Analysis of the NCSX PF1A Solenoid Coil Support Structure

Executive Summary:

A preliminary analysis of the PF1A coil and supports for NCSX high volt-second operations has been performed. This analysis evaluated simple operating conditions including EM (Electro-Magnetic) loads and thermal responses only. The preliminary results indicate adequate stress margins (for EM loading at 47 kA). The thermal response at 47 kA limits the I^2t to an ESW of 0.22sec assuming we want to avoid 2-phase flow in the LN2 cooling passages (the temperature rise for 47 kA, 0.22sec ESW pulse is ~20 deg.K).

For 67 kA operations the delta-T would limit I^2t to an ESW of slightly more than 0.1 sec to stay below the saturation temperature (assuming 120 psi pressure in the LN2 coolant duct). The EM loading at 67 kA produces a peak Tresca stress in the conductor of 21.9 ksi and a max shear of 6.6 ksi in the insulation. Both values are significantly above the allowables for these materials at 77 K (16 ksi for CDA 107 copper with 10% CW, 2.2 ksi for CTD-112 VPI'd epoxy/glass w/kapton).

Based on these results a peak 47 kA operation for PF1a coils appears feasible although the characteristics of the power supply and the circuit response of the serially bused coils needs to be evaluated to determine whether the required volt-sec discharge is achievable. Operation at 67 kA is problematic due to the copper stress levels, shear in the insulation, and the limited I^2t.

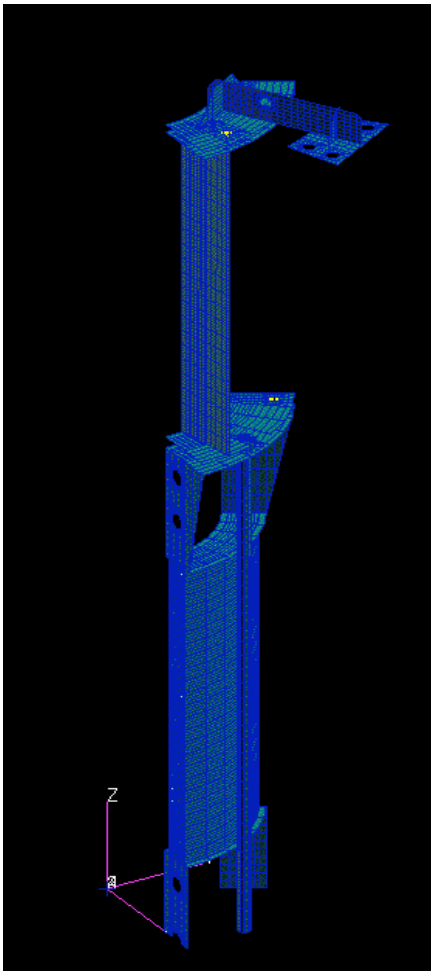
Preliminary Analysis:

Introduction:

The design basis for the PF1a coils (salvaged from NSTX) currently earmarked for use in NCSX MIE operations is 19.3 kA for a 0.16 ESW (I^2t = 6e7 Amp^2-sec.). To achieve 350 kA plasma discharges a significantly higher current is required in PF1a to provide the flux swing and volt-seconds. To evaluate the feasibility of using just the PF1a coils for this purpose, an analysis of the E-M loads, stresses, and thermal response when powered to a peak current of 47kA and 67 kA was performed. The analysis used FCOOL223-LN2 for modeling the thermal response of the coil, DFORCE-d2 and NASTRAN to model the E-M loads and stresses.

EM Analysis:

Appendix I contains the DFORCE-d2 summary output of runs at three current levels (23.4 kA, 47 kA, 67 kA) with an assumed 350 kA plasma current. Geometry, loads, mean stresses, and displacements are presented in columns for each of the PF coil systems in SI and English customary units. The code also calculated discrete vertical and radial Lorentz forces at internal points in the coil conductor which were used to generate force data records for the NASTRAN FEA input deck. The stresses shown in the summary outputs are simple average hoop stresses and bending stresses (for the discretely supported coils – PF4-PF6) based on the magnetic pressure and a laminated beam assumption for the bending stiffness of the coils. The DFORCE code is used primarily for scoping studies and load generation. To get a more detailed picture of the stresses in the coil a FEA NASTRAN model was used which included the coil conductors with internal cooling hole, turn-to-turn insulation layers, and the supporting structure. The FEA model and details are shown in fig.1 below.



FEA Model of PF1A & Supporting Structure:

- A 1/6th-Upper half Nastran linear FEA model was used.
- PF1A coil modeled as discrete turns with insulating layers (CHEXA & CPENTA).
- Structural components modeled with plate elements (CQUAD4 & CTRIA3).
- Tie rods modeled with solid elements (CHEXA & CPENTA).
- Bolts modeled with CBAR elements attaching plates & adjacent weldments.
- EM loads on PF1A determined from DFORCE-2d (Biot-Savart - U.C. code).
- Symmetry boundary conditions were applied (toroidal, vertical and rotational).
- Coil top & bottom surfaces not permitted to slide radially (rel. to supports).
- Model Summary:

Number of GRID Points	=	21979
Number of CBAR Element	=	57
Number of CHEXA Elements	=	13232
Number of CPENTA Elements	=	1696
Number of CQUAD4 Elements	=	2287
Number of CTRIA3 Elements	=	170

- Loading Conditions considered: 47 kA & 67 kA -350 kA Plasma

Figure 1. FEA NASTRAN model details for the NCSX PF1a coil assembly

Results For 47 kA Loading:

The results of the 47 kA loading indicated a peak Tresca stress in the conductor of 11.5 ksi which is less than the allowable stress for CDA107 Cu-10% C.W. (16 ksi @T=77 K). The Tresca stress contours for this loading are shown in figure 2 with the peak stress shown as the red contour at the inner surface of the coolant hole of the inner-middle turns. The maximum shear stress in the epoxy/glass turn-to-turn insulation also occurs in the same region (see figure 3) and peaks at about 2.2 ksi which is approaching the allowable for shear stress in thin epoxy/glass layers with no normal compression.

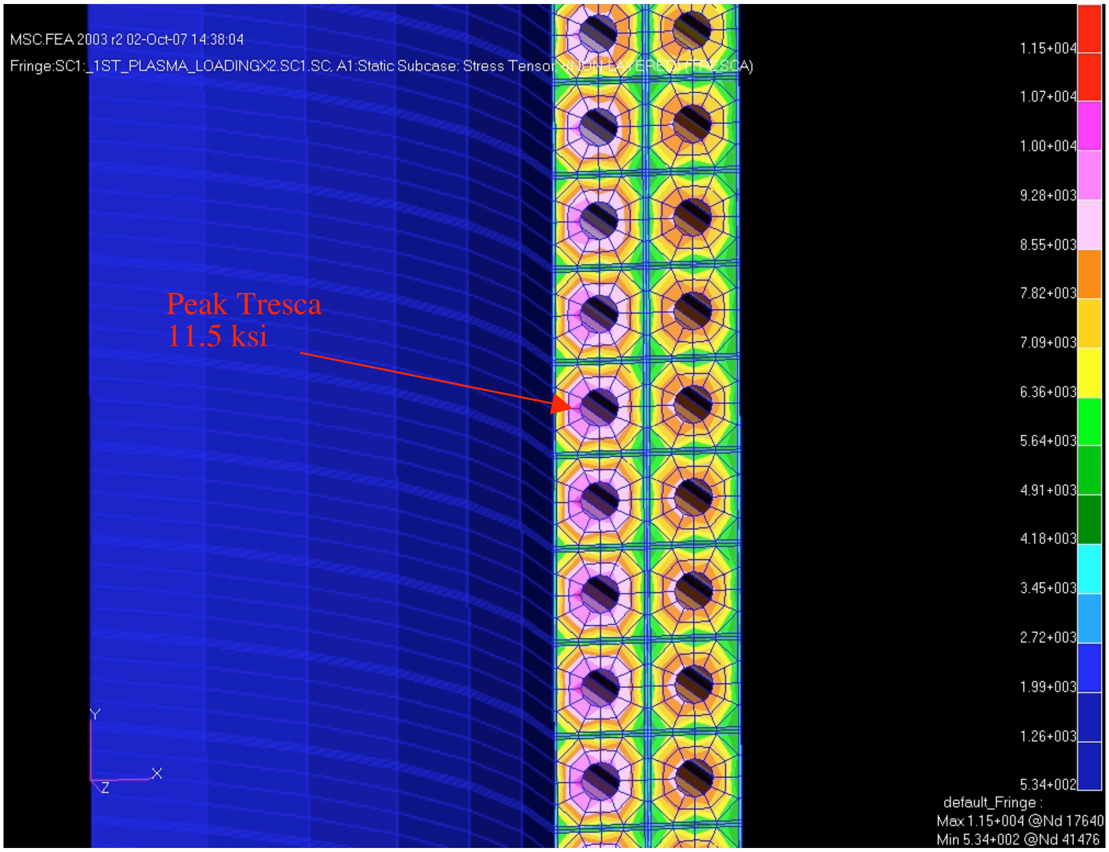


Figure 2. Tresca stress contours for 47 kA Loading -Peak Tresca stress of 11.5 ksi

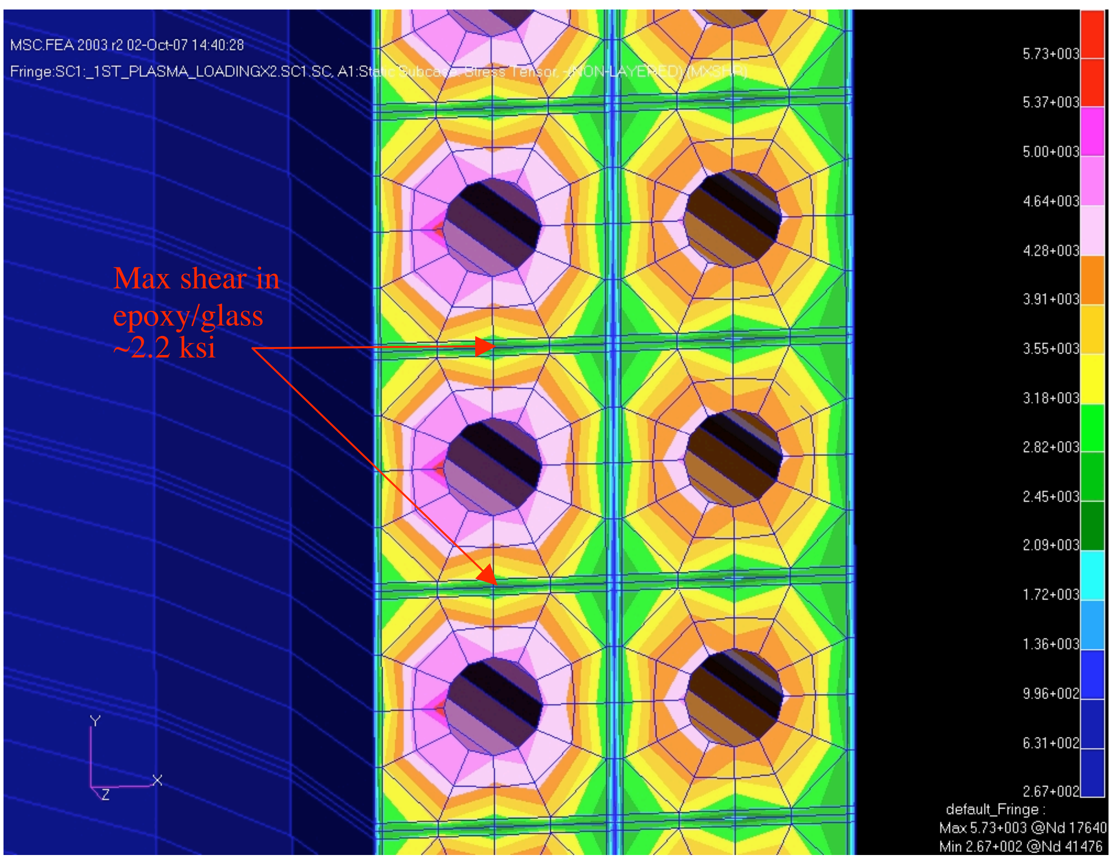


Figure 3. MaxShear contours for 47 kA Load -Peak Insulation shear of ~2.2 ksi

Results For 67 kA Loading:

The results of the 67 kA loading indicated a peak Tresca stress in the conductor of 21.9 ksi which is greater than the allowable stress for CDA107 Cu-10% C.W. (16 ksi @T=77 K). The Tresca stress contours for this loading are shown in figure 4 with the peak stress shown as the red contour again at the inner surface of the coolant hole of the inner-middle turns. The maximum shear stress in the epoxy/glass turn-to-turn insulation again occurs in the same region (see figure 5 below) and peaks at about 6.6 ksi which is exceeds the allowable for shear stress in thin epoxy/glass layers with no normal compression.

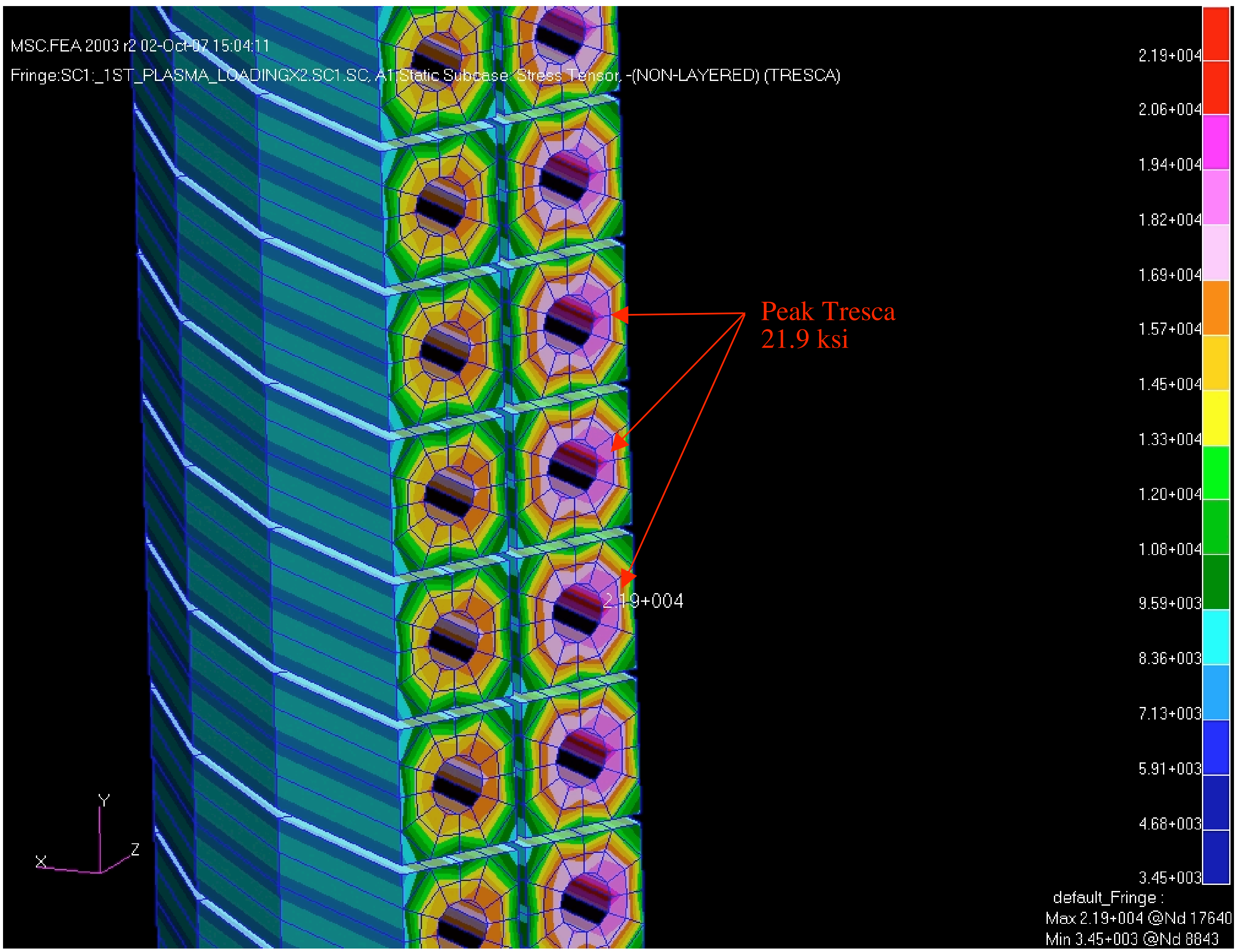


Figure 4. Tresca Stress Contours in Copper Conductor – 67 kA Loading – Peak 21.9 ksi

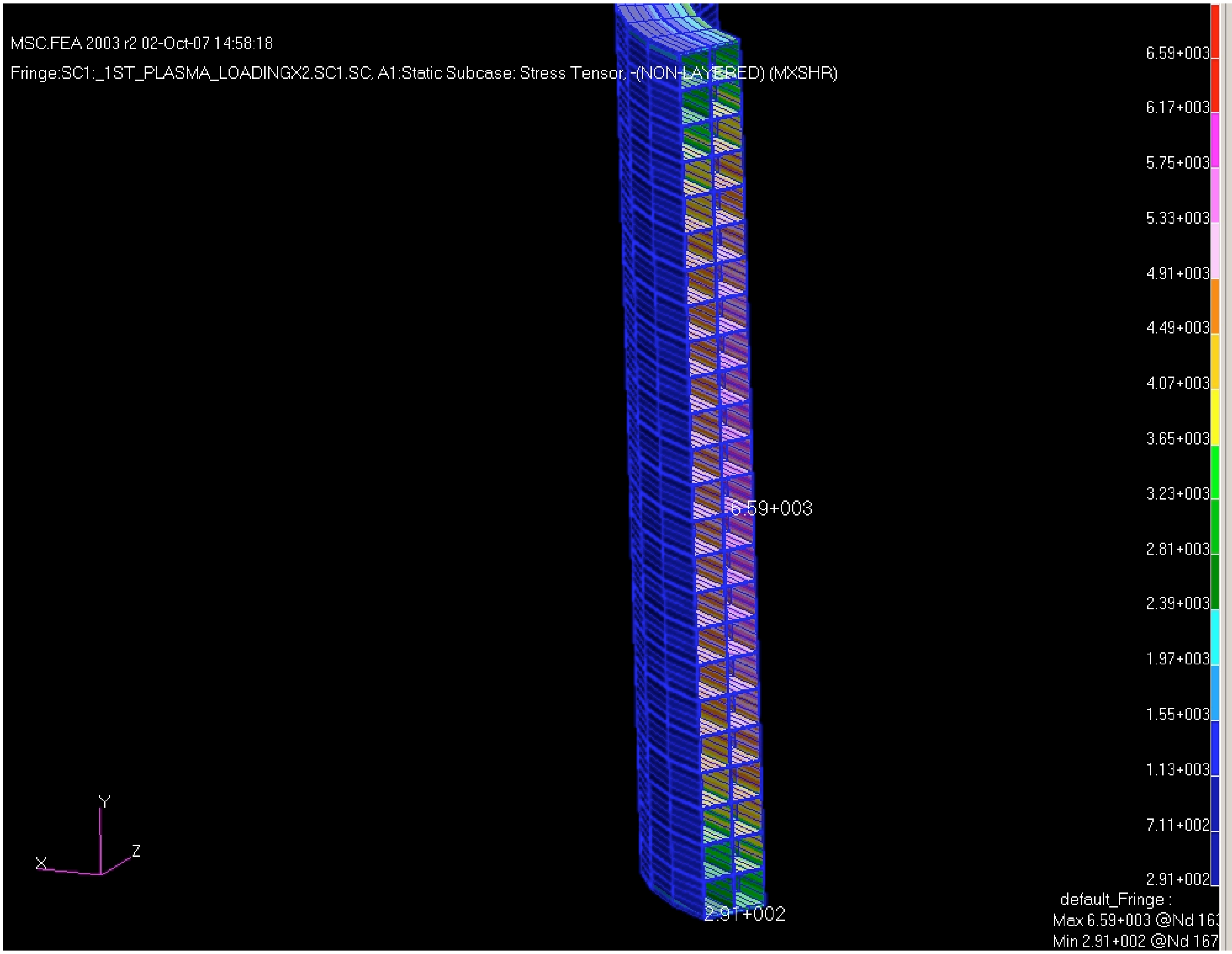


Figure 5. Max. Shear Stress Contours in Turn-to-turn epoxy/glass insulation -67 kA Loading

Thermal Analysis:

A transient thermal analysis of the PF1a coil was performed using FCOOL223-LN2, to determine the thermal response for 47 kA and 67 kA currents. The ESW was adjusted to limit the single pulse temperature rise to about 20 deg. K. Since we assume the starting coil temperature is a uniform 77 deg. K, and the saturation temperature for LN2 under 120 psi pressure is just slightly over 100 deg. K (see Appendix II), this appears to be a reasonable limit assuming we want to prevent 2-phase flow in the coil. The temperatures vs. time for the two current levels at the coolant exit are plotted in figures 6 and 7. It can be seen that the recovery time to cool down to 77 deg. K is about 180 sec, so ratcheting of the coil temperature for repetition rates greater than 3 minutes is not an issue (assuming the LN2 inlet temperature can be maintained at 77 deg. K and the sensible heat load from other sources is negligible). It appears that 0.10-0.11 seconds is the ESW limit for 67 kA if we are to stay under 100 deg. K. For 47 kA the ESW limit is about 0.22 seconds.

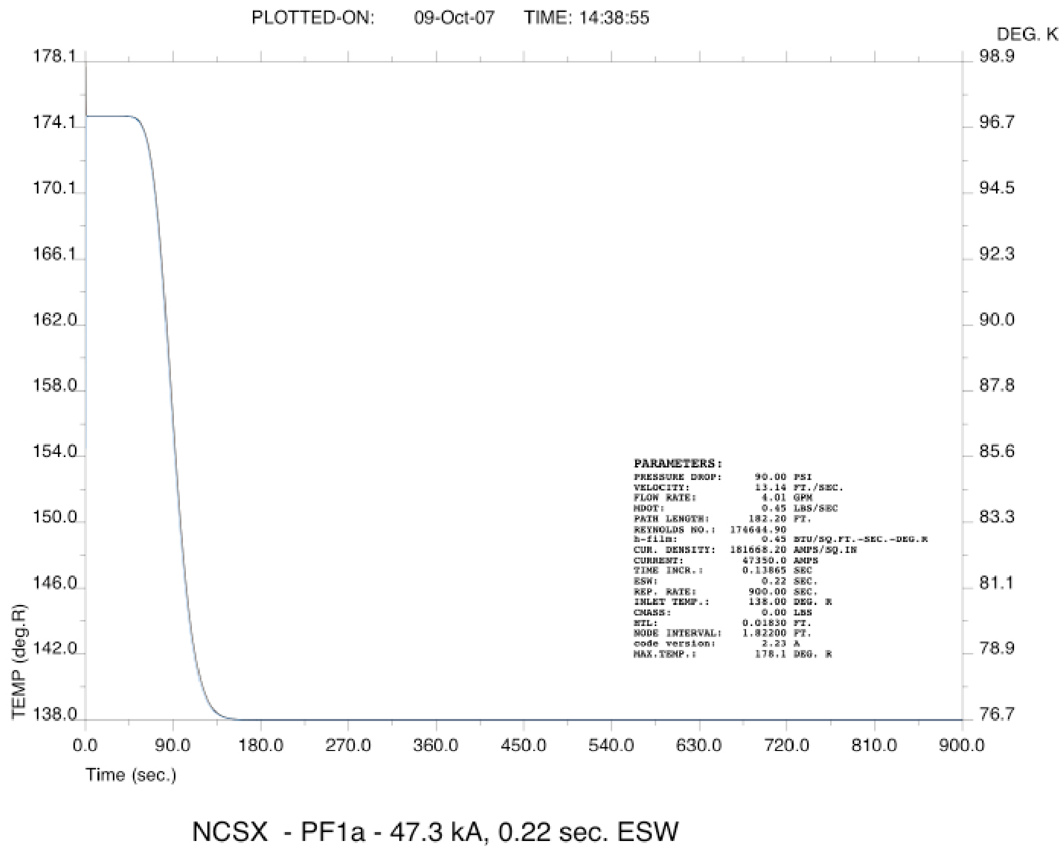


Figure 6. Thermal response to a 47 kA pulse with an ESW of 0.22 seconds

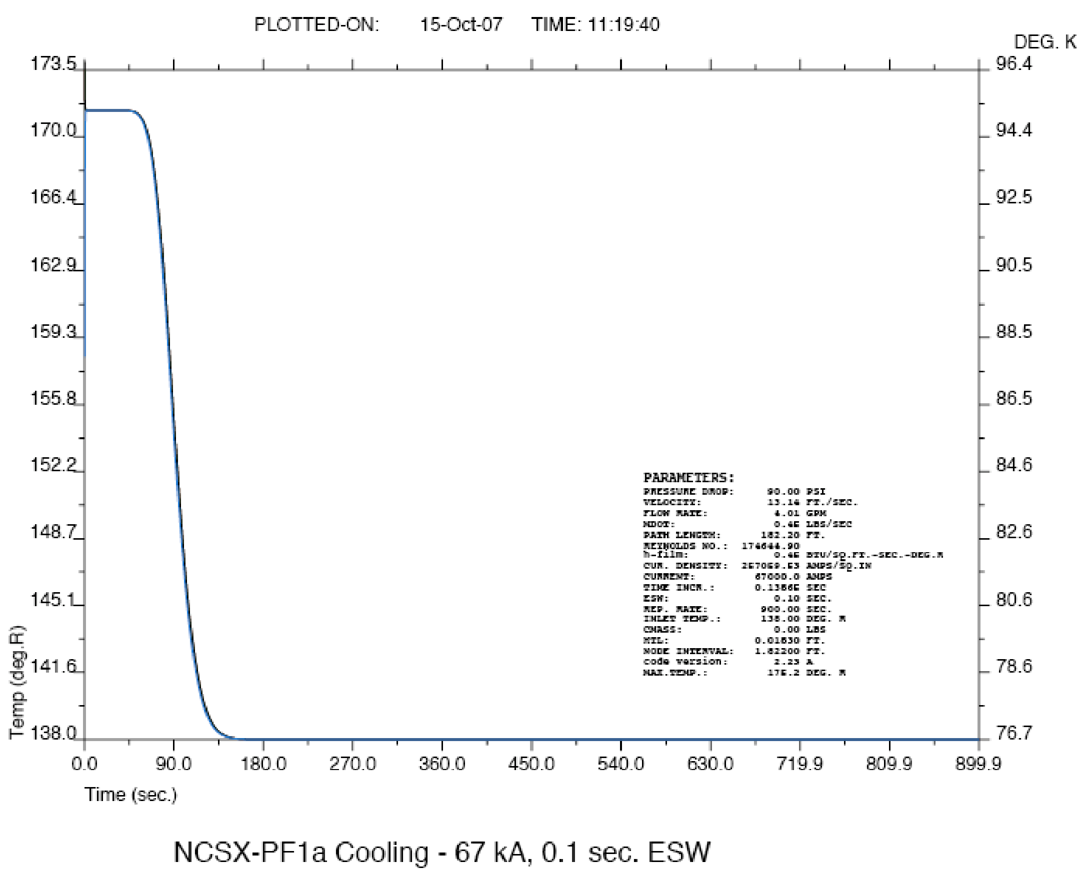


Figure 7. Thermal response to a 67 kA pulse with an ESW of 0.10 seconds

CONCLUSIONS:

Based on these results a peak 47 kA operation for PF1a coils appears feasible although the characteristics of the power supply and the L-R circuit response of the serially bused coils needs to be evaluated to determine whether the required volt-sec discharge is achievable. The practical limit on the ESW pulse length for 47 kA peak current is about 0.22 seconds. At this current level, loads and stresses on the lead-outs, lead stems, and interconnecting bus still need to be reviewed (and possibly re-designed) to insure adequate support.

Operation at 67 kA is problematic due to the copper stress levels, shear in the insulation, and the limited I^2t.

The coil heating is essentially adiabatic (ie. No significant heat removal during the pulse) with the limiting ESW scaling inversely with the square of the current.

APPENDIX I – DFORCE-2d Output Summaries

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320kA-ohmic:@t=0.206sec. PF1A CURRENT 23.2 kA

 NUMBER OF NON-CIRCULAR COILS:   12
 MOD COIL #   NO. OF SEGMENTS   CURRENT (A-T)  #SEG/GRP
    1            400              200530.0      400
    2            801              200530.0      400
    3           1202              182300.0      400
    4           1603              182300.0      400
    5           2004              200530.0      400
    6           2405              200530.0      400
    7           2806              200530.0      400
    8           3207              200530.0      400
    9           3608              182300.0      400
   10           4009              182300.0      400
   11           4410              200530.0      400
   12           4811              200530.0      400
 CURRENTS IN COIL GROUPS

     1  1   23348.0     2  2  -15155.0     3  3    5050.0     4  4    4730.0     5  5 -320000.0 BZE =     0.0000
  COAXIAL COIL FORCES AND STRESSES - LAMINATED BEAM APPROXIMATION - SHEAR FACTOR = .400
   0
  COIL NUMBER      NUMBER OF TURNS  SUPPORT WIDTH    SPAN  LENGTH      CU WIDTH   CU HEIGHT   # OF SUPPORTS   INDUCTANCE        STORED ENERGY
   1                   48.00000        0.04000        0.01781        0.04000       0.50800     20.0         0.0032034        0.873E+06
   2                   80.00000        0.05000        0.13221        0.19100       0.25300     18.0         0.0202973        0.233E+07
   3                   24.00000        0.06000        0.71597        0.09800       0.16300     18.0         0.0155657        0.198E+06
   4                   14.00000        0.06000        0.88981        0.05200       0.18600     18.0         0.0077726        0.869E+05
   5                    1.00000        0.05000        0.19435        0.30000       0.30000     36.0         0.0000106        0.545E+06

 Coil        R1             R2             Z1             Z2      Amp-Turns    Units       Z-center
  1          0.164          0.204          0.146          0.654    1120704.000    3          0.400
  2          0.427          0.618          1.456          1.709   -1212400.000    3          1.583
  3          2.174          2.272          1.448          1.612     121200.000    3          1.530
  4          2.695          2.747          0.861          1.047      66220.000    3          0.954
  5          1.250          1.550         -0.150          0.150    -320000.000    3          0.000
  6          0.164          0.204         -0.654         -0.146    1120704.000    3         -0.400
  7          0.427          0.618         -1.709         -1.456   -1212400.000    3         -1.583
  8          2.174          2.272         -1.612         -1.448     121200.000    3         -1.530
  9          2.695          2.747         -1.047         -0.861      66220.000    3         -0.954
 Note: un = 1 units are:  inch-tesla-weber
       un = 2 units are:  inch-gauss-maxwell
       un = 3 units are: meter-tesla-weber
0
  COIL     A       Z       NI           FZ           FR/L         FZ/L         S-HOOP       COMBINED
           M       M       A            N            N/M          N/M          N/M SQ       STRESS
          IN      IN       A            LB           LB/IN        LB/IN        PSI          PSI          DFL-R          DFL-Z      HOOP STRAIN


    1   0.184   0.400    1.121E+06   -2.856E+04    8.721E+05   -2.470E+04    9.946E+06
        7.244  15.748    1.121E+06   -6.424E+03    4.982E+03   -1.411E+02    1.443E+03    1.443E+03    6.534E-04   -1.317E-11    9.020E-05

    2   0.522   1.583   -1.212E+06    4.470E+04    8.603E+05    1.363E+04    1.670E+07
       20.551  62.323   -1.212E+06    1.005E+04    4.915E+03    7.786E+01    2.423E+03    2.426E+03    3.113E-03    3.700E-08    1.515E-04

    3   2.223   1.530    1.212E+05    8.724E+03    5.274E+03    6.246E+02    1.453E+06
       87.520  60.236    1.212E+05    1.962E+03    3.013E+01    3.568E+00    2.109E+02    2.288E+02    1.154E-03    1.036E-05    1.318E-05

    4   2.721   0.954    6.622E+04    4.198E+04    4.302E+02    2.455E+03    2.487E+05
      107.126  37.559    6.622E+04    9.441E+03    2.458E+00    1.403E+01    3.609E+01    1.978E+02    2.417E-04    1.245E-04    2.256E-06

    5   1.400   0.000   -3.200E+05    2.446E+05    2.627E+03    2.781E+04    4.072E+04
       55.118   0.000   -3.200E+05    5.501E+04    1.501E+01    1.589E+02    5.909E+00    8.732E+00    2.035E-05    5.464E-08    3.693E-07

    6   0.184  -0.400    1.121E+06    3.622E+04    8.674E+05    3.133E+04    9.892E+06
        7.244 -15.748    1.121E+06    8.146E+03    4.955E+03    1.790E+02    1.435E+03    1.436E+03    6.499E-04    1.671E-11    8.971E-05

    7   0.522  -1.583   -1.212E+06    2.315E+04    8.512E+05    7.058E+03    1.652E+07
       20.551 -62.323   -1.212E+06    5.206E+03    4.863E+03    4.032E+01    2.398E+03    2.399E+03    3.080E-03    1.916E-08    1.499E-04

    8   2.223  -1.530    1.212E+05    1.551E+04    8.020E+03    1.111E+03    2.210E+06
       87.520 -60.236    1.212E+05    3.489E+03    4.582E+01    6.346E+00    3.207E+02    3.525E+02    1.754E-03    1.842E-05    2.004E-05

    9   2.721  -0.954    6.622E+04   -1.403E+04    1.920E+03   -8.208E+02    1.110E+06
      107.126 -37.559    6.622E+04   -3.156E+03    1.097E+01   -4.689E+00    1.611E+02    2.152E+02    1.079E-03   -4.162E-05    1.007E-05

1
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320kA-ohmic:@t=0.206sec. -DOUBLED PF1A CURRENT TO 46.7 kA

NUMBER OF NON-CIRCULAR COILS: 12

MOD COIL #	NO. OF SEGMENTS	CURRENT (A-T)	#SEG/GRP
1	400	200530.0	400
2	801	200530.0	400
3	1202	182300.0	400
4	1603	182300.0	400
5	2004	200530.0	400
6	2405	200530.0	400
7	2806	200530.0	400
8	3207	200530.0	400
9	3608	182300.0	400
10	4009	182300.0	400
11	4410	200530.0	400
12	4811	200530.0	400

CURRENTS IN COIL GROUPS

1 1 46696.0 2 2 -15155.0 3 3 5050.0 4 4 4730.0 5 5 -320000.0 BZE = 0.0000

COAXIAL COIL FORCES AND STRESSES - LAMINATED BEAM APPROXIMATION - SHEAR FACTOR = .400

0

COIL NUMBER	NUMBER OF TURNS	SUPPORT WIDTH	SPAN LENGTH	CU WIDTH	CU HEIGHT	# OF SUPPORTS	INDUCTANCE	STORED ENERGY
1	48.00000	0.04000	0.01781	0.04000	0.50800	20.0	0.0032034	0.349E+07
2	80.00000	0.05000	0.13221	0.19100	0.25300	18.0	0.0202973	0.233E+07
3	24.00000	0.06000	0.71597	0.09800	0.16300	18.0	0.0155657	0.198E+06
4	14.00000	0.06000	0.88981	0.05200	0.18600	18.0	0.0077726	0.869E+05
5	1.00000	0.05000	0.19435	0.30000	0.30000	36.0	0.0000106	0.545E+06

Coil	R1	R2	Z1	Z2	Amp-Turns	Units	Z-center
1	0.164	0.204	0.146	0.654	2241408.000	3	0.400
2	0.427	0.618	1.456	1.709	-1212400.000	3	1.583
3	2.174	2.272	1.448	1.612	121200.000	3	1.530
4	2.695	2.747	0.861	1.047	66220.000	3	0.954
5	1.250	1.550	-0.150	0.150	-320000.000	3	0.000
6	0.164	0.204	-0.654	-0.146	2241408.000	3	-0.400
7	0.427	0.618	-1.709	-1.456	-1212400.000	3	-1.583
8	2.174	2.272	-1.612	-1.448	121200.000	3	-1.530
9	2.695	2.747	-1.047	-0.861	66220.000	3	-0.954

Note: un = 1 units are: inch-tesla-weber
un = 2 units are: inch-gauss-maxwell
un = 3 units are: meter-tesla-weber

0

COIL	A	Z	NI	FZ	FR/L	FZ/L	S-HOOP	COMBINED STRESS	DFL-R	DFL-Z	HOOP STRAIN
	M	M	A	N	N/M	N/M	N/M SQ				
	IN	IN	A	LB	LB/IN	LB/IN	PSI	PSI			
1	0.184	0.400	2.241E+06	-1.165E+05	3.910E+06	-1.007E+05	4.459E+07				
	7.244	15.748	2.241E+06	-2.619E+04	2.234E+04	-5.755E+02	6.471E+03	6.471E+03	2.930E-03	-5.372E-11	4.044E-04
2	0.522	1.583	-1.212E+06	7.501E+04	8.468E+05	2.287E+04	1.644E+07				
	20.551	62.323	-1.212E+06	1.687E+04	4.838E+03	1.307E+02	2.385E+03	2.390E+03	3.064E-03	6.209E-08	1.491E-04
3	2.223	1.530	1.212E+05	5.975E+03	5.254E+03	4.278E+02	1.448E+06				
	87.520	60.236	1.212E+05	1.344E+03	3.001E+01	2.444E+00	2.101E+02	2.223E+02	1.149E-03	7.093E-06	1.313E-05
4	2.721	0.954	6.622E+04	4.104E+04	3.862E+02	2.400E+03	2.233E+05				
	107.126	37.559	6.622E+04	9.230E+03	2.207E+00	1.371E+01	3.241E+01	1.905E+02	2.170E-04	1.217E-04	2.026E-06
5	1.400	0.000	-3.200E+05	2.446E+05	4.534E+03	2.781E+04	7.027E+04				
	55.118	0.000	-3.200E+05	5.501E+04	2.590E+01	1.589E+02	1.020E+01	1.302E+01	3.513E-05	5.464E-08	6.373E-07
6	0.184	-0.400	2.241E+06	1.318E+05	3.901E+06	1.140E+05	4.448E+07				
	7.244	-15.748	2.241E+06	2.964E+04	2.228E+04	6.512E+02	6.455E+03	6.456E+03	2.923E-03	6.078E-11	4.034E-04
7	0.522	-1.583	-1.212E+06	-7.163E+03	8.377E+05	-2.184E+03	1.626E+07				
	20.551	-62.323	-1.212E+06	-1.611E+03	4.786E+03	-1.248E+01	2.360E+03	2.360E+03	3.031E-03	-5.929E-09	1.475E-04
8	2.223	-1.530	1.212E+05	1.826E+04	8.000E+03	1.308E+03	2.204E+06				
	87.520	-60.236	1.212E+05	4.108E+03	4.570E+01	7.470E+00	3.199E+02	3.573E+02	1.750E-03	2.168E-05	1.999E-05
9	2.721	-0.954	6.622E+04	-1.309E+04	1.876E+03	-7.659E+02	1.085E+06				
	107.126	-37.559	6.622E+04	-2.945E+03	1.072E+01	-4.375E+00	1.574E+02	2.079E+02	1.054E-03	-3.884E-05	9.838E-06

1

320kA-ohmic:@t=0.206sec.

NUMBER OF NON-CIRCULAR COILS: 12

MOD COIL #	NO. OF SEGMENTS	CURRENT (A-T)	#SEG/GRP
1	400	200530.0	400
2	801	200530.0	400
3	1202	182300.0	400
4	1603	182300.0	400
5	2004	200530.0	400
6	2405	200530.0	400
7	2806	200530.0	400
8	3207	200530.0	400
9	3608	182300.0	400
10	4009	182300.0	400
11	4410	200530.0	400
12	4811	200530.0	400

CURRENTS IN COIL GROUPS

1 1 67000.0 2 2 -7795.0 3 3 2349.0 4 4 7300.0 5 5 -350700.0 BZE = 0.0000

COAXIAL COIL FORCES AND STRESSES - LAMINATED BEAM APPROXIMATION - SHEAR FACTOR = .400

0

COIL NUMBER	NUMBER OF TURNS	SUPPORT WIDTH	SPAN LENGTH	CU WIDTH	CU HEIGHT	# OF SUPPORTS	INDUCTANCE	STORED ENERGY
1	48.00000	0.04000	0.01781	0.04000	0.50800	20.0	0.0032034	0.719E+07
2	80.00000	0.05000	0.13221	0.19100	0.25300	18.0	0.0202973	0.617E+06
3	24.00000	0.06000	0.71597	0.09800	0.16300	18.0	0.0155657	0.429E+05
4	14.00000	0.06000	0.88981	0.05200	0.18600	18.0	0.0077726	0.207E+06
5	1.00000	0.05000	0.19435	0.30000	0.30000	36.0	0.0000106	0.654E+06

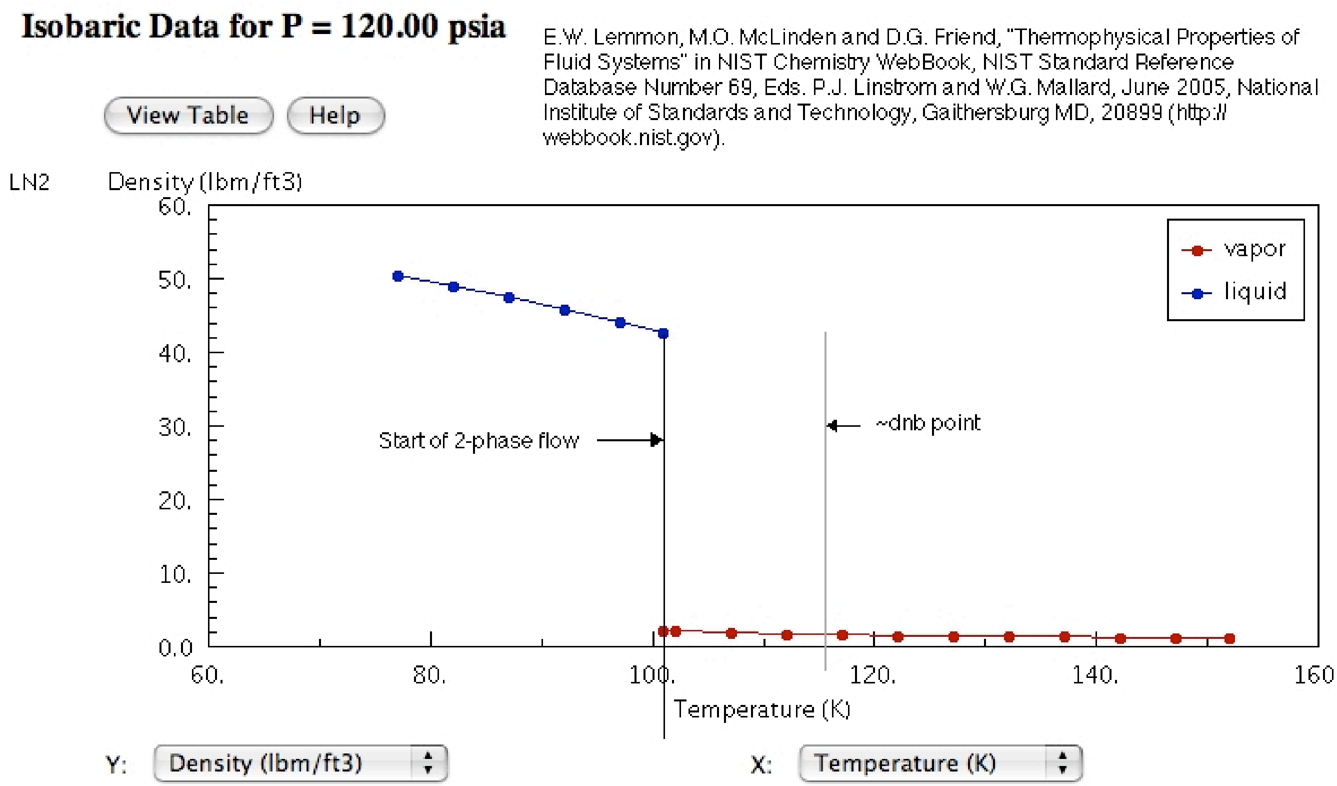
Coil	R1	R2	Z1	Z2	Amp-Turns	Units	Z-center
1	0.164	0.204	0.146	0.654	3216000.000	3	0.400
2	0.427	0.618	1.456	1.709	-623600.000	3	1.583
3	2.174	2.272	1.448	1.612	56376.000	3	1.530
4	2.695	2.747	0.861	1.047	102200.000	3	0.954
5	1.250	1.550	-0.150	0.150	-350700.000	3	0.000
6	0.164	0.204	-0.654	-0.146	3216000.000	3	-0.400
7	0.427	0.618	-1.709	-1.456	-623600.000	3	-1.583
8	2.174	2.272	-1.612	-1.448	56376.000	3	-1.530
9	2.695	2.747	-1.047	-0.861	102200.000	3	-0.954

Note: un = 1 units are: inch-tesla-weber
un = 2 units are: inch-gauss-maxwell
un = 3 units are: meter-tesla-weber

0

COIL	A M IN	Z M IN	NI A A	FZ N LB	FR/L N/M LB/IN	FZ/L N/M LB/IN	S-HOOP N/M SQ PSI	COMBINED STRESS PSI	DFL-R	DFL-Z	HOOP STRAIN
1	0.184	0.400	3.216E+06	-2.094E+05	8.443E+06	-1.811E+05	9.628E+07				
	7.244	15.748	3.216E+06	-4.710E+04	4.823E+04	-1.035E+03	1.397E+04	1.397E+04	6.326E-03	-9.660E-11	8.732E-04
2	0.522	1.583	-6.236E+05	5.183E+04	2.142E+05	1.580E+04	4.158E+06				
	20.551	62.323	-6.236E+05	1.166E+04	1.224E+03	9.028E+01	6.034E+02	6.070E+02	7.751E-04	4.290E-08	3.771E-05
3	2.223	1.530	5.638E+04	-3.539E+03	1.942E+03	-2.534E+02	5.350E+05				
	87.520	60.236	5.638E+04	-7.960E+02	1.109E+01	-1.447E+00	7.764E+01	8.489E+01	4.247E-04	-4.201E-06	4.852E-06
4	2.721	0.954	1.022E+05	4.531E+04	1.619E+03	2.650E+03	9.362E+05				
	107.126	37.559	1.022E+05	1.019E+04	9.250E+00	1.514E+01	1.358E+02	3.104E+02	9.096E-04	1.344E-04	8.491E-06
5	1.400	0.000	-3.507E+05	2.681E+05	7.626E+03	3.047E+04	1.182E+05				
	55.118	0.000	-3.507E+05	6.029E+04	4.357E+01	1.741E+02	1.715E+01	2.025E+01	5.909E-05	5.989E-08	1.072E-06
6	0.184	-0.400	3.216E+06	2.314E+05	8.429E+06	2.001E+05	9.613E+07				
	7.244	-15.748	3.216E+06	5.204E+04	4.816E+04	1.143E+03	1.395E+04	1.395E+04	6.316E-03	1.067E-10	8.718E-04
7	0.522	-1.583	-6.236E+05	-1.693E+04	2.095E+05	-5.162E+03	4.068E+06				
	20.551	-62.323	-6.236E+05	-3.808E+03	1.197E+03	-2.949E+01	5.902E+02	5.914E+02	7.581E-04	-1.401E-08	3.689E-05
8	2.223	-1.530	5.638E+04	1.481E+04	3.219E+03	1.061E+03	8.870E+05				
	87.520	-60.236	5.638E+04	3.332E+03	1.839E+01	6.059E+00	1.287E+02	1.591E+02	7.041E-04	1.758E-05	8.045E-06
9	2.721	-0.954	1.022E+05	-2.185E+03	3.918E+03	-1.278E+02	2.266E+06				
	107.126	-37.559	1.022E+05	-4.914E+02	2.239E+01	-7.300E-01	3.288E+02	3.372E+02	2.201E-03	-6.480E-06	2.055E-05

APPENDIX II – NIST WEBBOOK DATA FOR LN2



LN2 DATA FOR ISOBARIC 120 PSI – DENSITY VS. TEMPERATURE