# NSTX

# TF INNER LEG COOLING USING FCOOL

## NSTX-CALC-132-10-01

**March 24, 2013**


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# PPPL Calculation Form

Calculation # **132-10-00**_________ Revision # **00** WP #, if any **????** (ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

To estimate the cooling time and temperature of the TF inner leg during the cooling period between discharges. The analysis was performed to provide input to the coupled EM and thermal analysis as reported in calculation: NSTXU-CALC_132-05-00. In revision 1 the TF outer leg outlet fluid is input directly into the TF inner leg.

References (List any source of design information including computer program titles and revision levels.)

[1]The FCOOL code by Fred Dahlgren
[2] NSTX Design Point June 2010
http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

Assumptions (Identify all assumptions made as part of this calculation.)

For the assumptions about flow parameters see the calculation. An 8.5 second equivalent square wave (ESW) pulse of 135,000 Amperes for the first part of the analysis and a more realistic 7.6 second ESW for the second part are assumed to pass through each conductor during a shot.

Calculation (Calculation is either documented here or attached)

Attached

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

Calculation shows that for 135,000A flowing in each TF inner leg conductor for a pulse width (equivalent square wave) of 8.5 seconds, the cooling takes 600-700 seconds. The calculation shows the same current for 7.6-second ESW pulse with output of TF outer leg cooling water feeding the inner leg cooling will also cool the TF in less than approximately 700 seconds.

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

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(Checkers Calculation Included in Appendix A)

**Executive Summary**

The objective of this analysis was to estimate the cooling time and temperature of the TF inner leg during the cooling period between discharges. In part 1 of this report, the TF inner legs are cooled by fresh water flowing in the coolant channels in each of the 36 TF conductors. 1D Finite-section transient simulations of flow and cooling parameters were performed using the Fcool code developed by Fred Dhalgren and the PPPL team. Fcool uses input including the current flow and pulse length, coolant flow length, pressure drop, coolant channel size, and conductor size to model the flow and heat transfer in the coil and calculate the cooling time. We have calculated that for 135,000A flowing in each TF inner leg conductor for a pulse width (equivalent square wave) of 8.5 seconds, the cooling takes 600-700 seconds.

In part 2 cooling water from the outer leg of the TF coil is fed in the inner leg of the TF coil. The calculation of the cooling of both the outer leg (performed by Fcool) and the inner leg performed by CFX show that TF coil cooling can take under 700 seconds for 135,000A pulse flowing in each TF inner leg conductor for a pulse width (equivalent square wave) of 7.6 seconds.

## Part 1

### Modeling:

Figure 1 is a cross section of the TF inner bundle. The length of the TF conductor is 17.68 ft, the inner diameter of the cooling channel is 0.305 inches. The copper cross sectional area of the conductor is 4.97 square inches. The flow velocity is 3.3 m/s which equates to approximately 2.5 gallons per minute (GPM). An 8.5 second equivalent square wave (ESW) pulse of 135,000 Amperes is assumed to pass through each conductor during a shot.

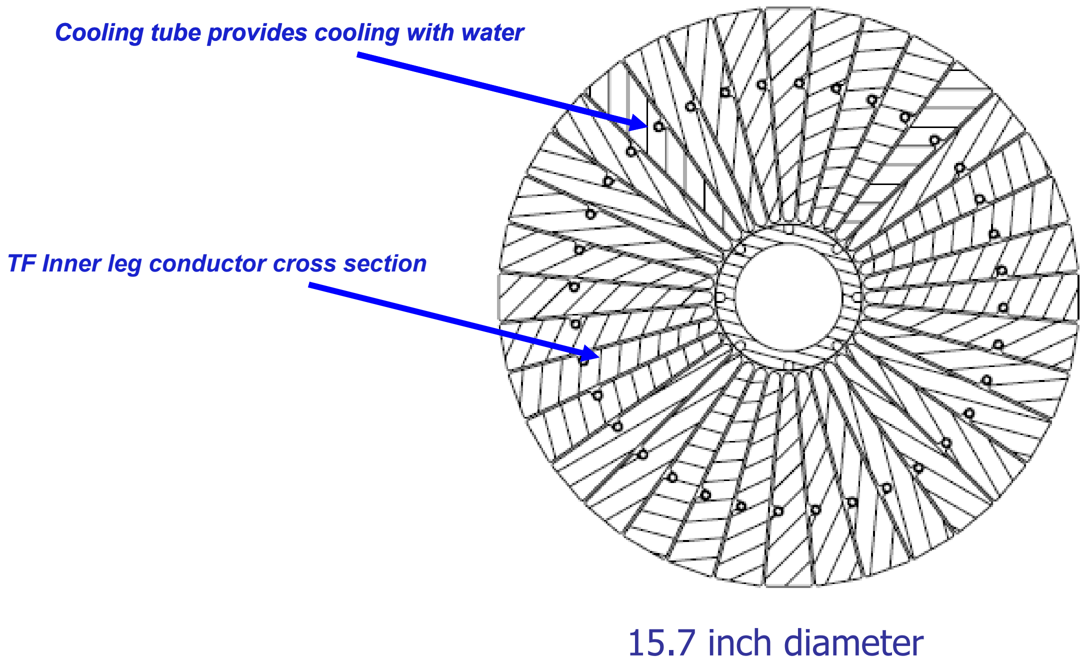



**Figure 1: TF inner leg bundle cross section**

Fcool program, developed by Fred Dhalgren and the PPPL team, was used for this analysis. Fcool uses input including the current flow and pulse length, coolant flow length, pressure drop, coolant channel size, and conductor size to calculate the heating due to the current pulse and model the flow and heat transfer in the coil in order to calculate the cooling time. It does this by dividing the coil into small finite length sections and sequentially solving the cooling and hydraulic parameters in the length sections using closed form equations.

**Results:**

Table 1 is a list of important parameters of the flow and cooling analysis. Figure 2 is a plot of coil temperature vs. time.

| | | |
|---|---|---|
| **PARAMETERS:** | | |
| PRESSURE DROP: | 15.50 | PSI |
| VELOCITY: | 11.25 | FT./SEC. |
| FLOW RATE: | 2.58 | GPM |
| MDOT: | 0.36 | LBS/SEC |
| PATH LENGTH: | 17.68 | FT. |
| REYNOLDS NO.: | 21349.44 | |
| h-film: | 0.60 | BTU/SQ.FT.-SEC.-DEG.F |
| CUR. DENSITY: | 27184.95 | AMPS/SQ.IN |
| TIME INCR.: | 0.01572 | SEC |
| ESW: | 8.50 | SEC. |
| REP. RATE: | 1800.00 | SEC. |
| INLET TEMP.: | 53.00 | DEG. F |
| CMASS: | 0.00 | LBS |
| HTL: | 0.24530 | FT. |
| NODE INTERVAL: | 0.17680 | FT. |

**Table 1: Analysis parameters**

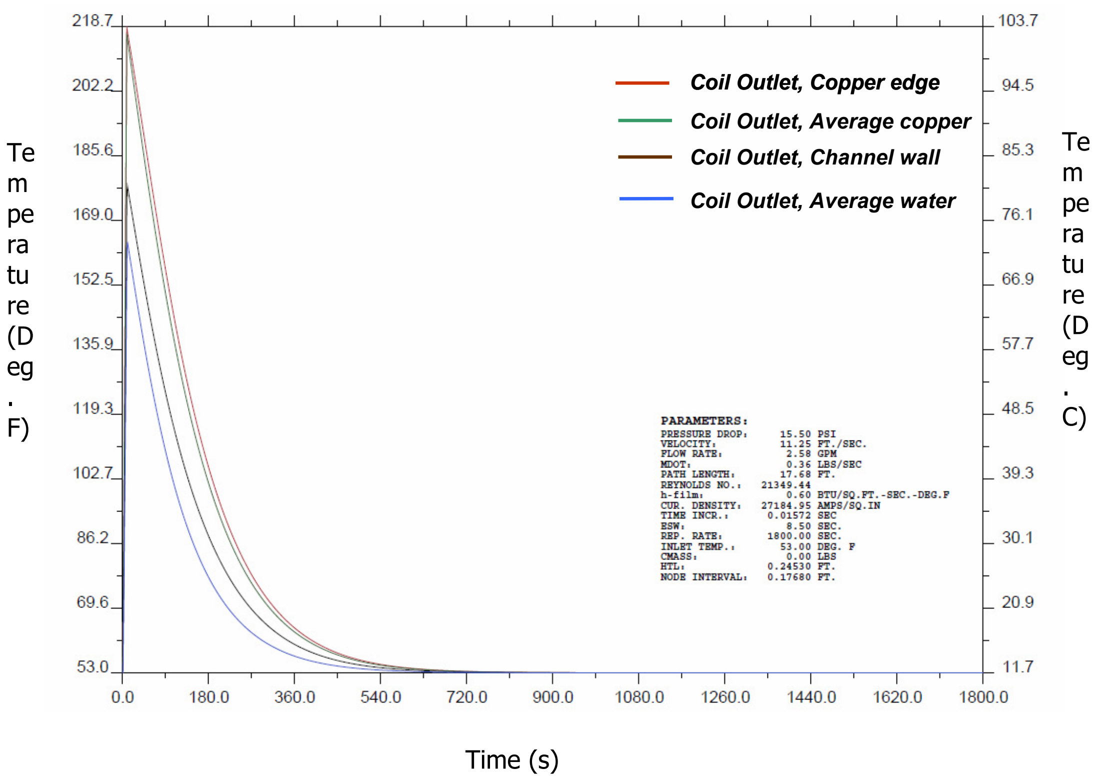



Figure 2: Temperature vs. time at the coil outlet

Figure 2 shows that the TF inner leg conductor is cooled in 600-700 seconds.

## Part 2

In this analysis it is assumed that the output of the TF outer leg coolant will be input in the TF inner leg during cool-down. The outlet temperature of the TF outer leg coolant was obtained from a separate fcool run. Figure 3 is the fcool cooling plot for the outer leg.

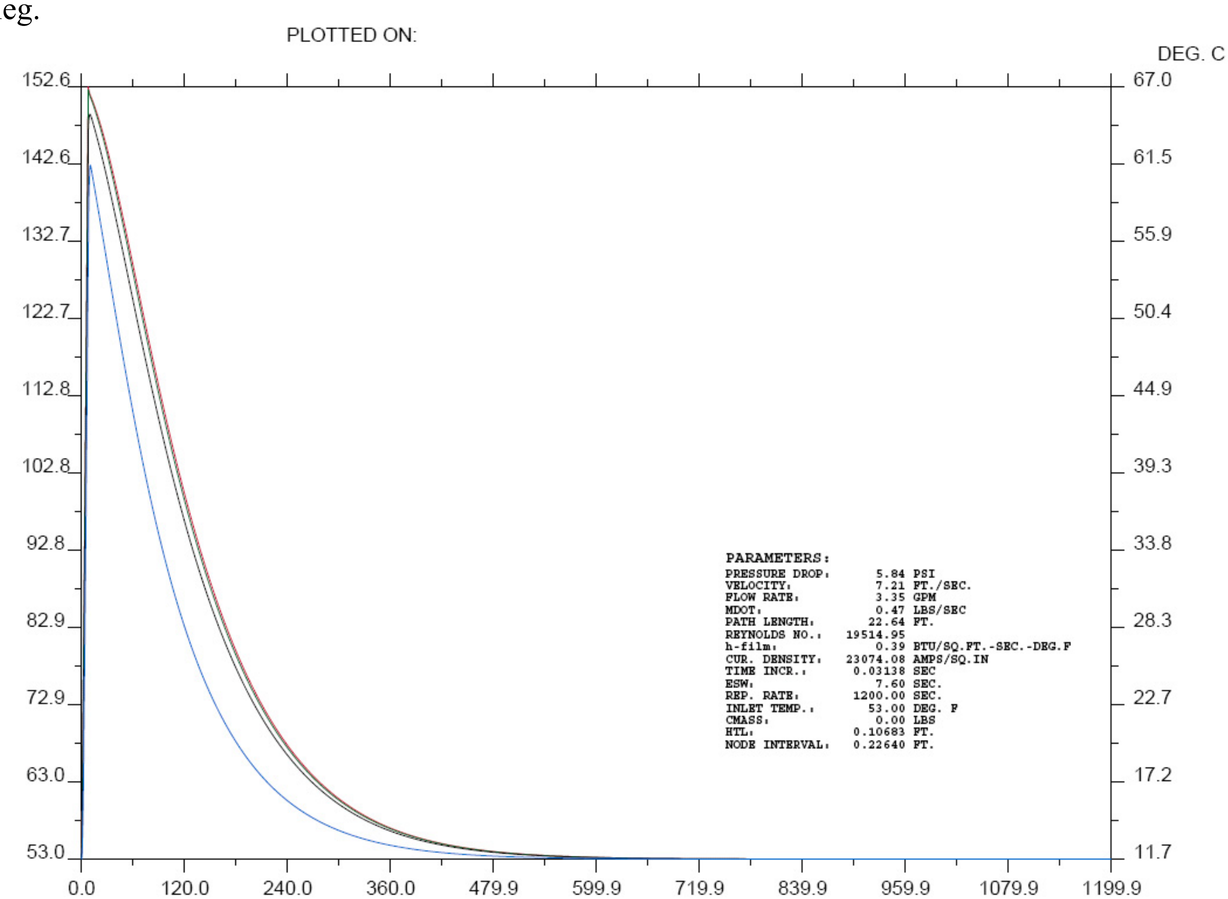


Figure 3

We fit the outlet cooling temperature of the outer TF vs. time (obtained from the fcool run) to a polynomial as seen on figure 4. Then we build a model of the TF inner leg in CFX and input the polynomial as the input water temperature as a function of time. The coolant channel on the TF inner leg is 7.62 mm in diameter and the flow velocity is 2.14 m/s. The length of the TF leg is 5.43 meters.

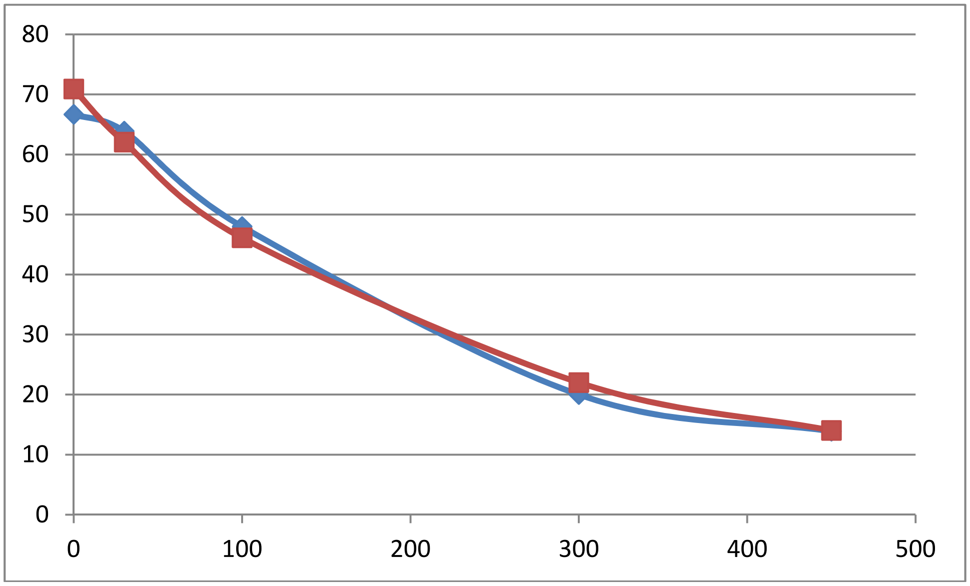


Figure 4- Data from fcool run is in blue, the polynomial fit is in red.

In Ansys CFX we model one inner leg ( which is wedge shaped in cross section with the coolant channel to the side) as a circular cross section of equal copper area and the same coolant hole in the center. This simpler model is quick to run and because copper has a high thermal conductivity, it is a good approximation. Figure 5 shows the modeled TF leg cross section.

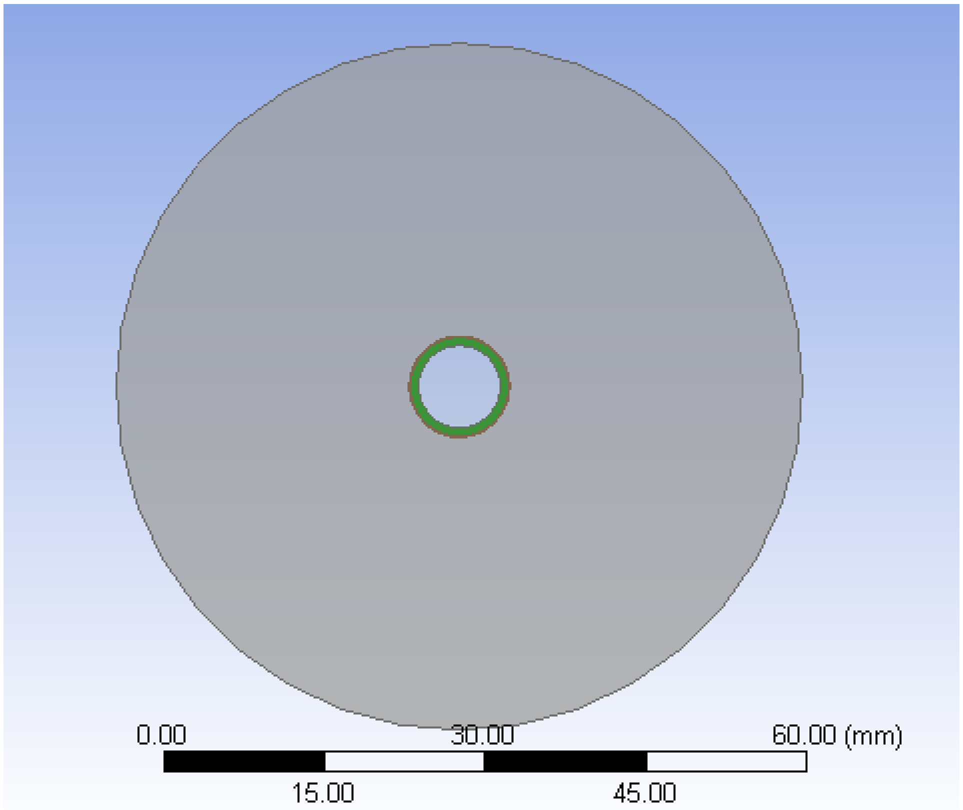


Figure 5

Figure 6 is the cooling plot for the TF **inner** leg and the outlet and inlet refers to the inner leg. “mid” in the legends means mid-way out radially in cross section (not in length). Each time-step in 1 sec.

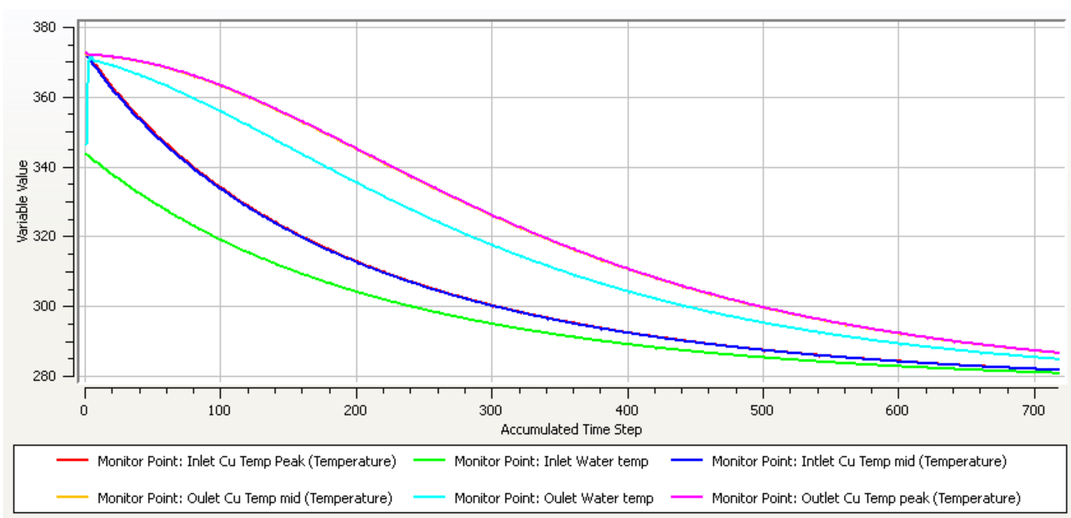


Figure 6

From figure 6 we can guess that at t=200s there is large temperature gradient in the coil. Figure 7 shows the temperature distribution in the inner leg at t=200s. Figures 6 and 3 for the inner and outer TF legs show that TF can be cooled in 700 seconds.

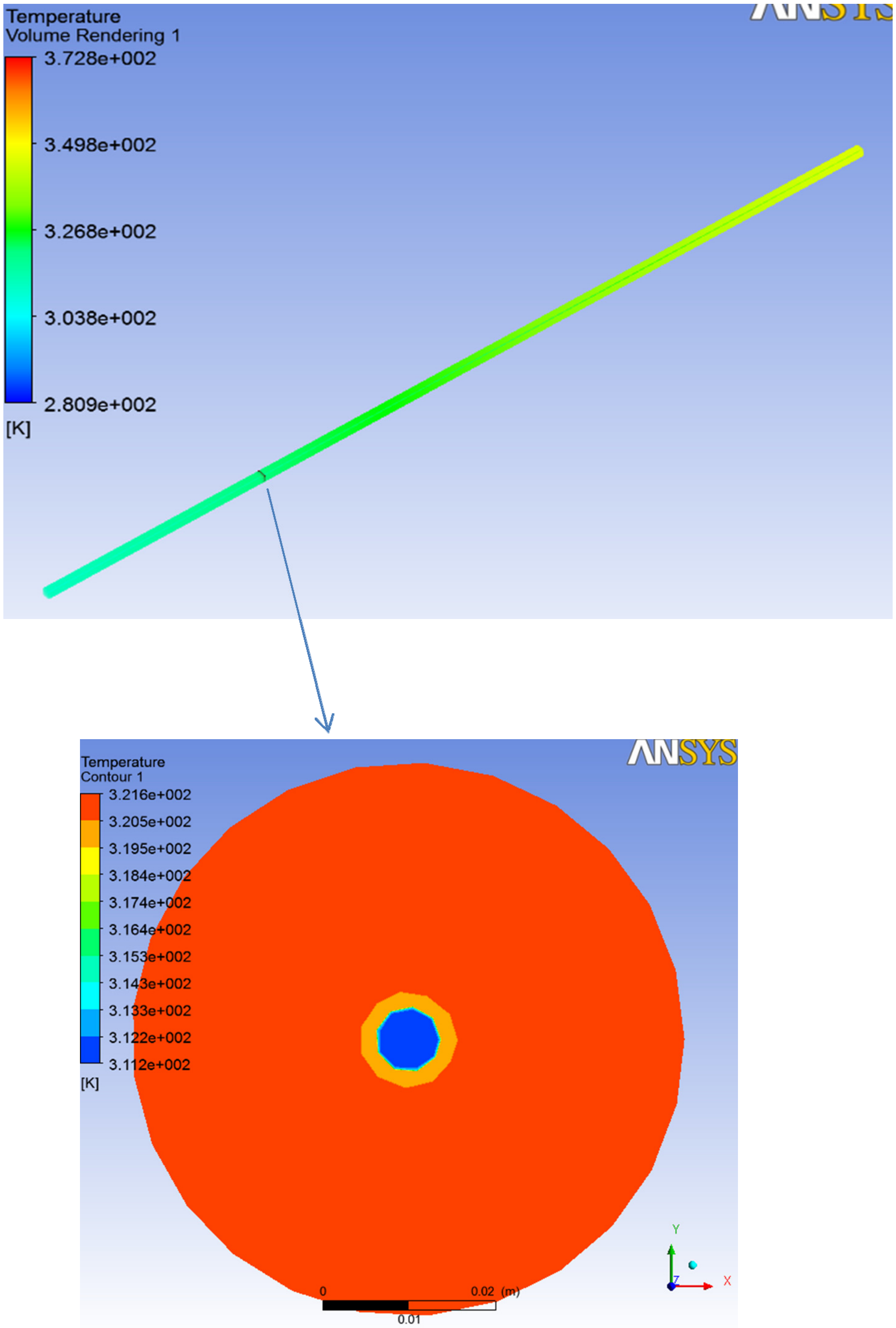



Figure 7

The temperature distribution from this CFX analysis has been communicated to Han Zhang to be used in the TF EM-Thermal coupled analysis. Below are some of these temperature results at different times along the TF inner leg.

t=0s

| Temp | Inlet | quarter | middle | 3 quarter | End |
|---|---|---|---|---|---|
| Water | 337.8 | 352.3 | 361.1 | 366.1 | 368.9 |
| Cu near tube | 360 | 365.7 | 368.7 | 370.4 | 370.4 |
| Cu | 362.6 | 367.2 | 369.6 | 370.9 | 370.9 |

t=100s

| Temp | Inlet | quarter | middle | 3 quarter | End |
|---|---|---|---|---|---|
| Water | 319.1 | 329.8 | 340 | 348.7 | 355.6 |
| Cu near tube | 332.4 | 342.7 | 351.5 | 358 | 362.5 |
| Cu | 333.9 | 344.2 | 352.7 | 359 | 363.3 |

t=200s

| Temp | Inlet | quarter | middle | 3 quarter | End |
|---|---|---|---|---|---|
| Water | 304.2 | 310.9 | 318.8 | 327 | 335.1 |
| Cu near tube | 312 | 320 | 328.7 | 337 | 344.2 |
| Cu | 312.9 | 321.1 | 329.8 | 338.1 | 345.1 |

t=300s

| Temp | Inlet | quarter | middle | 3 quarter | End |
|---|---|---|---|---|---|
| Water | 295 | 299.2 | 304.4 | 310.5 | 317.2 |
| Cu near tube | 299.8 | 305 | 311.4 | 318.5 | 325.2 |
| Cu | 300.3 | 305.6 | 312.2 | 319.3 | 326.1 |

t=400s

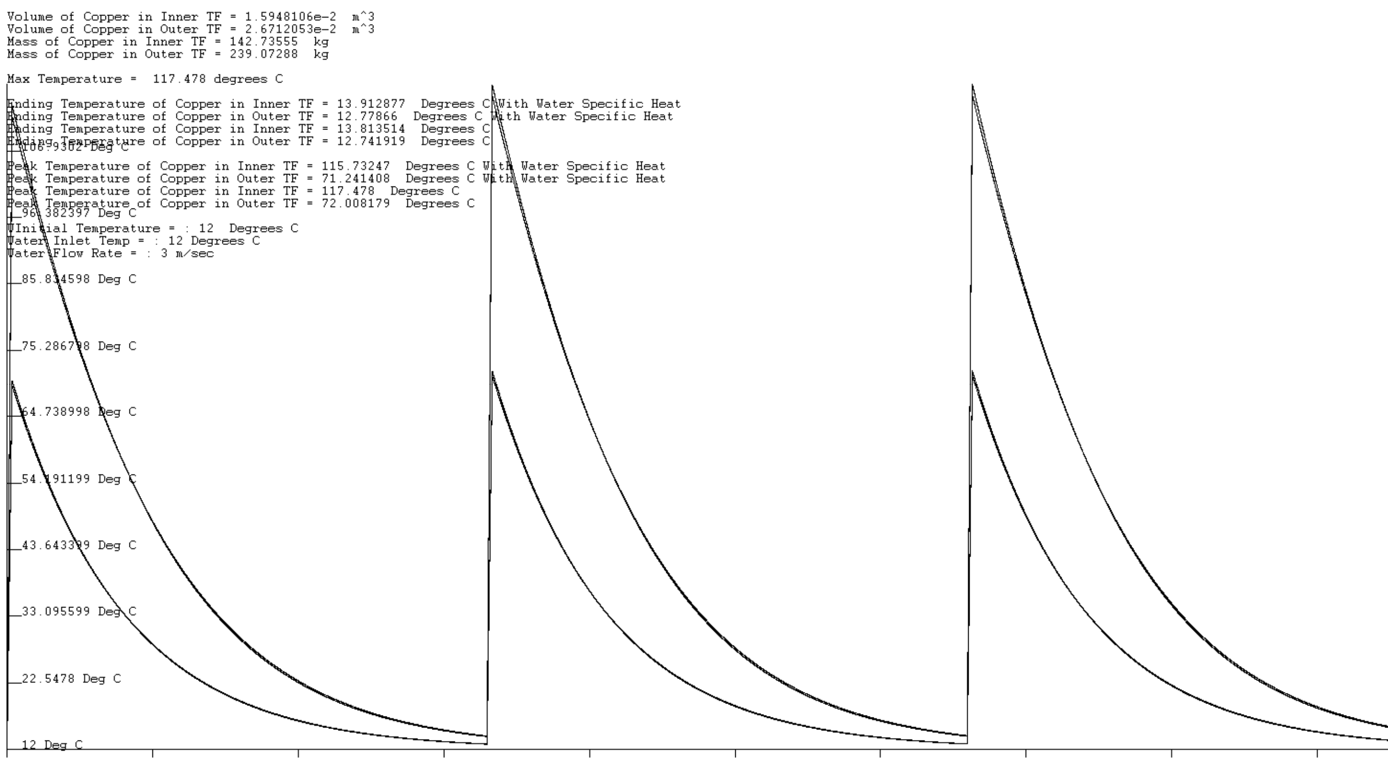
| Temp | Inlet | quarter | middle | 3 quarter | End |
|---|---|---|---|---|---|
| Water | 289.1 | 291.8 | 295.1 | 299.2 | 304 |
| Cu near tube | 292.2 | 295.5 | 299.7 | 304.7 | 310.1 |
| Cu | 292.5 | 295.9 | 300.2 | 305.3 | 310.7 |

t=500s

| Temp | Inlet | quarter | middle | 3 quarter | End |
|---|---|---|---|---|---|
| Water | 285.3 | 287 | 289.2 | 291.8 | 295.1 |
| Cu near tube | 287.3 | 289.4 | 292.1 | 295.5 | 299.2 |
| Cu | 287.5 | 289.6 | 292.5 | 295.9 | 299.7 |

# Appendix A
## Checkers Calculation

Treating the inner and outer TF coils as two lumped masses produces very similar results to the more complex FCOOL and CFX results. Ali's results are 103.7C peak for the inner TF and 67C for the outer TF leg. The checkers temperatures are 115C and 71C. The difference may relate to the packing fractions, but the conclusion that the inner TF can be cooled from the outlet fluid of the outer TF is confirmed.




```
dim cur(1000000),
poweru(1000000),powerl(1000000),CuTempu(1000000),CuTempl(1000000)
dim WCuTempu(1000000),WCuTempl(1000000),Wpoweru(1000000),Wpowerl(1000000)

         ! TF Current
let VSCurrent=135000

          !Temperature and Cooling
let Tinit=12
let TInlet = 12
let Flowrate=3   ! meters per sec

                             !Times
let numpulse=3
let dt=.1
let PulseLength=7.5    !Sec
let pulseinterval=700
          !  Plot Controls

let plotmint = 0
let plotmaxt = numpulse*(pulseinterval+pulselength)
let maxn=numpulse*(pulseinterval+pulselength)/dt

                           !Dimensions
let TFLengthInner=5.43  ! meters
let TFLengthOuter=6.9006   ! meters
let rocopper=15.7/2/39.37   ! Divide by 36 for per turn
```

```
let ricopper=.5/39.37
let packfractu=.85
let rhocopper =1.7074e-8     !RT zero field
let rhocopper =2.2494e-8     !100C zero field
let rhocopper =2.2576e-8     !100C 4T
let rhocopper =2.3931e-8     !120C 4T
let spheCopper=402.83        ! Joule/m^3/K   120C
let spheWater=4.1813*1000            ! at 20-100C Joule/g/degreeK*1000g/kg
let DensCopper=8950
let DensWater=1000.             !kg/cu meter


!             Areas and Volumes  are Per Conductor (Spine is Divided by 4)
let areacopperu=pi*(rocopper^2-ricopper^2)/36*PackFractu
let areacopperl=(2*3/39.37/39.37)
let areawateru=pi*.305^2/4/39.37/39.37
let areawaterl=pi*.305^2/4/39.37/39.37
let volcopperu=areacopperu*TFLengthInner
let volcopperl=areacopperl*TFLengthouter
let volwateru=areaWateru*TFLengthInner
let volwaterl=areaWaterl*TFLengthouter
let flowratel=flowrate
let flowrateu=flowratel*areawaterl/areawateru
!             Thermal Computed Values
let Wheatcapu=spheCopper*densCopper*volCopperu +spheWater*densWater*volWateru
let Wheatcapl=spheCopper*densCopper*volCopperl +spheWater*densWater*volWaterl
let heatcapu=spheCopper*densCopper*volCopperu
let heatcapl=spheCopper*densCopper*volCopperl
let WaterPoweru=spheWater*densWater*AreaWateru*flowrateu
let WaterPowerl=spheWater*densWater*AreaWateru*flowratel


!             Electrical Computed Values
let resistu=rhoCopper*TFLengthInner/areacopperu
let resistl=rhoCopper*TFLengthOuter/areacopperl

print "Inner TF cross sectional area of copper ";areacopperu
print "Outer TF cross sectional area of copper ";areacopperl
print "TF Equivalent Square Wave = ";Pulselength ;" Seconds"
print "TF Pulse Interval = ";pulseinterval; " Seconds"
print " TF Cooldown Time = ";Pulseinterval-pulselength;"Seconds"
print "Inner TF Flow Rate = ";flowrateu; "m/sec"
print "Outer TF Flow Rate = ";flowratel; "m/sec"
get key kinp

                  ! Create Current Profile

for i=1 to maxn
let ptime=dt*i
if ptime>0 and ptime<(Pulselength)  then
let cur(i)=cur(i)+VSCurrent
end if
if ptime>(Pulseinterval)and ptime<(Pulselength+pulseinterval)  then
let cur(i)=cur(i)+VSCurrent
end if
if ptime>(Pulseinterval*2) and ptime<(Pulselength+pulseinterval*2)  then
let cur(i)=cur(i)+VSCurrent
end if
next i
                             !Compute Power,Temperature Arrays
let maxpower=0
let maxtemp=0
let CuTempU(1)=Tinit
let CuTempL(1)=Tinit
let WCuTempU(1)=Tinit
let WCuTempL(1)=Tinit

for i=2 to MaxN
let pTime=dt*i
let poweru(i) = cur(i)^2*resistu
let powerl(i) = cur(i)^2*resistl
```

```
let CuTempU(i)= CuTempU(i-1) +(powerU(i)-WaterPoweru*(CuTempU(i-1)-CuTempL(i-
1)))*dt/HeatCapu
let CuTempL(i)= CuTempL(i-1) +(powerL(i)-WaterPowerl*(CuTempL(i-1)-Tinlet
))*dt/HeatCapl
let WCuTempU(i)=WCuTempU(i-1)+(poweru(i)-WaterPoweru*(WCuTempU(i-1)-WCuTempL(i-
1)))*dt/WHeatCapu
let WCuTempL(i)=WCuTempL(i-1)+(powerL(i)-WaterPowerl*(WCuTempL(i-1)-
Tinlet))*dt/WHeatCapl


    if CuTempU(i) >maxTemp then Let MaxTemp=CuTempU(i)
    if CuTempL(i) >maxTemp then Let MaxTemp=CuTempL(i)
    if WCuTempU(i)>maxTemp then Let MaxTemp=WCuTempU(i)
    if WCuTempL(i)>maxTemp then Let MaxTemp=WCuTempL(i)

    if CuTempU(i) >maxTempU then Let MaxTempU=CuTempU(i)
    if CuTempL(i) >maxTempL then Let MaxTempL=CuTempL(i)
    if WCuTempU(i)>maxTempUW then Let MaxTempUW=WCuTempU(i)
    if WCuTempL(i)>maxTempLW then Let MaxTempLW=WCuTempL(i)

let WpowerU(i)=Waterpower*(WCuTempU(i)-Tinlet)
let WpowerL(i)=Waterpower*(WCuTempL(i)-Tinlet)

if poweru(i)>maxpower then let maxpower=poweru(i)
if powerl(i)>maxpower then let maxpower=powerl(i)
if Wpoweru(i)>maxWaterpoweru then let maxWaterpoweru=Wpoweru(i)
if Wpowerl(i)>maxWaterpowerl then let maxWaterpowerl=Wpowerl(i)


next i

!set window -100,MaxN,-10000,VSCurrent*1.1
set window plotmint/dt,plotmaxt/dt,-10000,VSCurrent*1.1
call YScale2(VSCurrent,0,plotmint/dt,plotmaxt/dt," Amps")
call Timescale2(0,vscurrent,plotmint/dt,plotmaxt/dt)
for i=1 to MaxN
plot i,cur(i);
next i

print "enter any key"
get key kinp

clear
set window -100,MaxN,-.1*maxpower,maxpower*1.1
call YScale(maxpower,0,maxn," Watts")
call Timescale(0,maxpower,maxn)

print "Max Joule Power = "; maxpower;" Watts"
print "Power Removed by Water Flow Inner TF= ";MaxWaterPoweru
print "Power Removed by Water Flow Outer TF= ";MaxWaterPowerl

for i=1 to MaxN
plot i,poweru(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,powerl(i);
next i
plot i-1,0
print "enter any key"
get key kinp

clear
print "Volume of Copper in Inner TF =";volcopperu;" m^3"
print "Volume of Copper in Outer TF =";volcopperl;" m^3"
print "Mass of Copper in Inner TF =";volcopperu*denscopper;" kg"
print "Mass of Copper in Outer TF =";volcopperl*denscopper;" kg"

print ""
print "Max Temperature = ";maxtemp;"degrees C"
print ""
```

```
print "Ending Temperature of Copper in Inner TF =";WCuTempu(maxn);" Degrees C
With Water Specific Heat"
print "Ending Temperature of Copper in Outer TF =";WCuTempl(maxn);" Degrees C
With Water Specific Heat"
print "Ending Temperature of Copper in Inner TF =";CuTempu(maxn);" Degrees C"
print "Ending Temperature of Copper in Outer TF =";CuTempl(maxn);" Degrees C"
print ""
print "Peak Temperature of Copper in Inner TF =";MaxtempUW;" Degrees C With
Water Specific Heat"
print "Peak Temperature of Copper in Outer TF =";MaxtemplW;" Degrees C With
Water Specific Heat"
print "Peak Temperature of Copper in Inner TF =";MaxtempU;" Degrees C"
print "Peak Temperature of Copper in Outer TF =";Maxtempl;" Degrees C"
Print ""
print "WInitial Temperature = :" ;tinit; " Degrees C"
print "Water Inlet Temp = :" ;Tinlet; "Degrees C"
print "Water Flow Rate = :" ;flowrate; "m/sec"
set window plotmint/dt,plotmaxt/dt,Tinit*.9,MaxTemp*1.1
!set window -100,MaxN,Tinit*.9,MaxTemp*1.1
call YScale2(maxtemp,tinit,plotmint/dt,plotmaxt/dt," Deg C")
!call Timescale(tinit,maxtemp,maxn)
call Timescale2(tinit,maxtemp,plotmint/dt,plotmaxt/dt)
for i=1 to MaxN
plot i,CuTempU(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,CuTempL(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,WCuTempU(i);
next i
plot i-1,0
for i=1 to MaxN
plot i,WCuTempL(i);
next i

Sub YScale(min,max,maxn,unit$)
for i=1 to 10
plot 0,min+i*(max-min)/10    ;  .01*(maxn),min+i*(max-min)/10
plot text, at .01*(maxn),min+i*(max-min)/10: str$(min+i*(max-min)/10)&unit$
next i
end sub

Sub YScale2(min,max,minn,maxn,unit$)
for i=1 to 10
plot minn,min+i*(max-min)/10    ;  minn+.01*(maxn-minn),min+i*(max-min)/10
plot text, at minn+.01*(maxn-minn),min+i*(max-min)/10: str$(min+i*(max-
min)/10)&unit$
next i
end sub

Sub Timescale(min,max,maxn)
plot 1,0 ;1,max
plot 0,min;maxn/dt,min

for i=1 to 10
plot i*maxn/10,min;i*maxn/10,min-.1*(max-min)
next i
for i=1 to 10
plot text, at i*maxn/10,min-.05*(max-min): str$(i*maxn/10*dt)&" sec"
next i
end sub

Sub Timescale2(min,max,minn,maxn)
plot 1,0 ;1,max
plot 0,min;maxn/dt,min

for i=1 to 10
plot minn+i*(maxn-minn)/10,min;minn+i*(maxn-minn)/10,min-.1*(max-min)
next i
```

```
for i=1 to 10
plot text, at minn+i*(maxn-minn)/10,min-.05*(max-min): str$(minn*dt+i*(maxn-minn)/10*dt)&" sec"
next i
end sub

end
```