
/filnam,%jobid%_st
!!!!!!!!!!!!!!!!!!!!!!!!!!!

/prep7
et,1,183,,,1
esel,s,type,,2,10
edel,all
etdel,2,10
esel,all
nsle
nsel,invert
ndel,all
allsel
fini

/solu
antype,stat,new
outres,all,all
nsubst,1
tunif,Tin

d,node(0,-10,0),uy,0
*do,istep,1,100
tim=trep*istep/100
time,tim
```

PF Coil Cooldown Thermal Stresses

```
ldread,temp,,,tim,,%jobid%,rst
solve
*enddo
fini

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!post1
/post1
szmax=
szmin=
sintmax=
/post1
allsel
smxmn=
tims=
*dim,tims,table,100
*dim,smxmn,table,100,3

/show,jpeg

! Reverse video for plots
/RGB,INDEX,100,100,100,0
/RGB,INDEX,0,0,0,15

*do,i,1,100
set,i
*get,tims(i),active,,set,time

plnsol,s,z
*get,szmax,plnsol,,max
*get,szmin,plnsol,,min

plnsol,s,int
*get,sintmax,plnsol,,max

smxmn(i,1)=szmax*1e-6
smxmn(i,2)=szmin*1e-6
smxmn(i,3)=sintmax*1e-6
*enddo




/gcolum,1,'Sz_Max'
/gcolum,2,'Sz_Min'
/gcolum,3,'Sint_Max'
```

PF Coil Cooldown Thermal Stresses

```
/axlab,x, 'Time, s'
/axlab,y,'Stress, MPa'



*vplot,tims(1),smxmn(1,1),2,3

/RGB,INDEX,100,100,100,15
/RGB,INDEX,0,0,0,0

/show,close
/show,term

fini
*endif

/exit,all
```