NCSX

Design Basis Analysis

Thermal Analysis TF Coil Cooling

NCSX-CALC-131-01-00

4 Feb. 2005

Prepared by:

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F..Dahlgren, Engineering Analyst

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct. I concur with analysis methodology and inputs and with the reasonableness of the results and their interpretation.

Reviewed by:

Michael Kalish Digitally signed by Michael Kalish DN: cn=Michael Kalish, o=PPPL, ou=Engineering, email=mkalish@pppl.gov, c=US Date: 2008.10.01 09:03:13 -04'00'

M. Kalish, Cognizant Engineer

I. Executive Summary:

A transient analysis was performed to determine the thermal response of the NCSX TF Coils to a maximum required pulse (0.5 Tesla TF field). The peak conductor temperature rise was 3.5 ^{o}K for a 16.2 kA peak current with a 1.64 second equivalent square wave (ESW). The thermal recovery time was roughly 720 seconds providing a margin of 180 seconds for the stipulated duty cycle of 900 seconds (15 minute rep. rate).

II. Assumptions:

Reference thermo-hydraulic properties for LN2 from 138 to 225 degrees R (used in Fcool3tc LN2 subroutines) are taken from the NIST Webbook.

Thermo-physical properties for OFHC Copper from 138 to 225 degrees R (used in Fcool3tc subroutines) are taken from Ref 1.

All TF coils are cooled in parallel with one coolant channel of 355.3 ft per coil.

An assumed pressure drop of 60 psi is applied to each TF coil cooling channel.

The inlet temperature of the LN2 coolant is maintained at 144 degrees R (80 deg.K).

III. Analysis Methodology and Inputs:

Codes Used:

ESW-2 - PPPL in-house code to calculate the ESW heating equivalent for a given coil current waveform.

Fcool3tcLN - ver.2.23 - PPPL in-house 2-D Finite difference code that calculates the thermal response of pulsed coils with forced convection LN2 internal cooling.

Reference Drawings:

Pro-E dwg. NCSX-TF_COND - TF COIL BARE CONDUCTOR DETAIL
Pro-E dwg. SE131-009 - TF COIL GEOMETRY shts.1 to 3

References:

NIST Monograph 177: “Properties of Copper and Copper Alloys at Cryogenic Temperatures”, N.J. Simon, E.S. Drexter, R.P. Reed

IV. Results and Disscussion:

Figure 1 is a plot of a typical 0.5T (possible required flexibility) TF coil pulse. This waveform conforms to the A.31 ID #7 0.5T reference scenario defined in Table 2, and defines the most severe heating condition on the TF coil system (for an earlier M45 scenario). Figure 2. is a plot of I^2vs.t for a 0.5 Tesla TF Coil pulse. The calculated ESW (equivalent square wave) for heating input was 2.09 seconds at the 16.2 kA maximum coil current. Subsequent scenarios have reduced the I^2t requirements and the maximum stipulated ESW is now 1.64 seconds for the 0.5T case.
Using the 1.64 sec. ESW, a transient thermal analysis was run to determine the temperature rise in the TF conductor for the 0.5T pulse. A PPPL finite difference code (Fcool3tcLN-ver.2.23) with temperature dependent thermo-hydraulic LN2 coolant properties was used for the analysis. The conductor starting temperature and the LN2 coolant inlet temperature were assumed to be at 80 ^oK (144 ^oR). Figure 3 shows the thermal response of the TF coil at the coolant exit to the 1.64 sec. ESW heating pulse and subsequent cool down. The peak conductor temperature is 83.5 ^oK at the end of the heating pulse. Since the actual pulse duration will be longer than the 1.64 sec ESW, some additional minimal cooling during the pulse will occur making this peak temperature an upper-bound of the actual temperature excursion for the coil. (Since the joule heating of the coil is nearly adiabatic – ie. there will be negligible additional cooling during the actual extended pulse - the actual peak temperature will be very close to this value). The plot lines in Figure 3 represent the coil conductor (black) and coolant (blue) temperatures at the coolant exit and shows a fairly rapid equilibration of coolant exit temperature with the conductor, occuring on a time scale of roughly 3-4 seconds, after which the temperatures remain relativly constant for about 360 seconds. This is the amount of time required for the cooling wave (a steeper thermal gradient traveling from the entrance to the coolant exit) to propagate down the length of the coolant channel. The coil is seen to return to it's initial temperature in roughly 720 seconds, providing a 180 second margin on the assumed 900 second rep. rate required of the coil system. Since this is basically a 2-D analysis no heat conduction is assumed to occur through the turn-to-turn coil insulation, so this again will be an upper bound on the thermal recovery time. For a full 3-D transient response we would expect to see some minor conduction cooling from the warmer turns nearer the coolant exit to the more rapidly cooling interior turns nearer the coolant entrance. In reality this would produce a slightly less pronounced knee in the cooldown and a slightly negative slope to the equilibrated temperature lines, but would not significantly change the overall coil thermal recovery time.

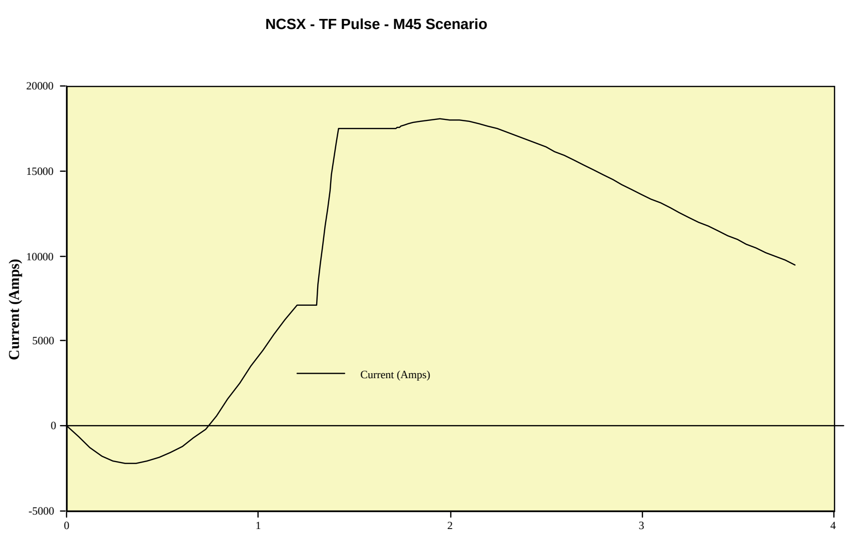

FIGURE 1. Typical TF current waveform for a 0.5 Tesla field

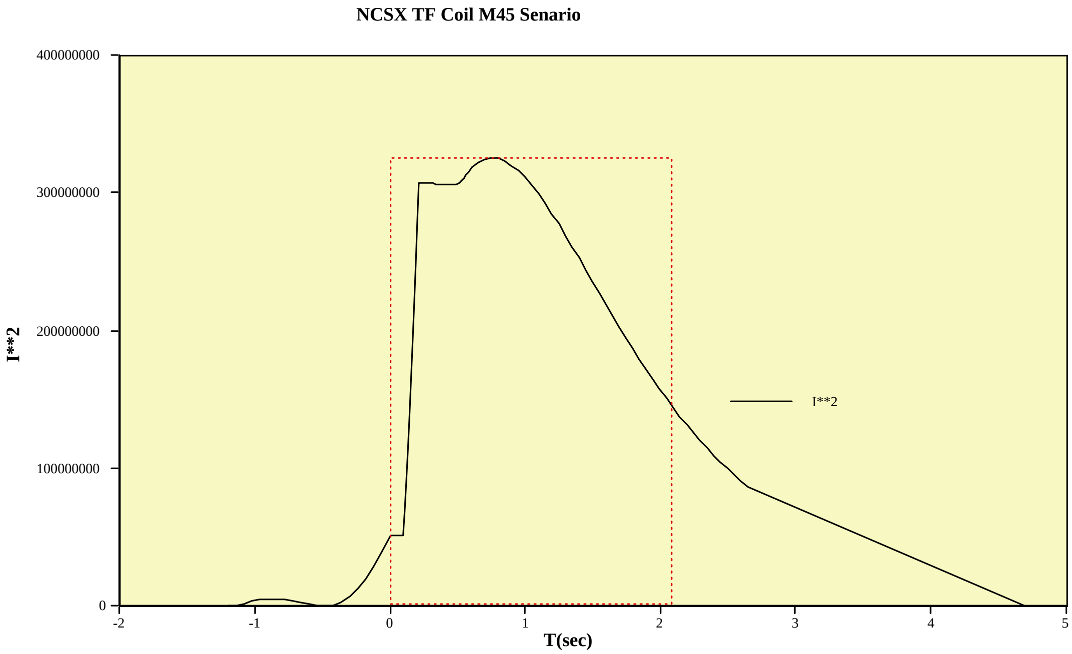

FIGURE 2. I^2 vs. T for a Typical (0.5 Tesla) TF Coil Pulse

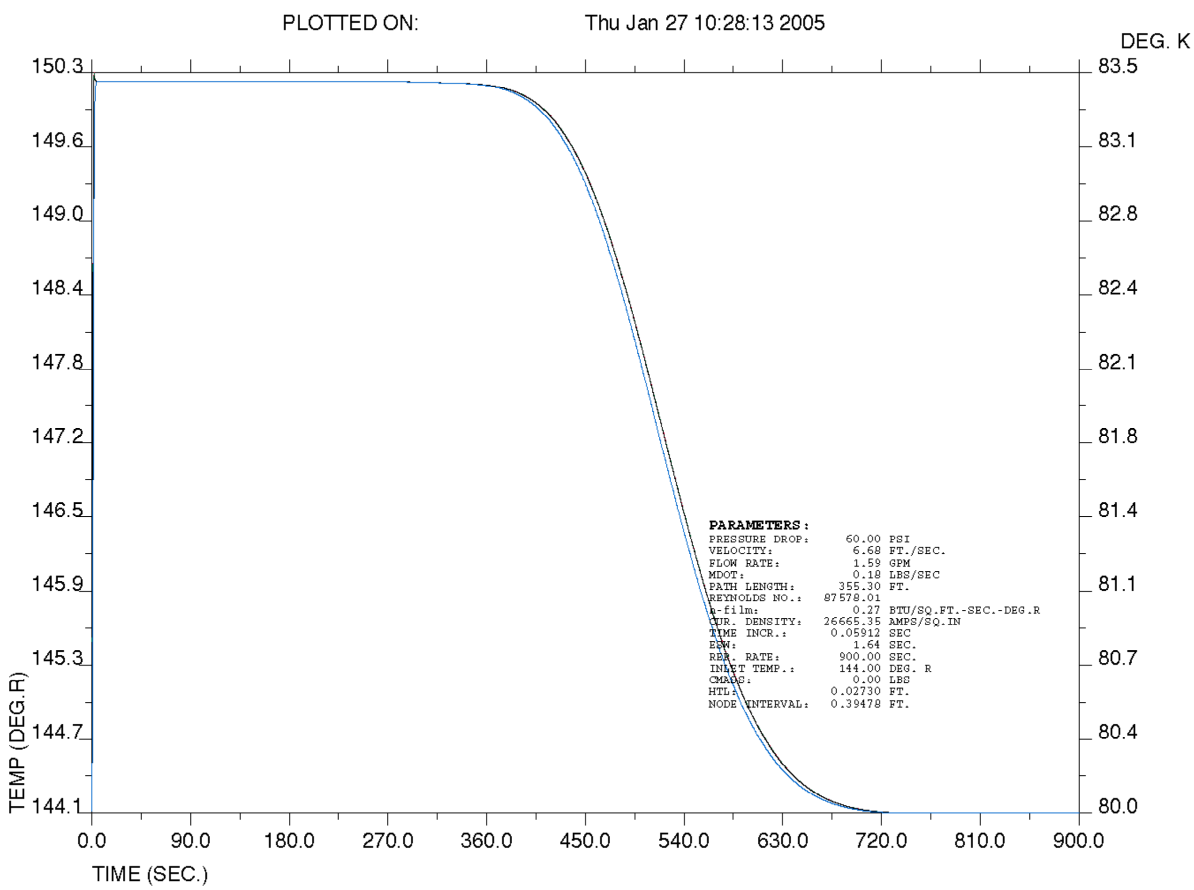

FIGURE 3. Thermal Response of TF Coil – 1.64 ESW, 60 psi Pressure Drop, 80 ^{0} C

Results & Discussion (Con’t.)

Figure 4 shows the cool down cycle if the applied pressure drop across the coil is increased from 60 psi to 80 psi. This results in a 17% increased flow of 0.28 GPM and similar increases in the flow velocity and film coefficient. The overall effect is to increase the cooling wave velocity and shorten the recovery time from 720 seconds to 620 seconds. Note that the peak temperature is still 83.5 K indicating only minimal cooling is occuring during the discharge.

An additional run was made to determine the sensitivity to longer ESW pulses in the event the TF current decays in it’s shorted L/R time. Figure 5 is a run with a 60 psi pressure drop and a 2 second ESW. It can be seen that the peak temperature rise is higher (85.3 K vs. 83.5 K), and the equilibration temperature increased by roughly 3 deg. K, while the coil recovery time is only slightly longer than the 1.64 ESW pulse. These results indicate a fairly high margin for heat removal in the TF coils.

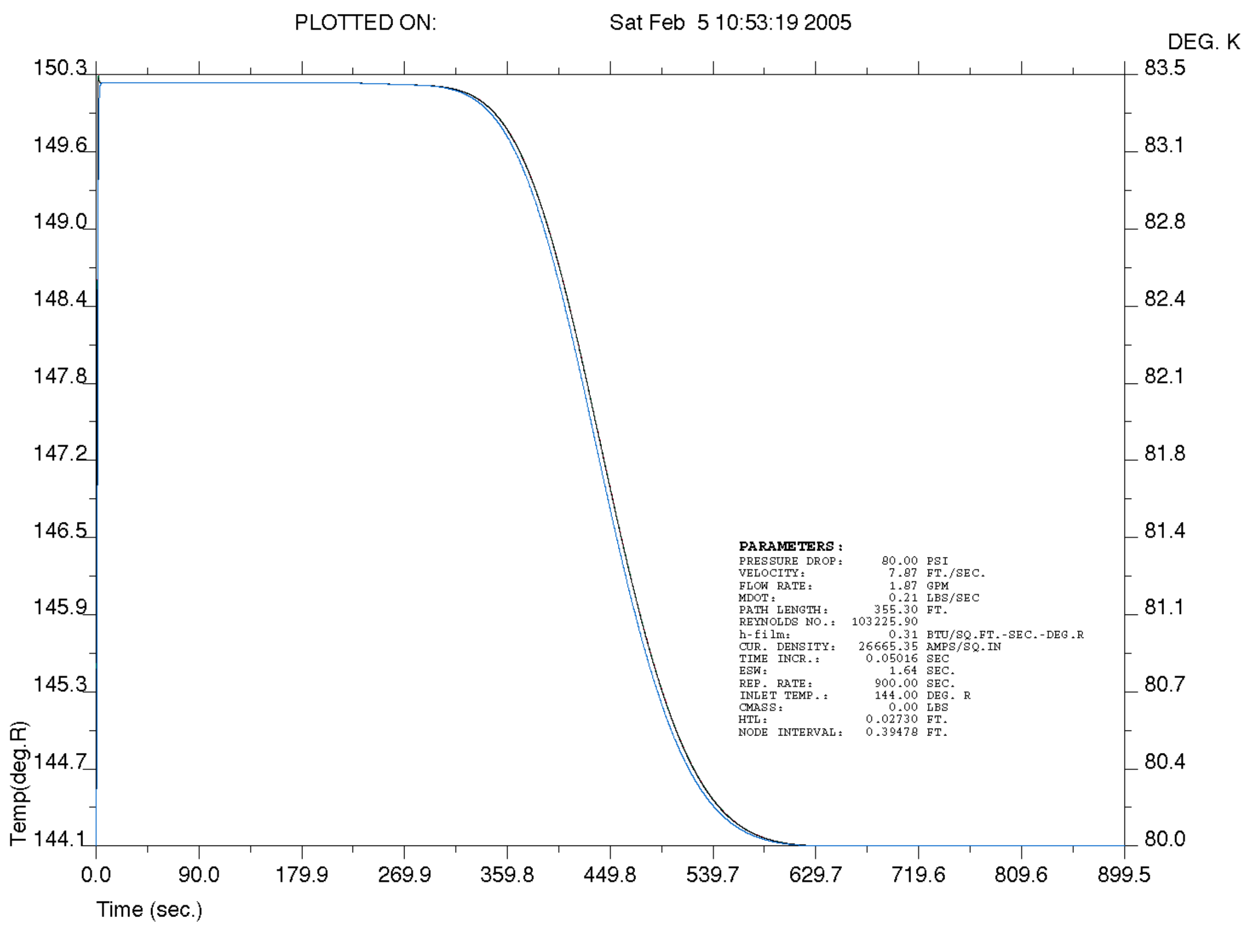

FIGURE 4. Thermal Response of TF Coil - 80 psi Pressure Drop, 80 ^{0} C Inlet Temperature

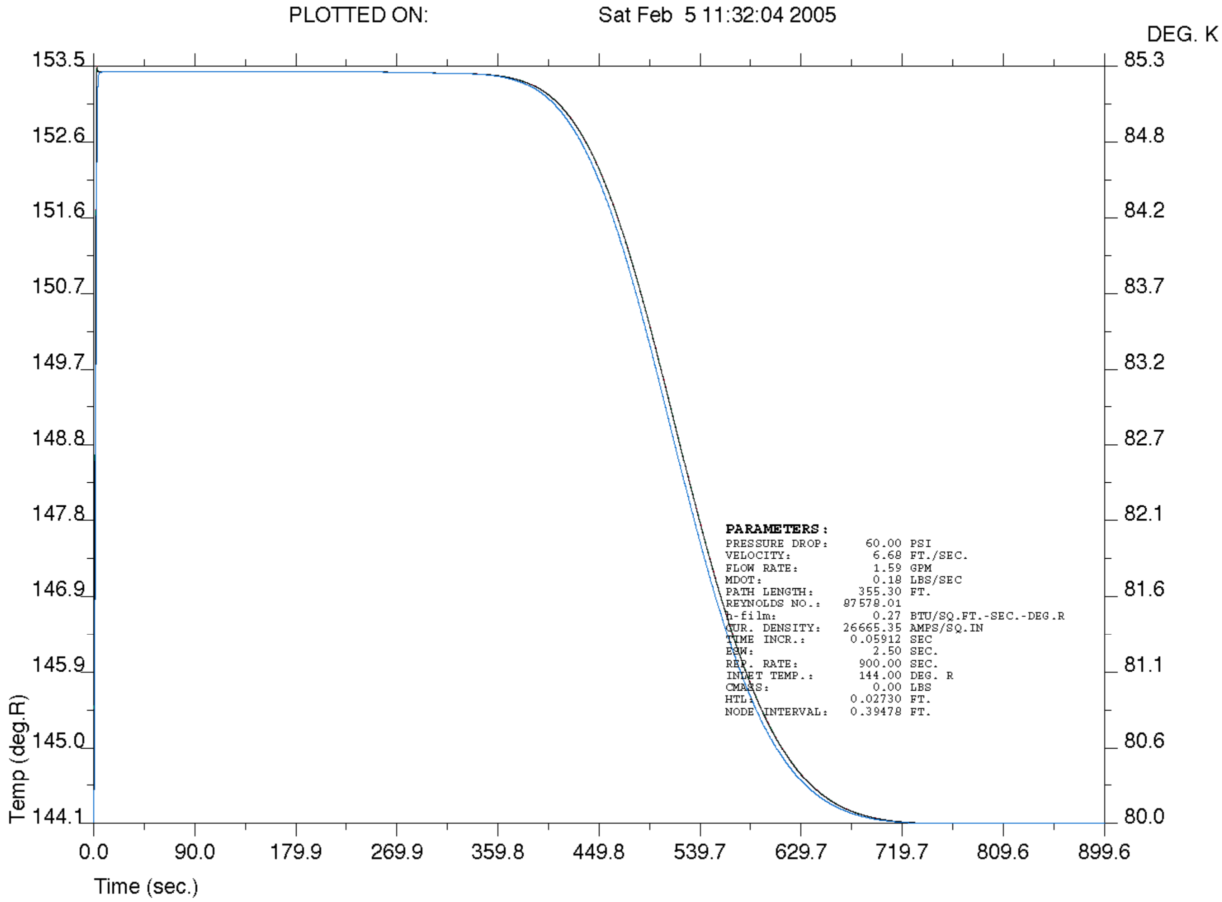

FIGURE 5. Thermal Response of TF COIL – 2.0 sec. ESW – 60 psi Pressure Drop

Table 1 below is a summary list of the main thermal model parameters and indicates a 1.59 GPM LN2 flow is produced when a pressure drop of 60.0 psi is applied across the 355.3 ft. coolant channel length (parameters with a * are calculated by the code).

Table 1. Basic FcooltcLN-2.23 Parameters

PARAMETERS:	
PRESSURE DROP:	60.00 PSI
*VELOCITY:	6.68 FT./SEC.
*FLOW RATE:	1.59 GPM
*MDOT:	0.18 LBS/SEC
PATH LENGTH:	355.30 FT.
*REYNOLDS NO.:	87578.01
*h-film:	0.27 BTU/SQ.FT.-SEC.-DEG.R
*CUR. DENSITY:	26665.35 AMPS/SQ.IN
*TIME INCR.:	0.05912 SEC
ESW:	1.64 SEC.
REP. RATE:	900.00 SEC.
INLET TEMP.:	144.00 DEG. R
CMASS:	0.00 LBS
HTL:	0.02730 FT.
*NODE INTERVAL:	0.39478 FT.
HOLE DIAMETER:	0.02598 FT.
*CPCU(TI)	0.048800 BTU/LB-DEG.R
*CKCU(TI):	0.085278 BTU/SEC.FT-DEG.R
*CKFT(TI):	0.0000226 BTU/SEC-FT-DEG.R
*CPCF(TI):	0.4897398 BTU/LB-DEG.R
*RHOFT(TI):	49.6747360 LBS/CU.FT.
RHOC:	558.000000 (CONDUCTOR)LBS/CU.FT.
code version:	2.23

Table 2. A.3.1 Reference Equilibria

A.3.1 Reference Equilibria

Equlibrium ID	M1	M2	M3	PF1	PF2	PF3	PF4	PF5	PF6	TF	Plasma		Comment
1	7.63E+05	7.10E+05	6.38E+05	0.00E+00	0.00E+00	3.05E+05	2.40E+05	2.03E+05	-1.05E+05	-4.26E+04	0		iota>0.5
2	6.95E+05	7.06E+05	6.21E+05	0.00E+00	0.00E+00	1.60E+05	-1.92E+05	2.42E+04	1.07E+04	-1.33E+04	0		iota<0.5
3	6.95E+05	7.06E+05	6.21E+05	0.00E+00	0.00E+00	1.60E+05	-1.92E+05	2.05E+04	7.53E+04	-1.33E+04	-120000		120kA, zero beta
4	6.59E+05	6.54E+05	5.43E+05	0.00E+00	0.00E+00	1.05E+05	-3.54E+05	5.58E+04	9.00E+04	4.53E+04	-179000		179kA, full beta
5	6.82E+05	6.40E+05	5.78E+05	0.00E+00	0.00E+00	-1.30E+06	-1.50E+06	1.07E+05	6.12E+04	2.62E+04	-320000		320kA, zero beta
6	6.69E+05	6.44E+05	5.57E+05	0.00E+00	0.00E+00	-1.14E+05	-2.09E+05	-3.27E+05	2.60E+05	3.77E+04	-160000		160kA, zero beta
7	6.95E+05	7.06E+05	6.21E+05	0.00E+00	0.00E+00	1.60E+05	-1.92E+05	2.42E+04	1.07E+04	1.94E+05	0		0.5T TF +S1b
8	7.63E+05	7.10E+05	6.39E+05	0.00E+00	0.00E+00	0.00E+00	9.64E+05	0.00E+00	-9.72E+03	-4.26E+04	0		First Plasma
9	6.95E+05	6.98E+05	6.29E+05	0.00E+00	0.00E+00	0.00E+00	-8.17E+04	0.00E+00	8.42E+04	-1.33E+04	-120000		First Plasma

IV. Summary and Conclusions:

A finite difference analysis of the LN2 cooled NCSX TF coil was performed. The results indicate that the peak temperature rise of the coil will be ~3.5 deg.K (~6 deg.R) per pulse with full recovery to 80 deg.K after ~720 seconds. The recovery time was found to be relatively insensitive to the pulse length and to scale roughly inversely with the coolant flow rate (mass flow).