

Updated Thermal Analysis of Modular Coil

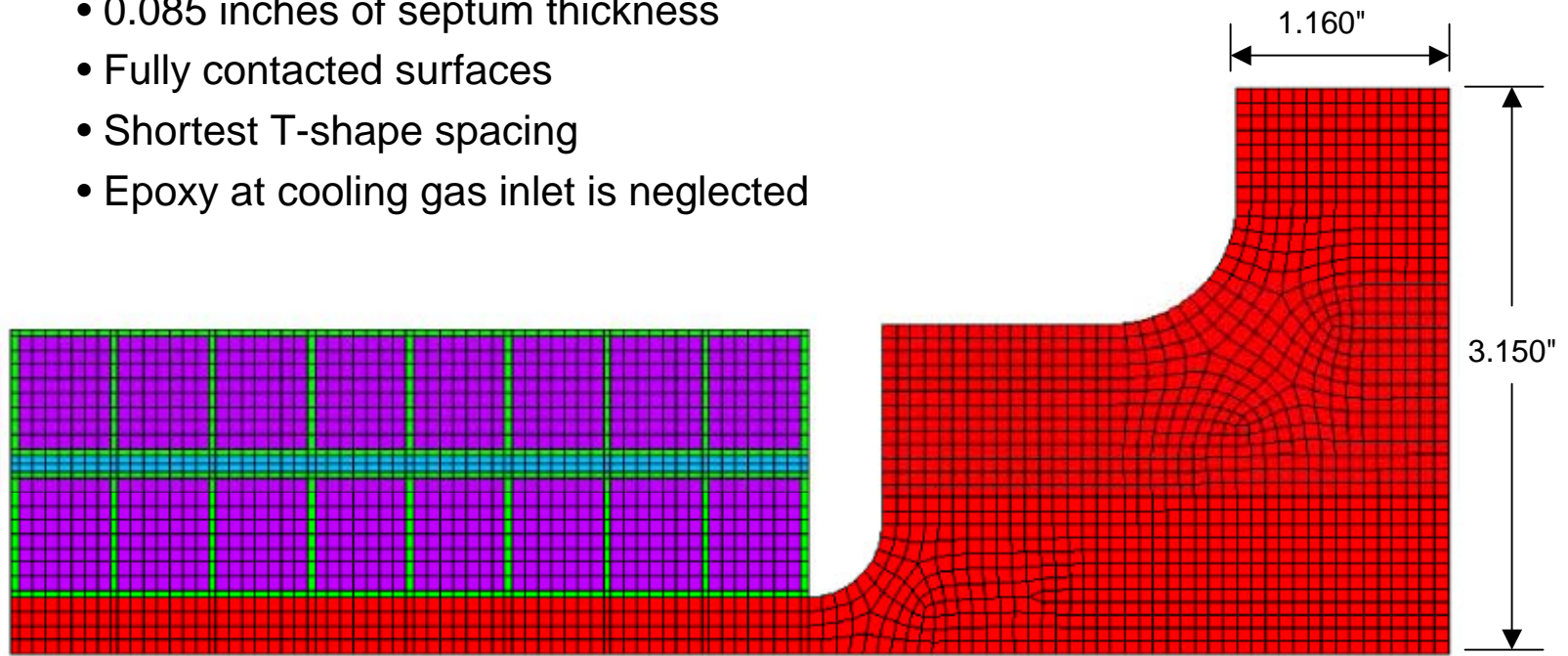
H. M. Fan

PPPL

August 15, 2001

Finite Element Model

- 2-D model
- Half symmetry is used
- T-shape is cast into the shell
- Cable contains 75% of copper and 25% of epoxy
- 0.040 inches of insulation thickness
- 0.085 inches of septum thickness
- Fully contacted surfaces
- Shortest T-shape spacing
- Epoxy at cooling gas inlet is neglected



Cryogenics Material Properties

- **Specific Heat (J/kg-K)**

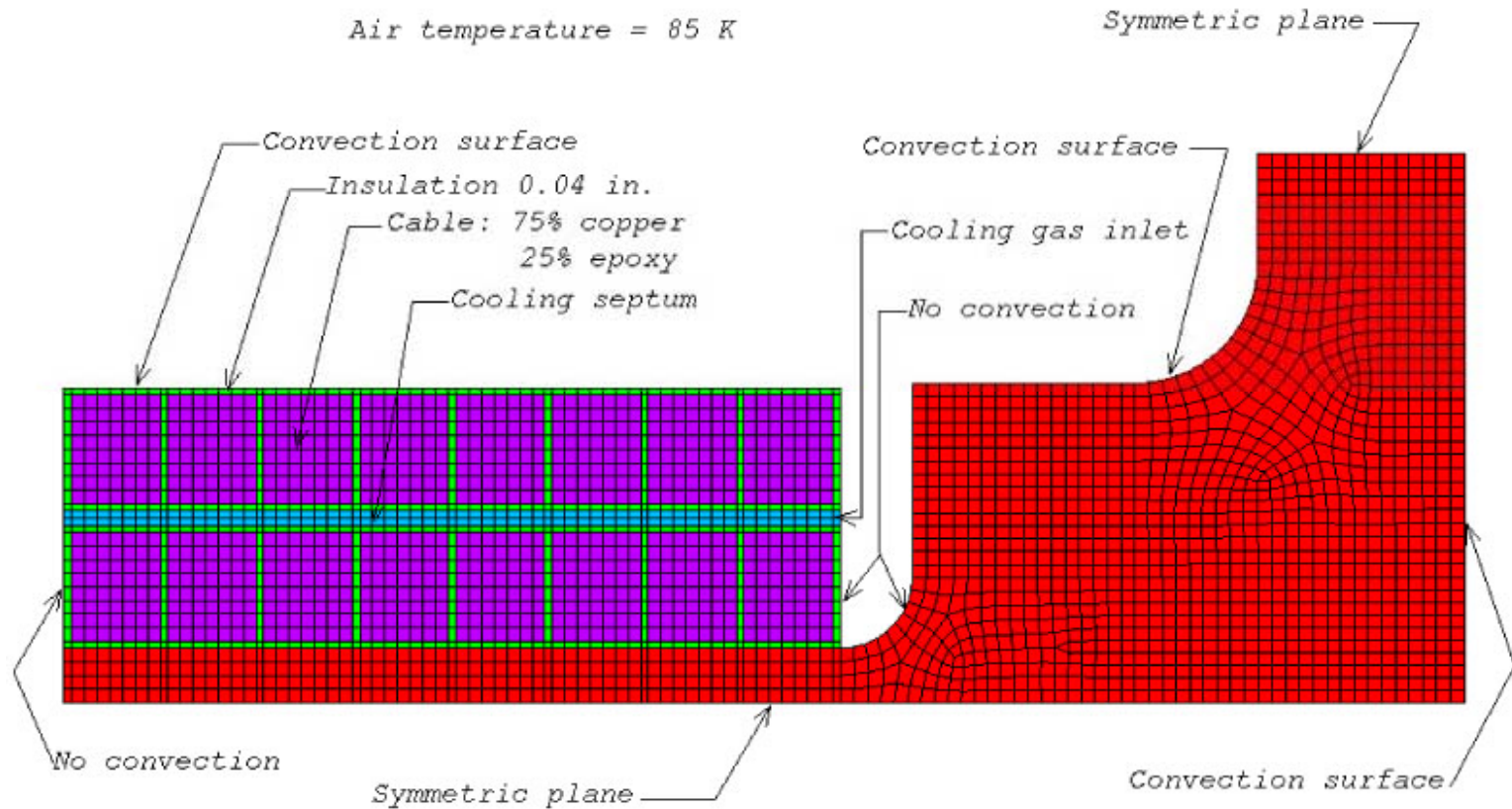
	80K	100K	150K	200K
Cable	171.4	212.3	270.1	300.7
Septum	205.1	255.3	324.1	359.0
Insulation 348.9	413.7	537.0	626.8	
Shell & T-beam	215.3	275.5	362.1	416.4

- **Thermal Conductivity (W/m-K)**

	80K	100K	150K	200K
Cable	397.0	346.2	313.7	305.2
Septum	529.3	461.5	418.1	407.0
Insulation 0.128	0.142	0.163	0.175	
Shell & T-beam	8.114	9.224	11.17	12.63

Note: Cable contains 75% of copper and 25% of epoxy

Boundary Conditions



Coil Currents and Ohmic Heating

- Current profile from web address:
http://www.pppl.gov/me/NCSX_Engineering/Technical_Data/MOD00/Inputs_1.7T.htm

Turn Current Profile of Modular Coil (A)

Coil	Time (s)								
	-1.8	-1.5	0	0.1	0.158083	0.258083	0.458083	1.658083	1.958083
M1	0	0	19832	19832	16897	17907	17907	0	0
M2	0	0	18553	18553	16574	17649	17649	0	0
M3	0	0	19189	19189	17158	18352	18352	0	0
M4	0	0	20287	20287	16626	17755	17755	0	0

Power of ohmic Heating (W/m³)

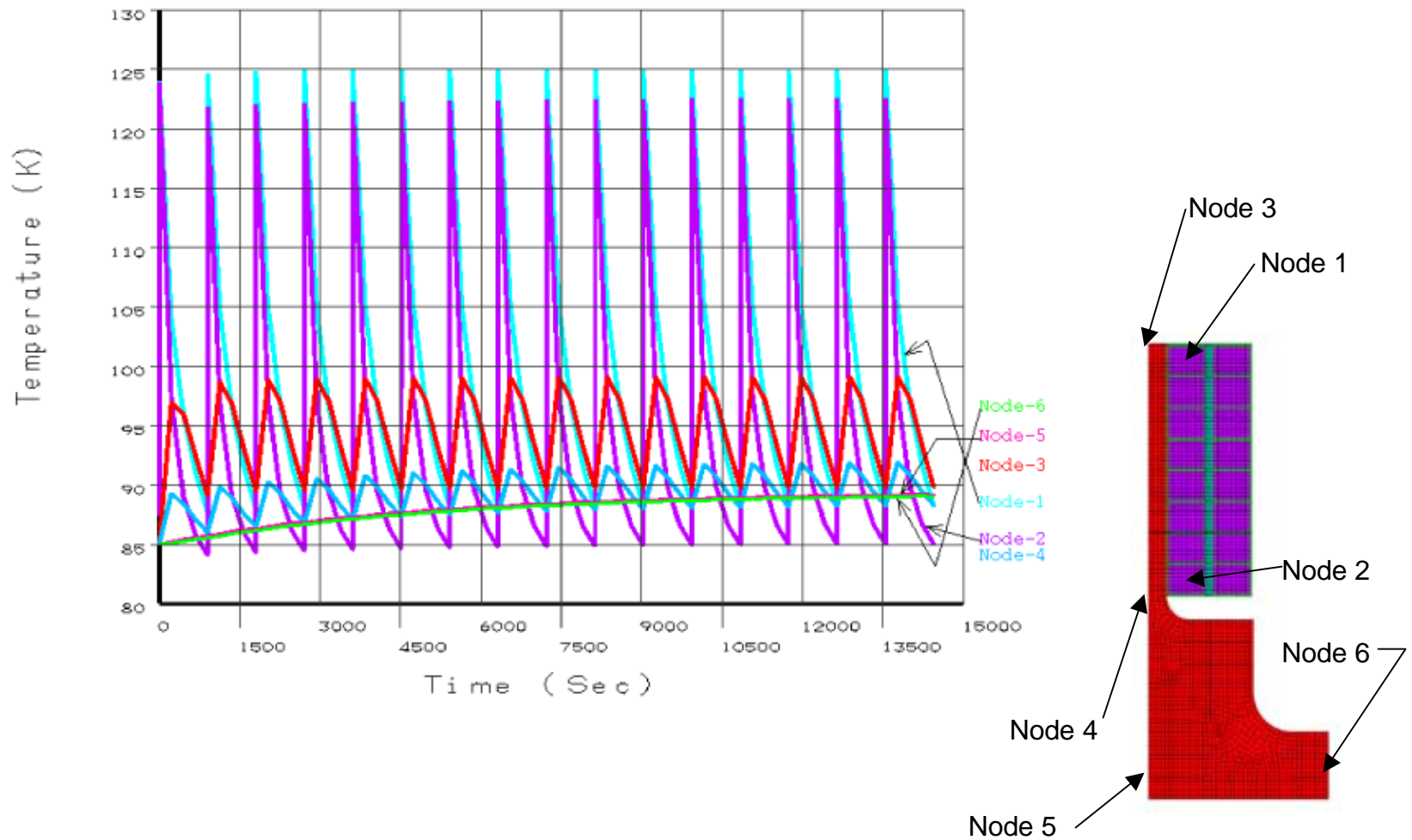
Time (s)	-1.8	-1.5	0	0.1	0.158083	0.258083	0.458083	1.658083	1.958083
μ (ohm-m)	2.36E-09	2.36E-09	3.52E-09	3.78E-09	3.91E-09	4.11E-09	4.55E-09	5.52E-09	5.52E-09
M1	0.00E+00	0.00E+00	3.41E+07	3.66E+07	2.75E+07	3.24E+07	3.59E+07	0.00E+00	0.00E+00
M2	0.00E+00	0.00E+00	2.98E+07	3.20E+07	2.64E+07	3.15E+07	3.49E+07	0.00E+00	0.00E+00
M3	0.00E+00	0.00E+00	3.19E+07	3.42E+07	2.83E+07	3.41E+07	3.77E+07	0.00E+00	0.00E+00
M4	0.00E+00	0.00E+00	3.56E+07	3.83E+07	2.66E+07	3.19E+07	3.53E+07	0.00E+00	0.00E+00

- Heat of ohmic heating in one pulse is 6.31 J/m³ for M4 coil

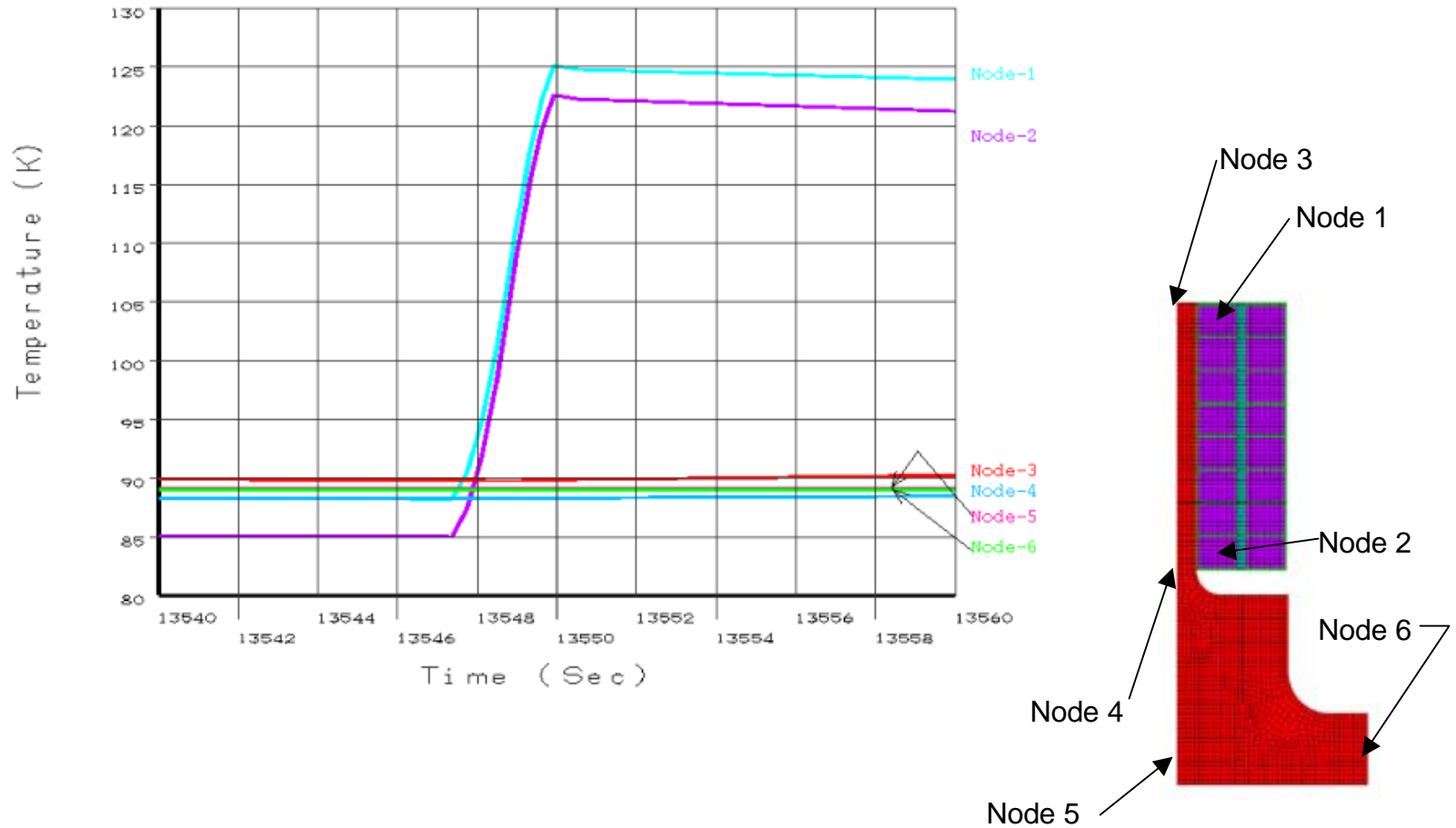
Transient Thermal Analysis

- Temperature constraint at cooling gas inlet is 80 K.
- The starting temperatures for both the coil and coil structure are 85 K.
- Ambient air temperature is fixed at 85 K.
- The film coefficient is assumed to be $4.0 \text{ W/m}^2\text{-K}$.
- The thermal properties for specific heat and thermal conductivity are temperature-dependent.
- Values of cable resistivity depend on the M4 coil temperatures which are calculated from adiabatic condition as shown in web address:
http://www.pppl.gov/me/NCSX_Engineering/Technical_Data/MOD00/Calculations_1.7T.htm
- Power of ohmic heating calculated for the M4 coil from -1.5 seconds to 1.658083 seconds is used for thermal load input.
- Thermal load varies linearly between two time steps.
- Cooling period between pulses is 15 minutes.
- Total running period consists of 16 pulse cycles with a total running time of 14451 seconds (or 4 hr. and 51 sec.)

Temperature vs. Time on Selected Nodes



Temperature vs. Time During the 16th Heating Cycle



Temperature Distribution in The First Heating and Cooling Cycles

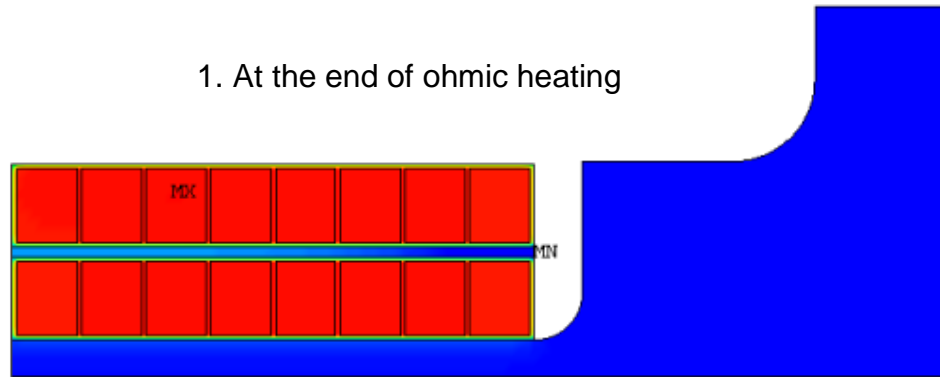
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ANSYS 5.6.2
JUL 24 2001
10:15:35
NODAL SOLUTION
STEP=6
SUB =3
TIME=3.158
TEMP (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =80
SMX =124.113

```

80
84.901
89.803
94.704
99.606
104.507
109.409
114.31
119.212
124.113

1. At the end of ohmic heating



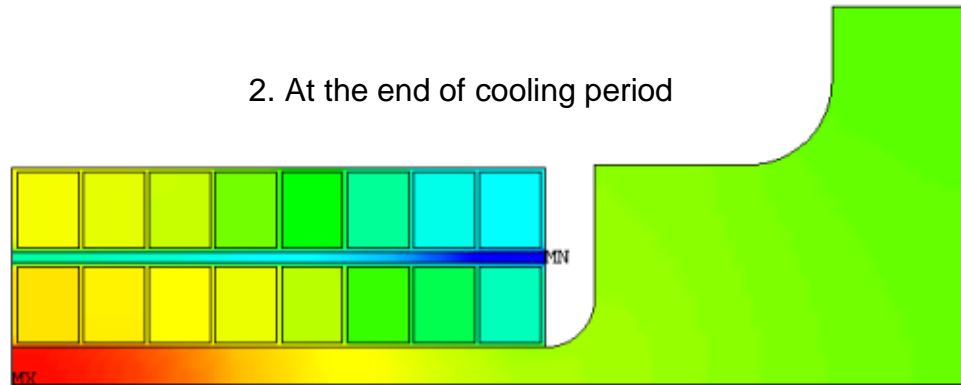
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ANSYS 5.6.2
JUL 24 2001
10:17:28
NODAL SOLUTION
STEP=7
SUB =4
TIME=903.158
TEMP (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =80
SMX =89.118

```

80
81.013
82.026
83.039
84.053
85.066
86.079
87.092
88.105
89.118

2. At the end of cooling period

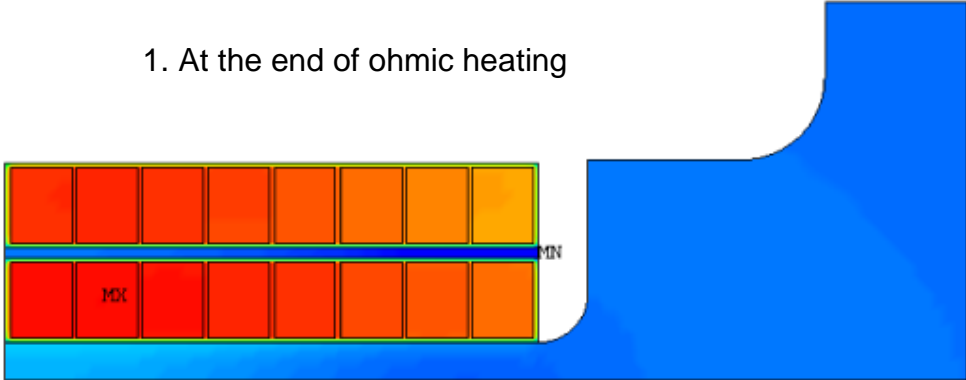


Temperature Distribution in The 8th Heating and Cooling Cycles

ANSYS 5.6.2
 JUL 24 2001
 09:51:40
 NODAL SOLUTION
 STEP=55
 SUB =3
 TIME=6325
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =80
 SMX =124.849

80
84.983
89.966
94.95
99.933
104.916
109.899
114.883
119.866
124.849

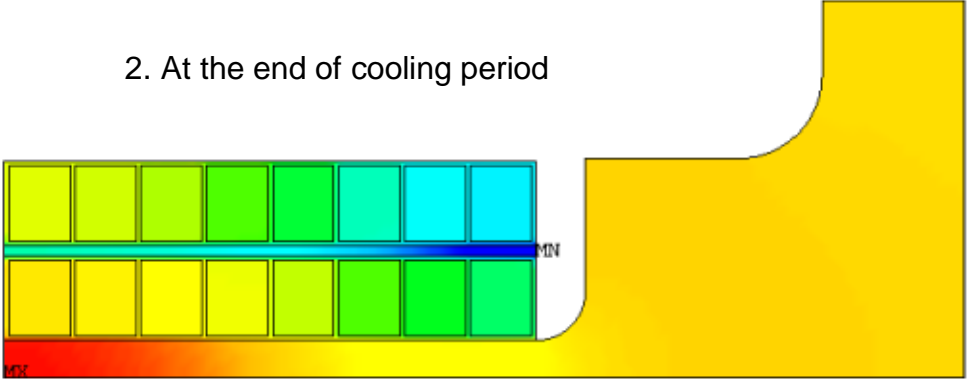
1. At the end of ohmic heating



ANSYS 5.6.2
 JUL 24 2001
 09:53:56
 NODAL SOLUTION
 STEP=56
 SUB =4
 TIME=7225
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =80
 SMX =89.715

80
81.079
82.159
83.238
84.318
85.397
86.476
87.556
88.635
89.715

2. At the end of cooling period

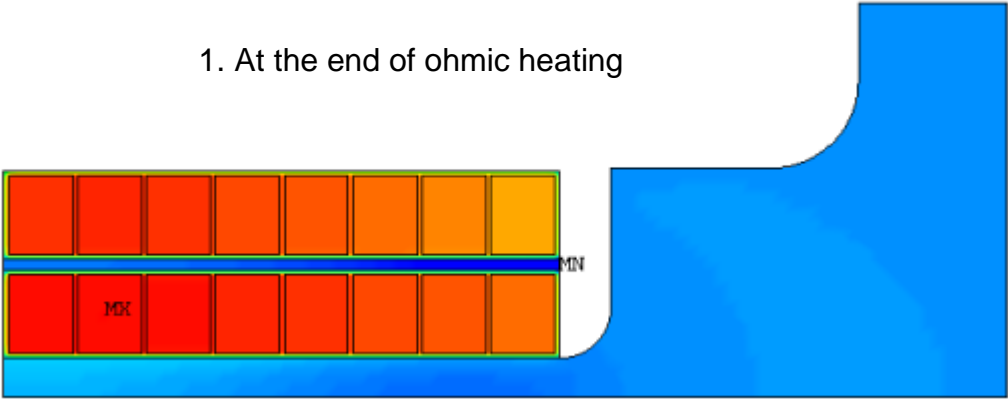


Temperature Distribution in The 16th Heating and Cooling Cycles

ANSYS 5.6.2
 JUL 24 2001
 09:47:09
 NODAL SOLUTION
 STEP=111
 SUB =3
 TIME=13551
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =80
 SMX =124.91

80
84.99
89.98
94.97
99.96
104.95
109.94
114.93
119.92
124.91

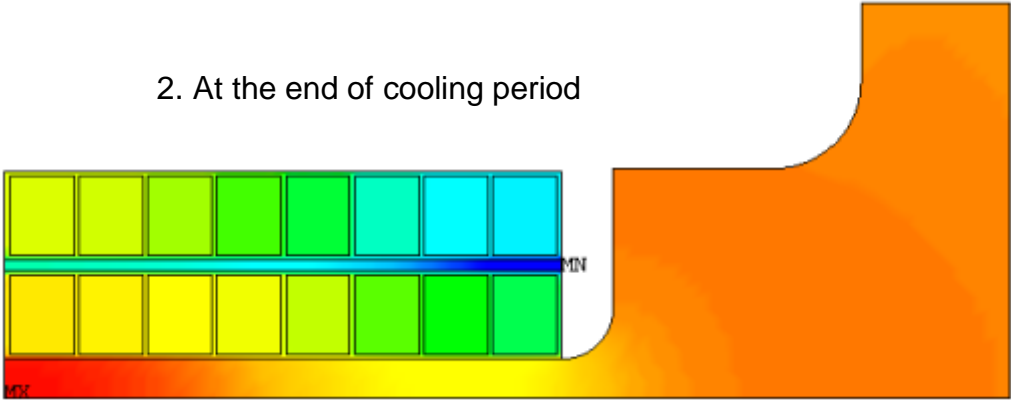
1. At the end of ohmic heating



ANSYS 5.6.2
 JUL 24 2001
 09:45:06
 NODAL SOLUTION
 STEP=112
 SUB =4
 TIME=14451
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =80
 SMX =89.793

80
81.088
82.176
83.264
84.352
85.44
86.528
87.616
88.705
89.793

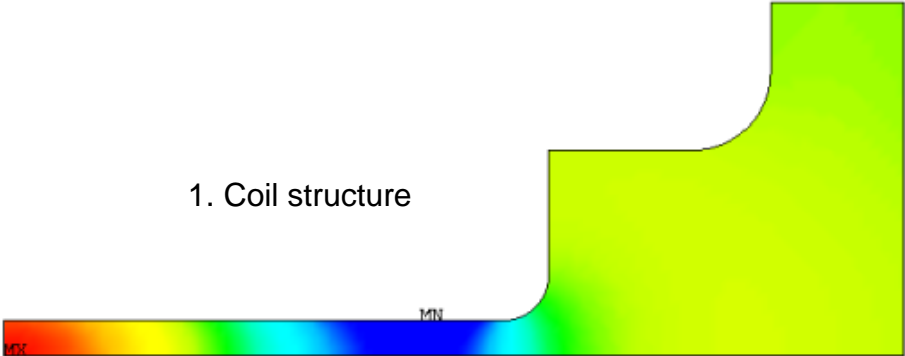
2. At the end of cooling period



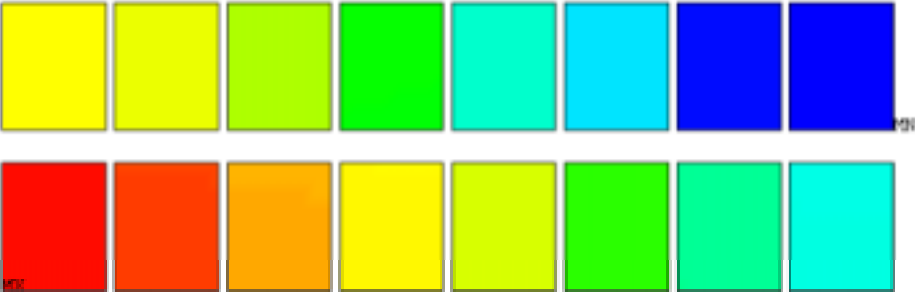
Temperature Distribution in Coil Structure and Coil at The End of 16th Cooling Cycles

NODAL SOLUTION
 STEP=112
 SUB =4
 TIME=14451
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =87.631
 SMX =89.793

87.631
87.871
88.111
88.352
88.592
88.832
89.072
89.312
89.552
89.793



2. Coil turns



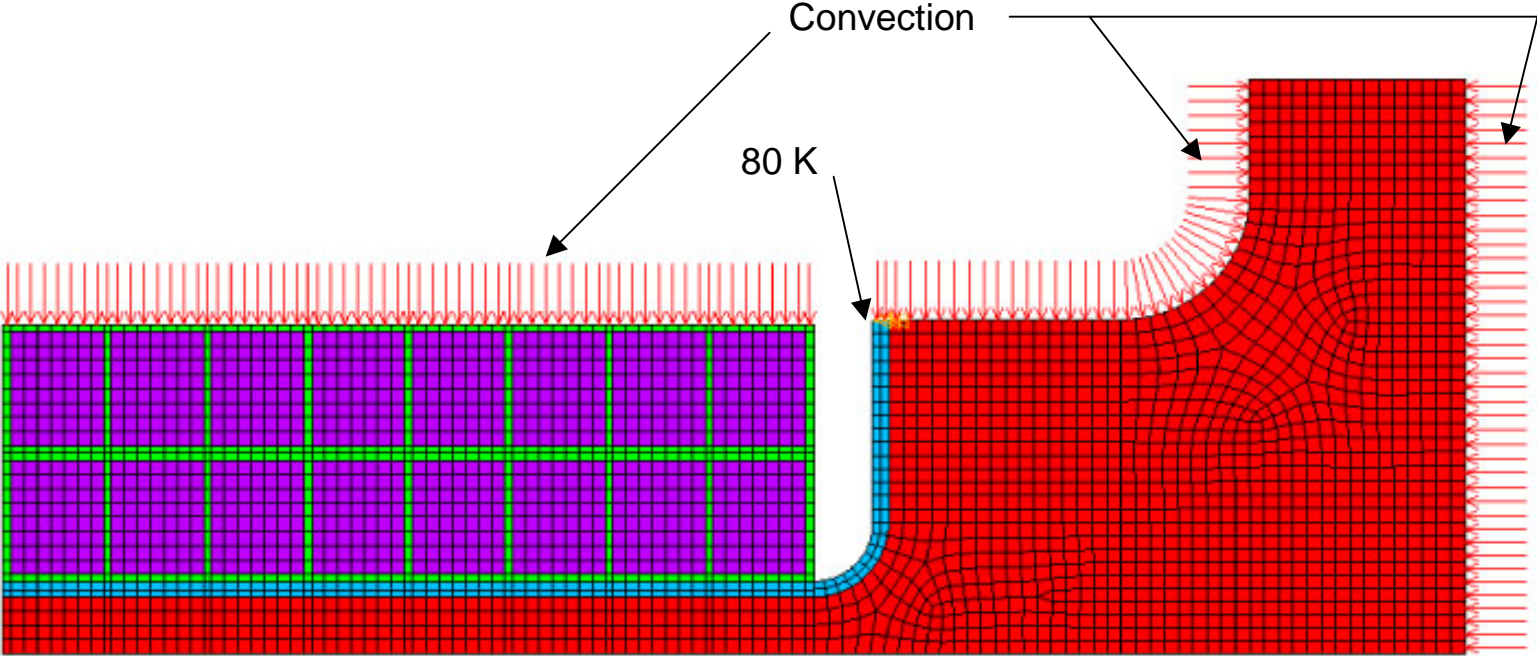
NODAL SOLUTION
 STEP=112
 SUB =4
 TIME=14451
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =82.913
 SMX =88.206

82.913
83.501
84.089
84.677
85.266
85.854
86.442
87.03
87.618
88.206

Summary of Results

- With a cooling period of 15 minutes, the temperature cycles become nearly steady in a few heating cycles.
- The ohmic heating raise the cable temperature 39.11 K in each pulse.
- The peak thermal gradient which produces the highest thermal stresses occurs close to the end of the ohmic heating period.
- At the end of 16th cycle, the maximum temperature of the coil structure is 89.793 K, occurred at the tip of the T-shape. The minimum temperature of 87.631 K was found adjacent to the gas inlet.
- The coil temperature is lower at the gas inlet end. The temperatures of exterior turns are slightly smaller than the temperatures of interior turns because of air-cooling.
- At the end of 16th cycle, the shell temperature at Node-6 is 89.035 K, which is 4.035 K higher than the starting temperature of 85 K.
- The cooling effect from the air is relatively smaller than the cooling gas.
- The analysis is conservative due to: 1) epoxy near the gas inlet is not included in the model, and 2) the shortest shell structure length is used.
- The assumed resistivity values from the first pulse may yield small errors on the following pulses when the starting temperatures of all turns are not necessary to be at 85 K.

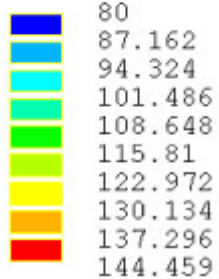
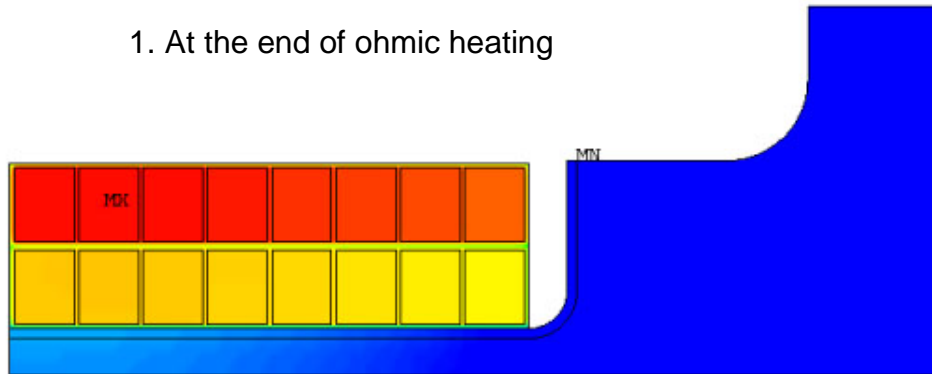
Septum Placed Between Coil and Coil Structure



Temperature Distribution in The 16th Heating and Cooling Cycles (2)

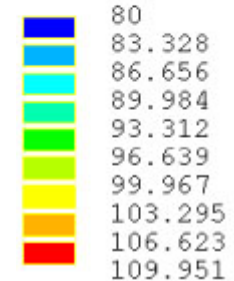
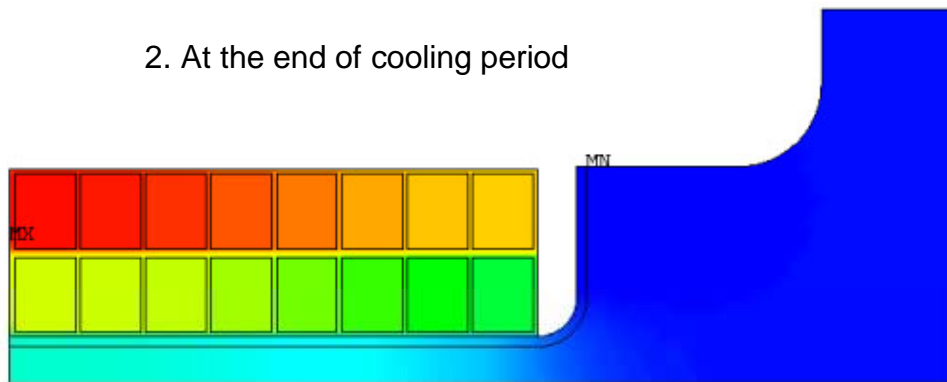
ANSYS 5.6.2
 AUG 10 2001
 09:32:32
 NODAL SOLUTION
 STEP=111
 SUB =3
 TIME=13551
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =80
 SMX =144.459

1. At the end of ohmic heating

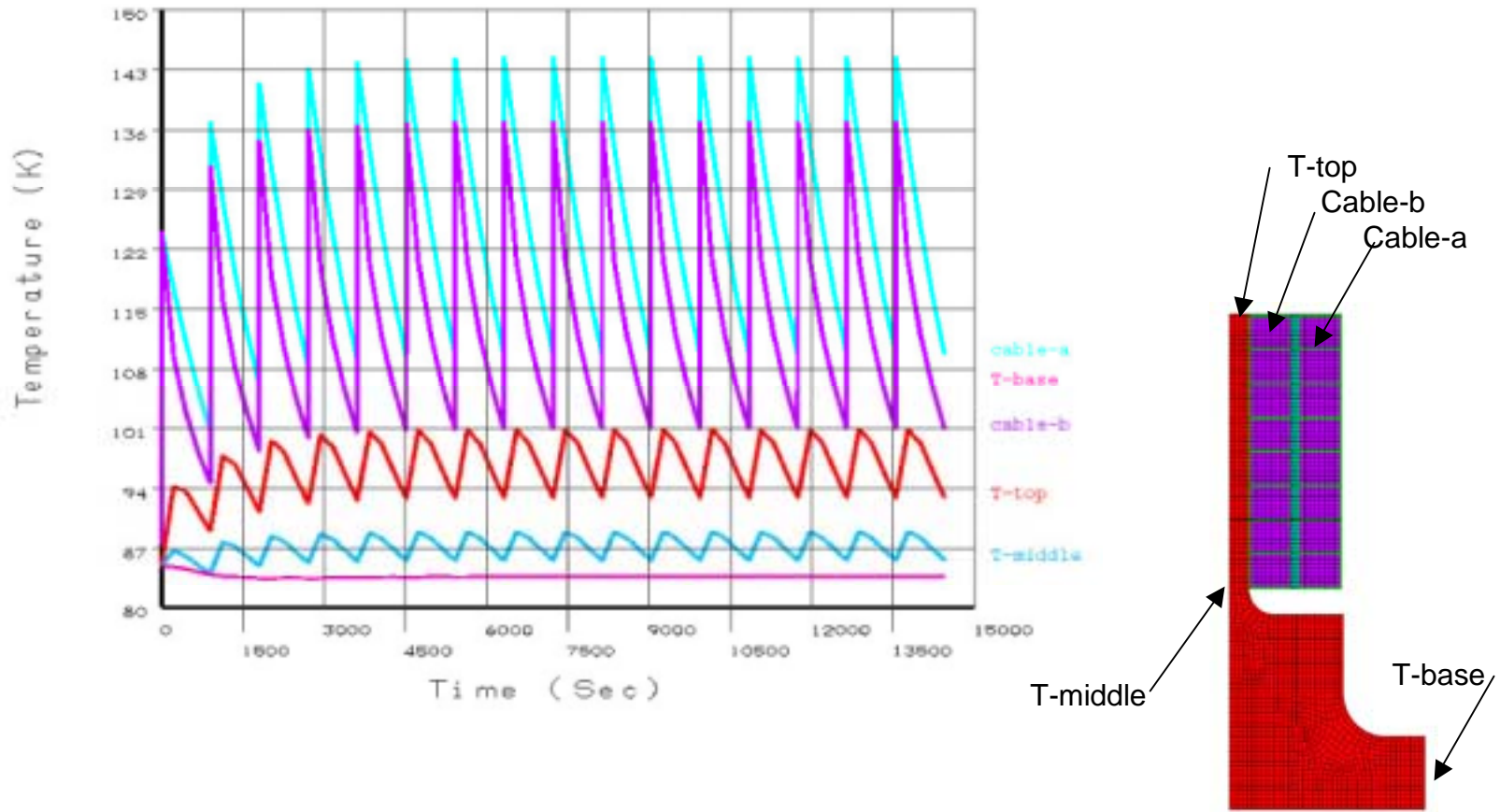


ANSYS 5.6.2
 AUG 10 2001
 09:31:05
 NODAL SOLUTION
 STEP=112
 SUB =4
 TIME=14451
 TEMP (AVG)
 RSYS=0
 PowerGraphics
 EFACET=1
 AVRES=Mat
 SMN =80
 SMX =109.951

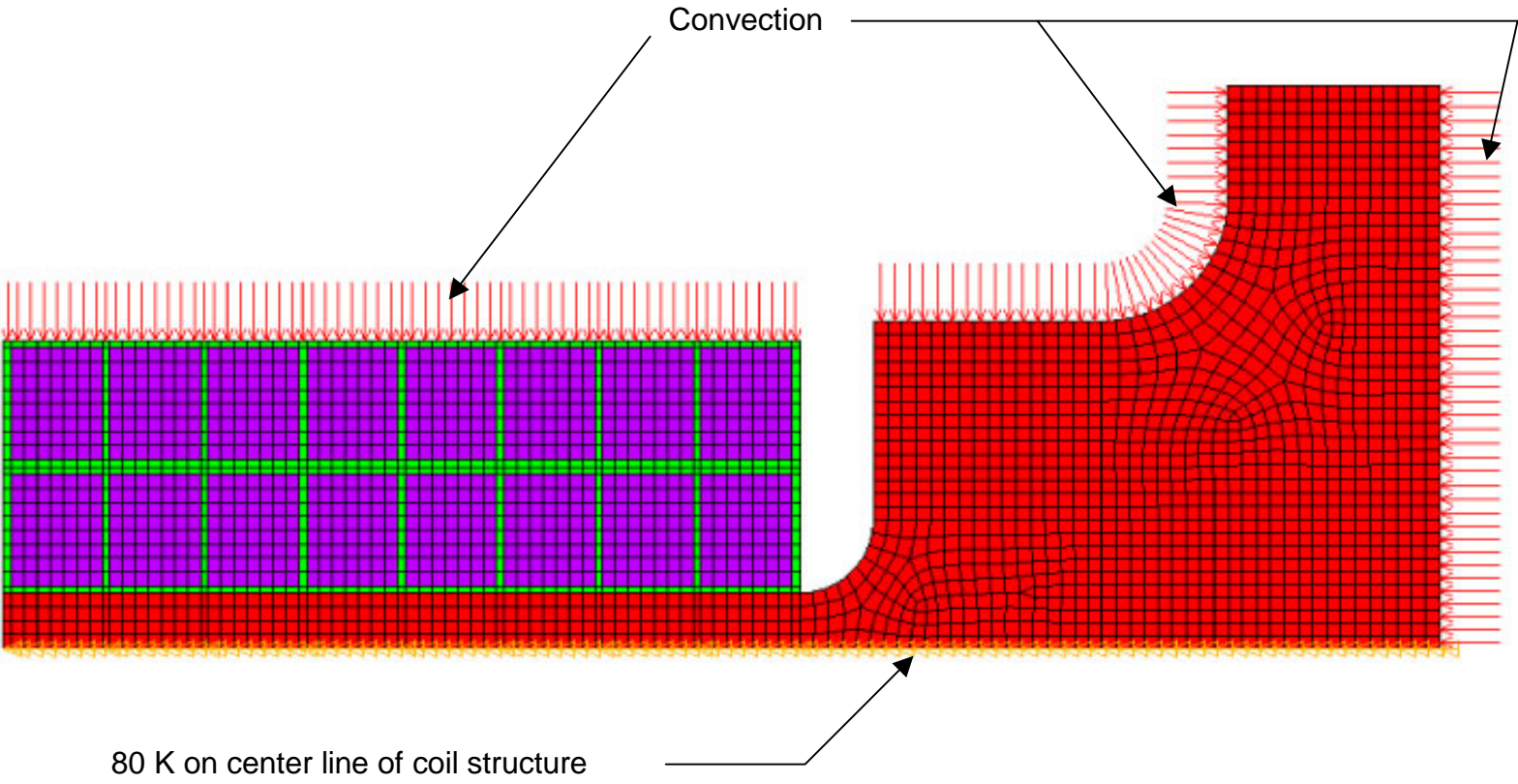
2. At the end of cooling period



Temperature vs. Time on Selected Nodes (2)



Temperature Constraint on Center Line of T-Shape Coil Structure (3)



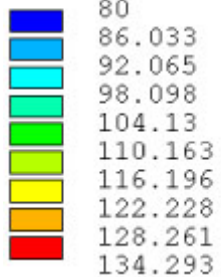
Temperature Distribution in The 16th Heating and Cooling Cycles (3)

ANSYS 5.6.2
 AUG 14 2001
 11:27:46
 NODAL SOLUTION

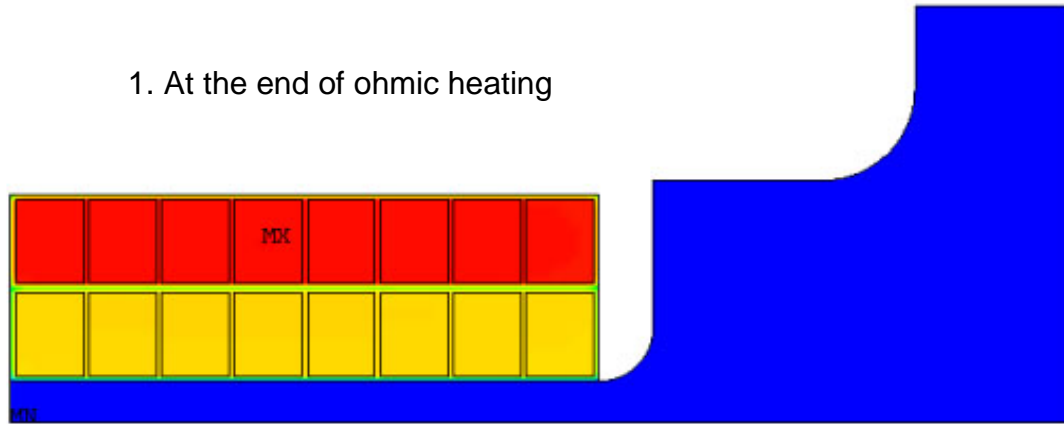
STEP=69
 SUB =3
 TIME=8132
 TEMP (AVG)

RSYS=0
 PowerGraphics
 EFACET=1

AVRES=Mat
 SMN =80
 SMX =134.293



1. At the end of ohmic heating

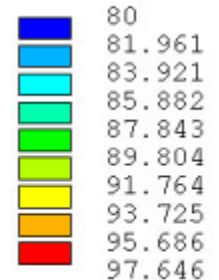


ANSYS 5.6.2
 AUG 14 2001
 11:24:02
 NODAL SOLUTION

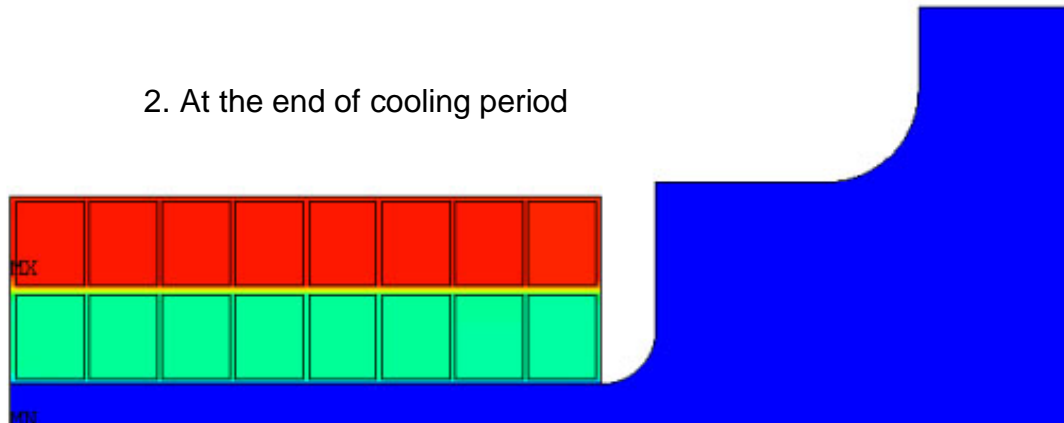
STEP=70
 SUB =4
 TIME=9032
 TEMP (AVG)

RSYS=0
 PowerGraphics
 EFACET=1

AVRES=Mat
 SMN =80
 SMX =97.646



2. At the end of cooling period



Temperature vs. Time on Selected Nodes (3)

