Updated Thermal Analysis of Modular Coil

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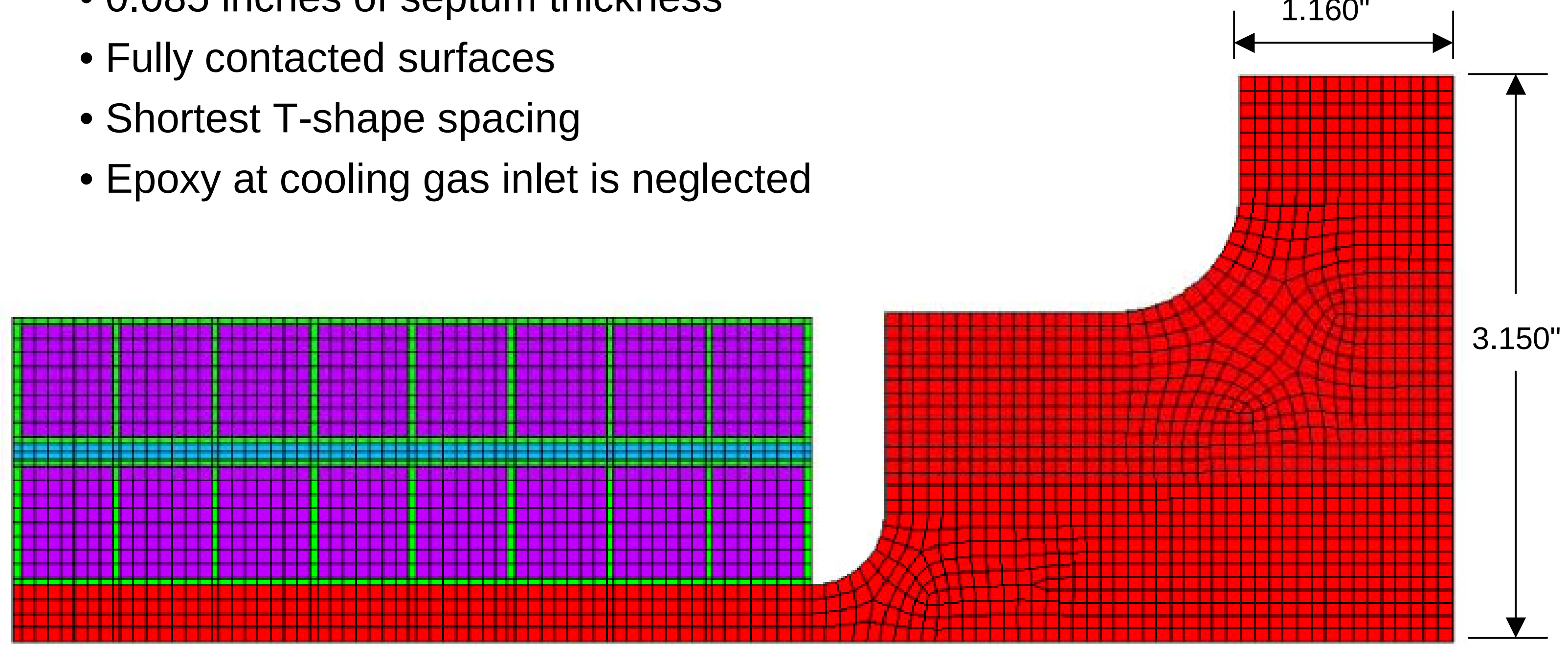
August 15, 2001

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)**

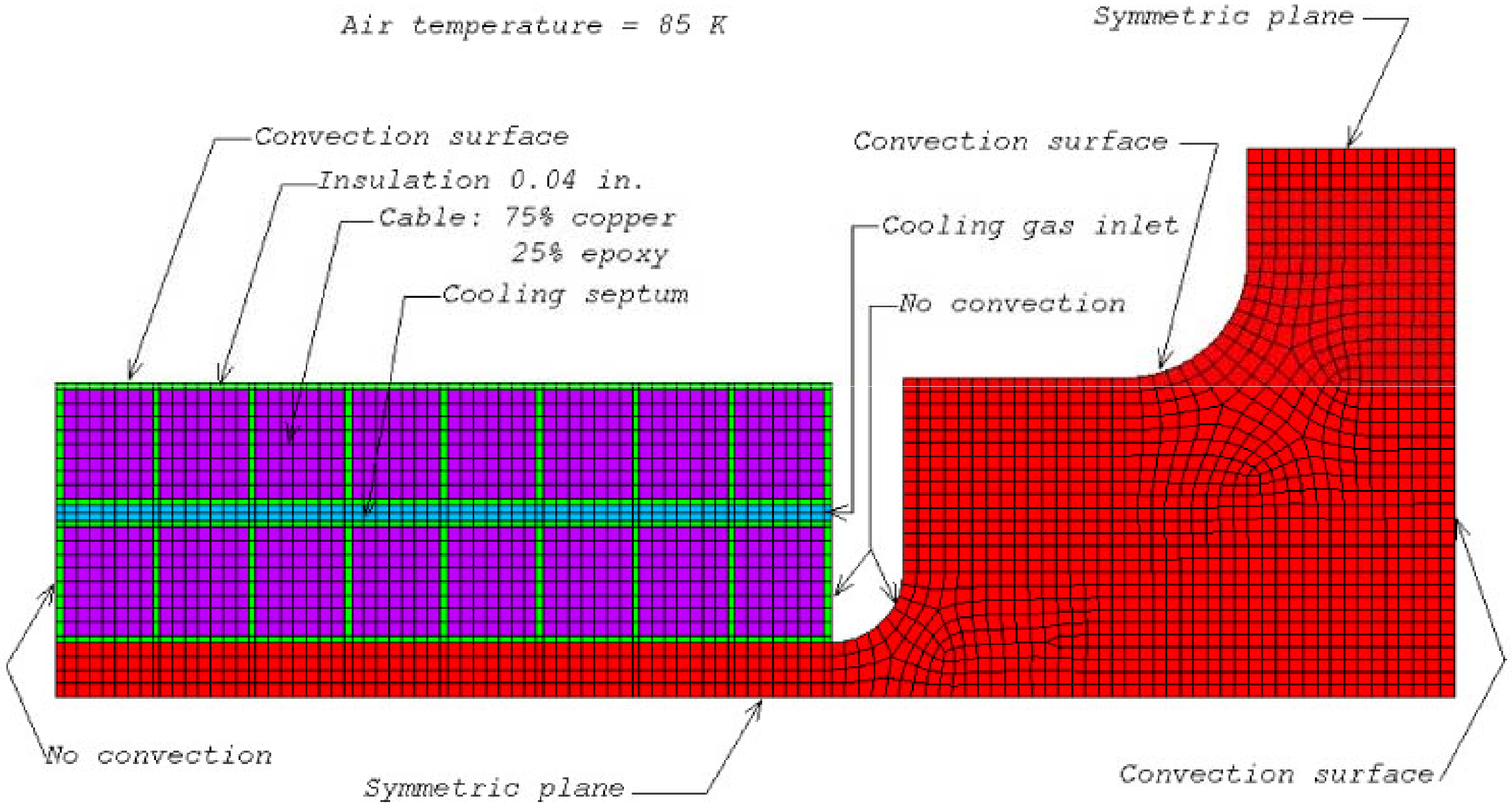
	80K	100K	150K	200K
Cable	171.4	212.3	270.1	300.7
Septum	205.1	255.3	324.1	359.0
Insulation	348.9	413.7	537.0	626.8
Shell & T-beam	215.3	275.5	362.1	416.4

- **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/m^3)

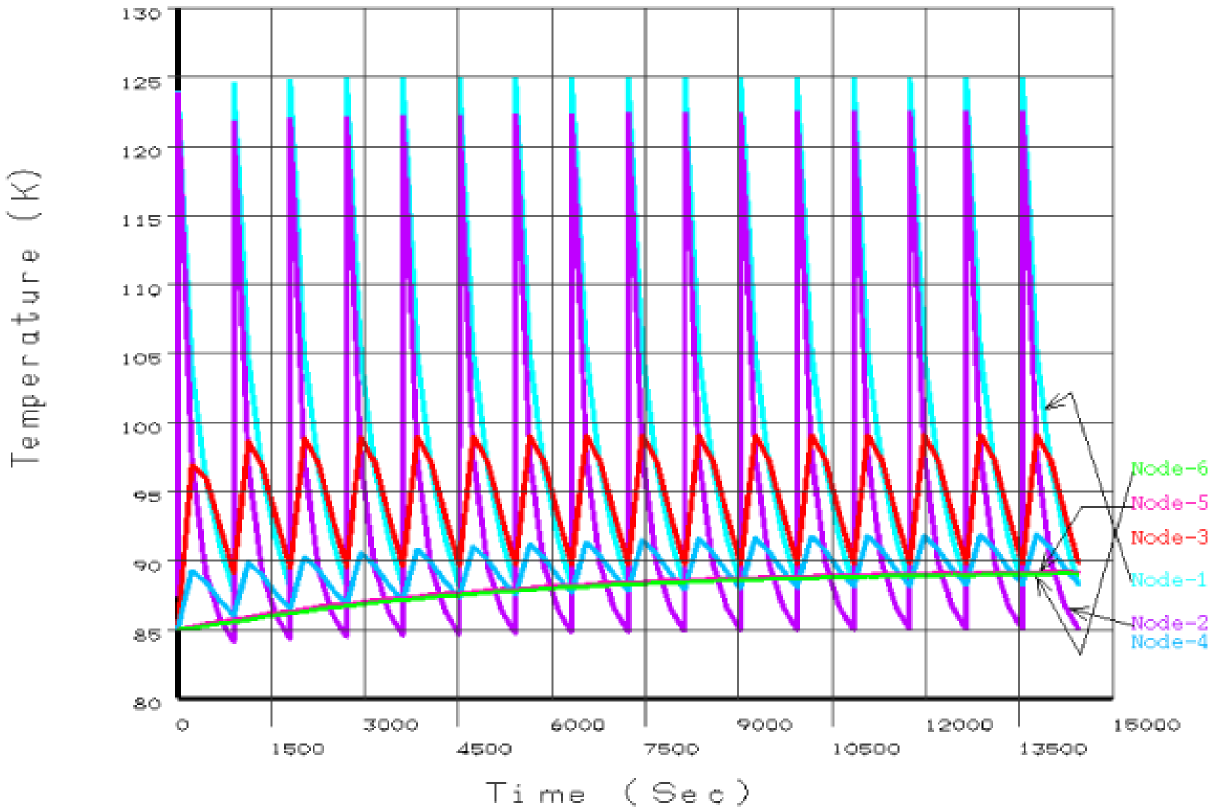
Time (s)	-1.8	-1.5	0	0.1	0.158083	0.258083	0.458083	1.658083	1.958083
μ (ohm-m)	2.36E-09	2.36E-09	3.52E-09	3.78E-09	3.91E-09	4.11E-09	4.55E-09	5.52E-09	5.52E-09
M1	0.00E+00	0.00E+00	3.41E+07	3.66E+07	2.75E+07	3.24E+07	3.59E+07	0.00E+00	0.00E+00
M2	0.00E+00	0.00E+00	2.98E+07	3.20E+07	2.64E+07	3.15E+07	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

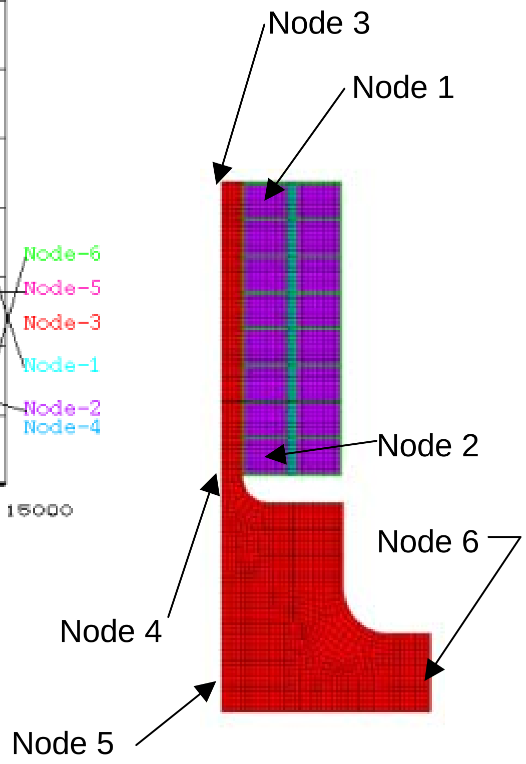
- Heat of ohmic heating in one pulse is 6.31 J/m^3 for M4 coil

Transient Thermal Analysis

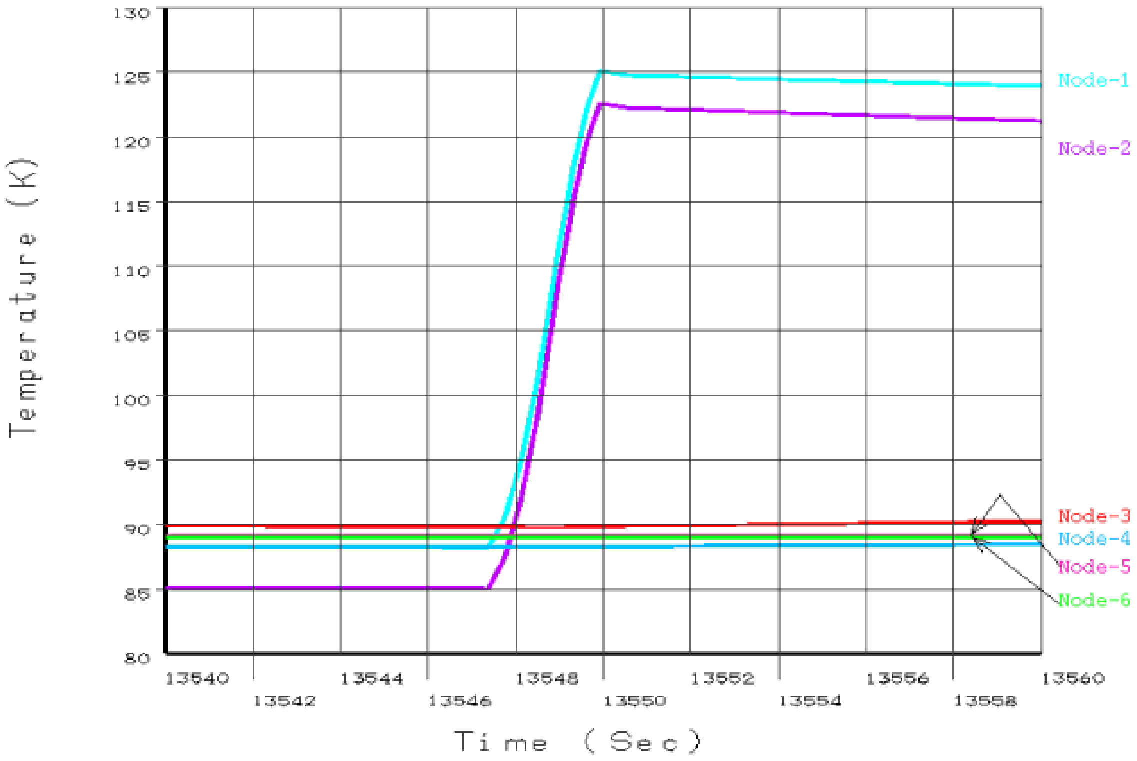
- Temperature constraint at cooling gas inlet is 80 K.
- The starting temperatures for both the coil and coil structure are 85 K.
- Ambient air temperature is fixed at 85 K.
- The film coefficient is assumed to be 4.0 W/m^2-K.
- The thermal properties for specific heat and thermal conductivity are temperature-dependent.
- 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.)

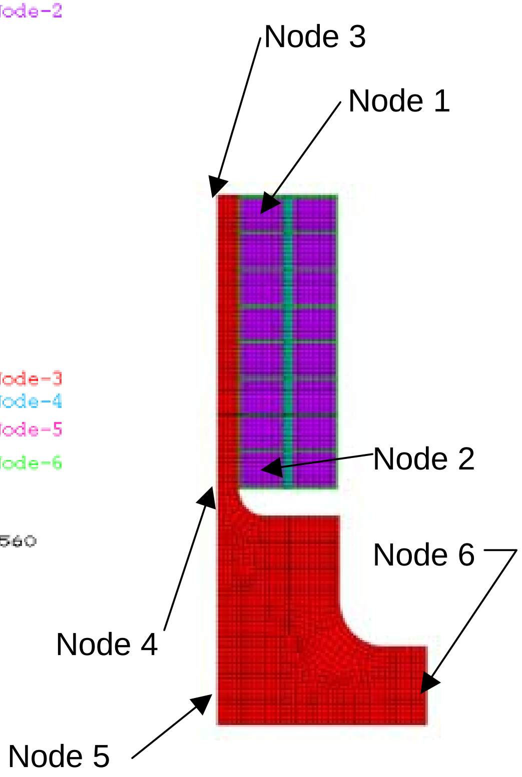
Temperature vs. Time on Selected Nodes



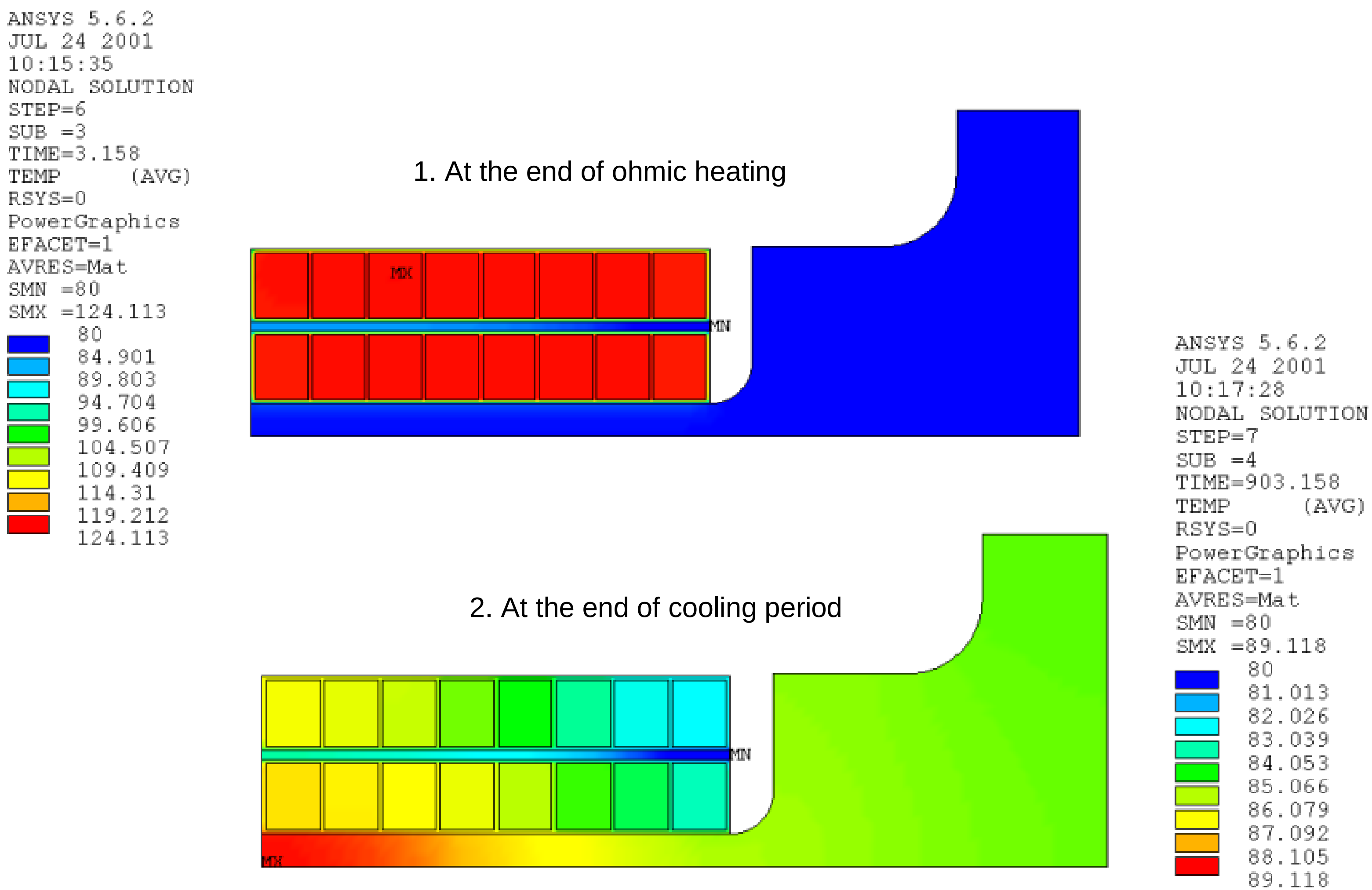


Temperature vs. Time During the 16th Heating Cycle

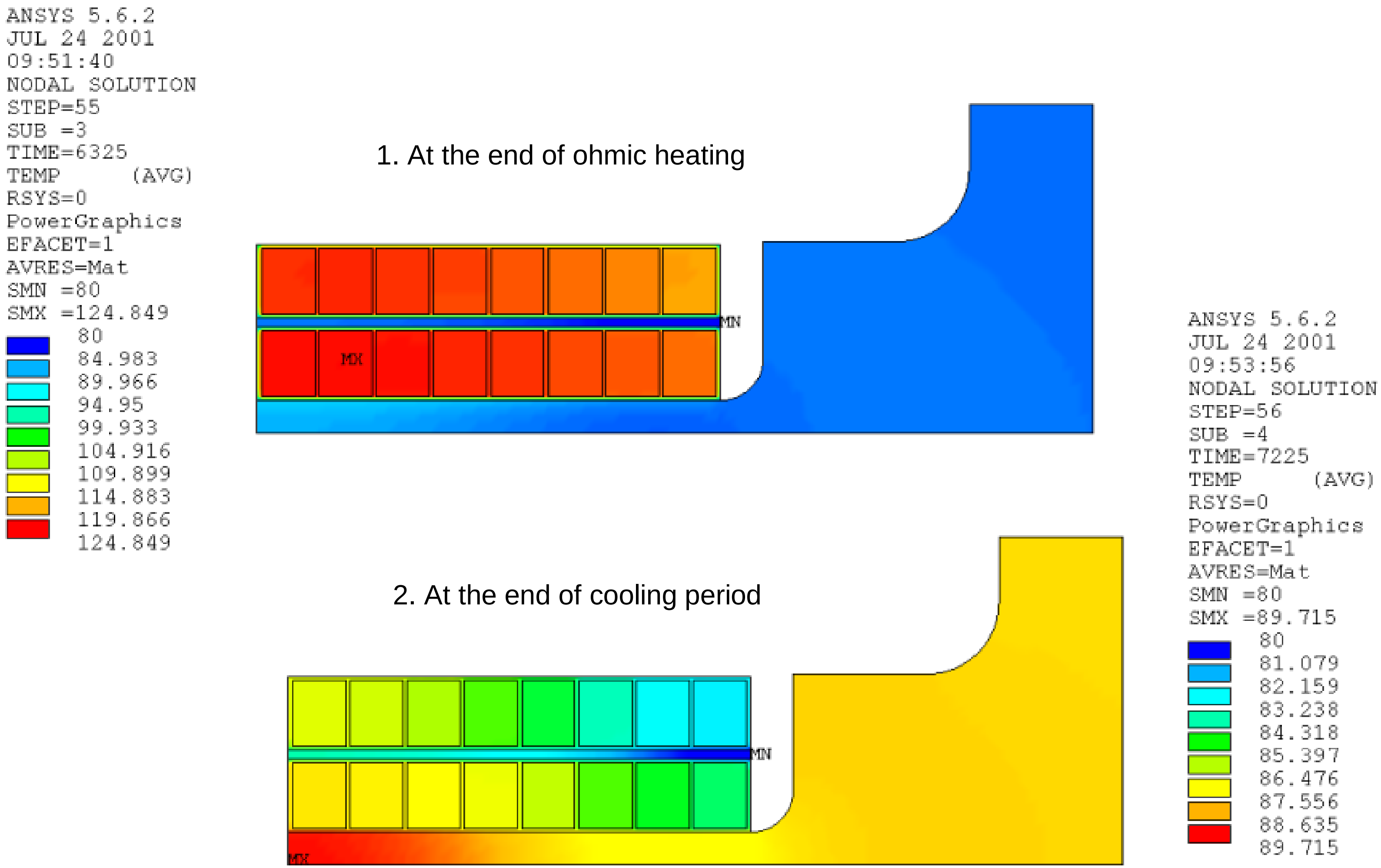




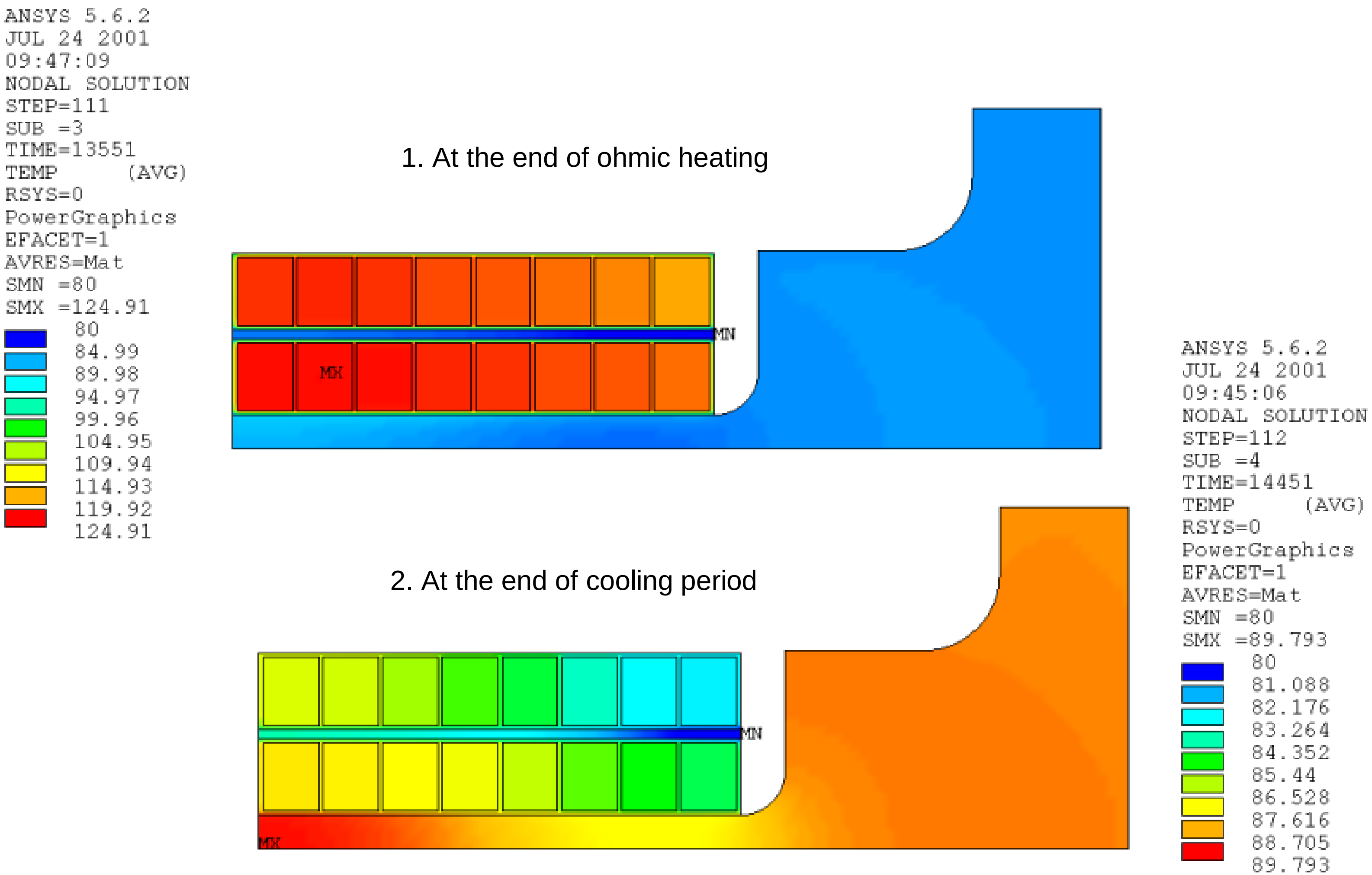
Temperature Distribution in The First Heating and Cooling Cycles



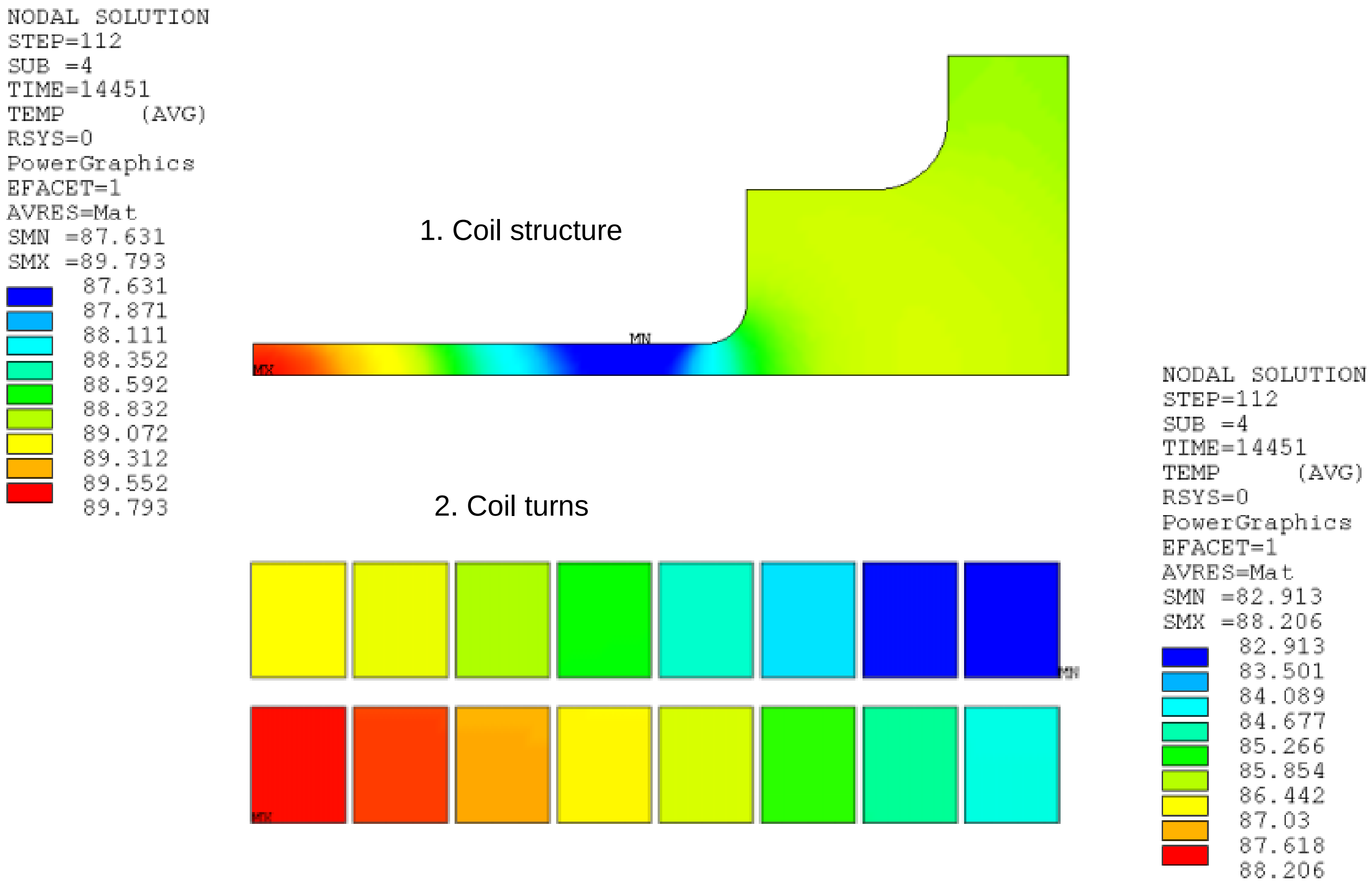
Temperature Distribution in The 8th Heating and Cooling Cycles



Temperature Distribution in The 16th Heating and Cooling Cycles



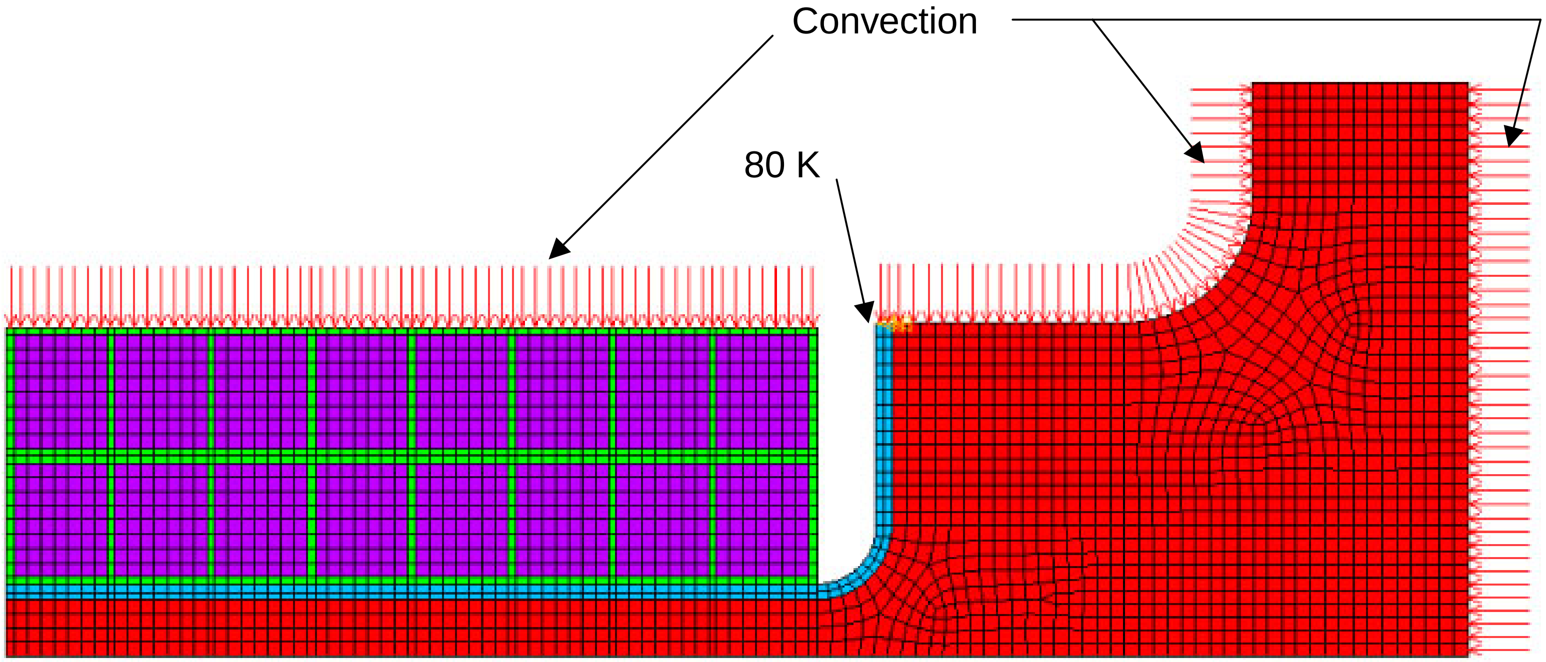
Temperature Distribution in Coil Structure and Coil at The End of 16th Cooling Cycles



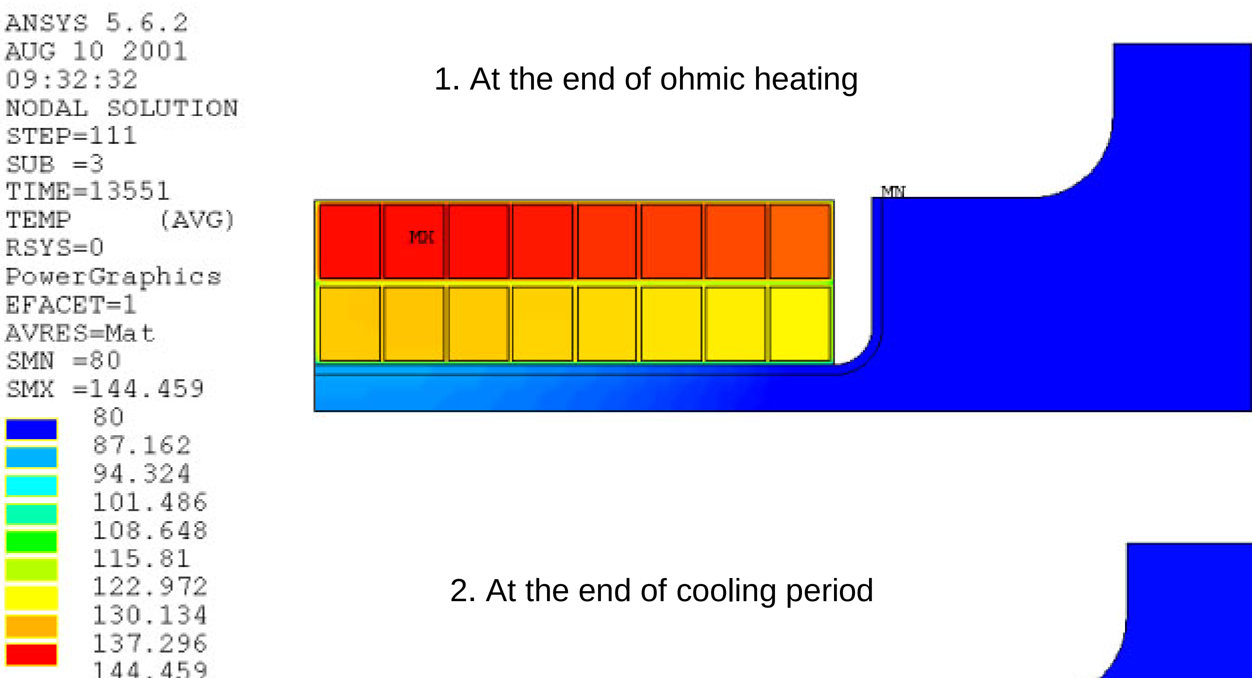
Summary of Results

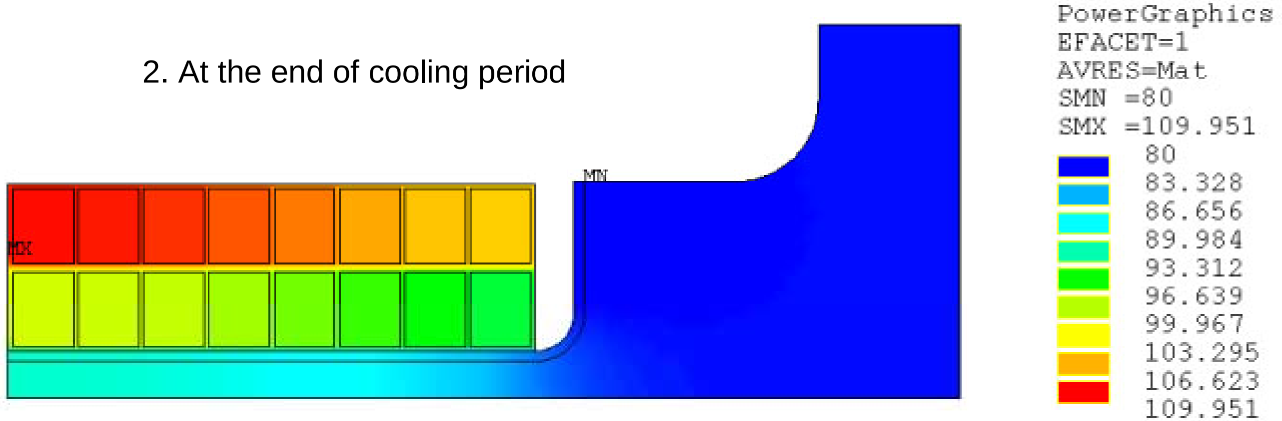
- With a cooling period of 15 minutes, the temperature cycles become nearly steady in a few heating cycles.
- The ohmic heating raise the cable temperature 39.11 K in each pulse.
- The peak thermal gradient which produces the highest thermal stresses occurs close to the end of the ohmic heating period.
- 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 resistivitiy 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

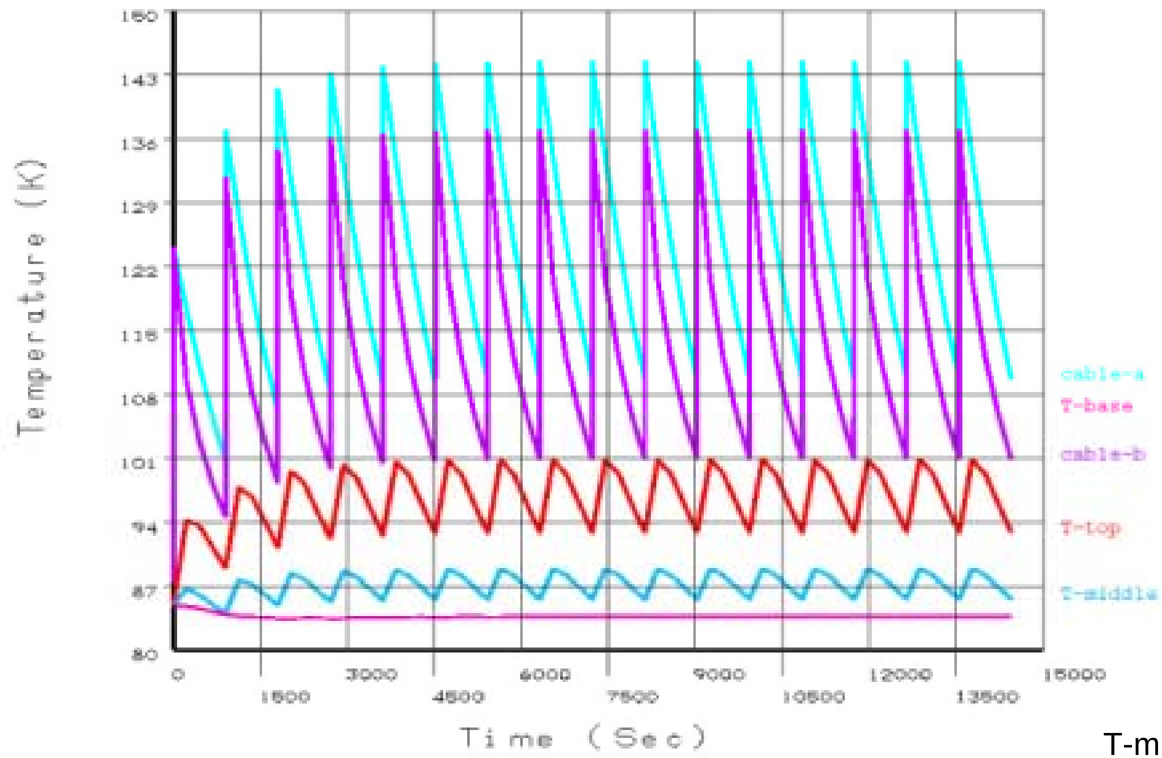


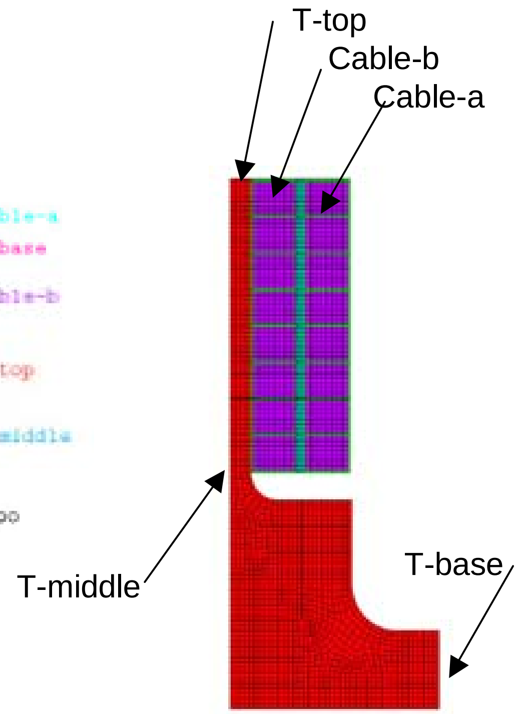
Temperature Distribution in The 16th Heating and Cooling Cycles (2)



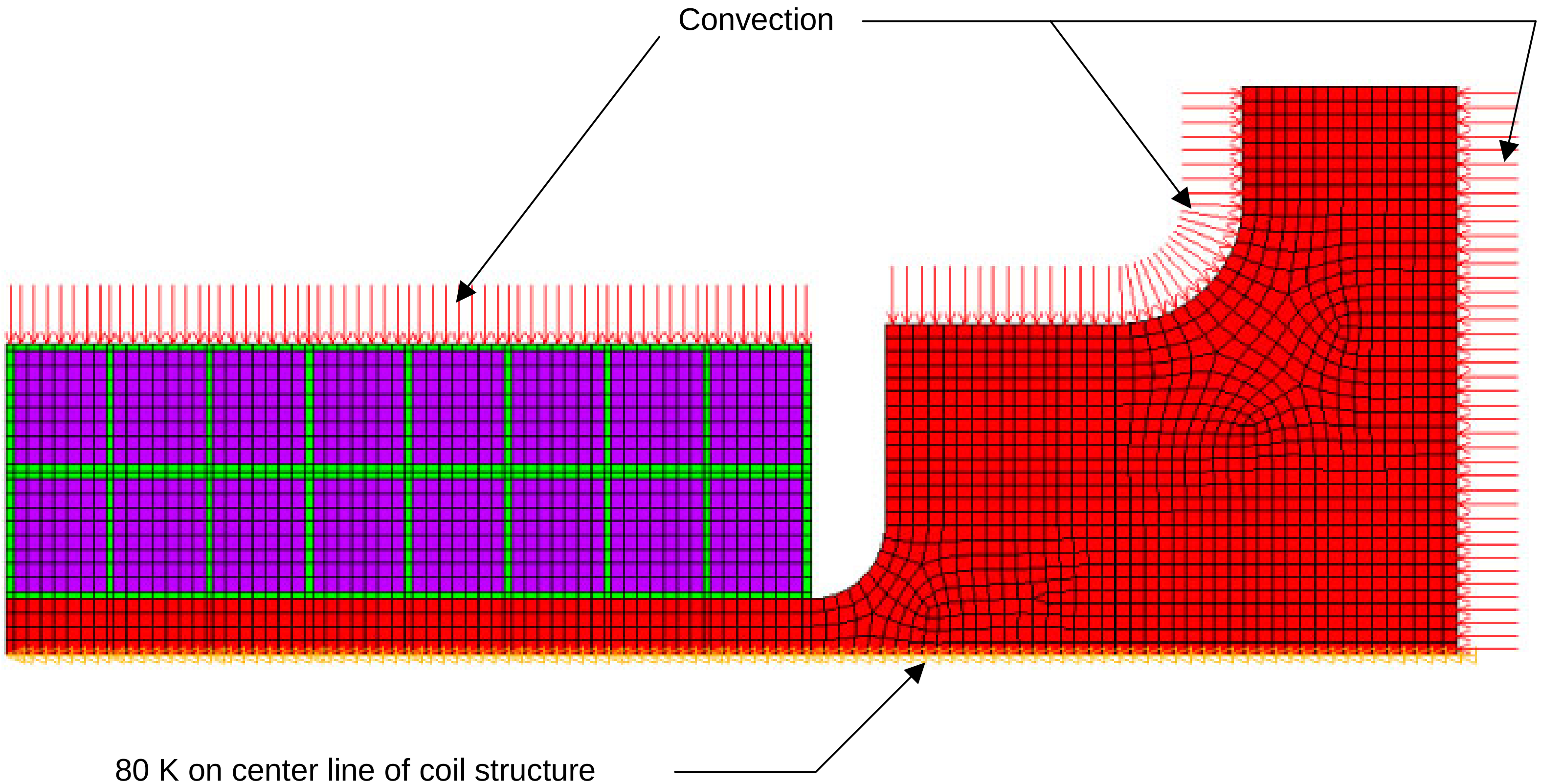


Temperature vs. Time on Selected Nodes (2)

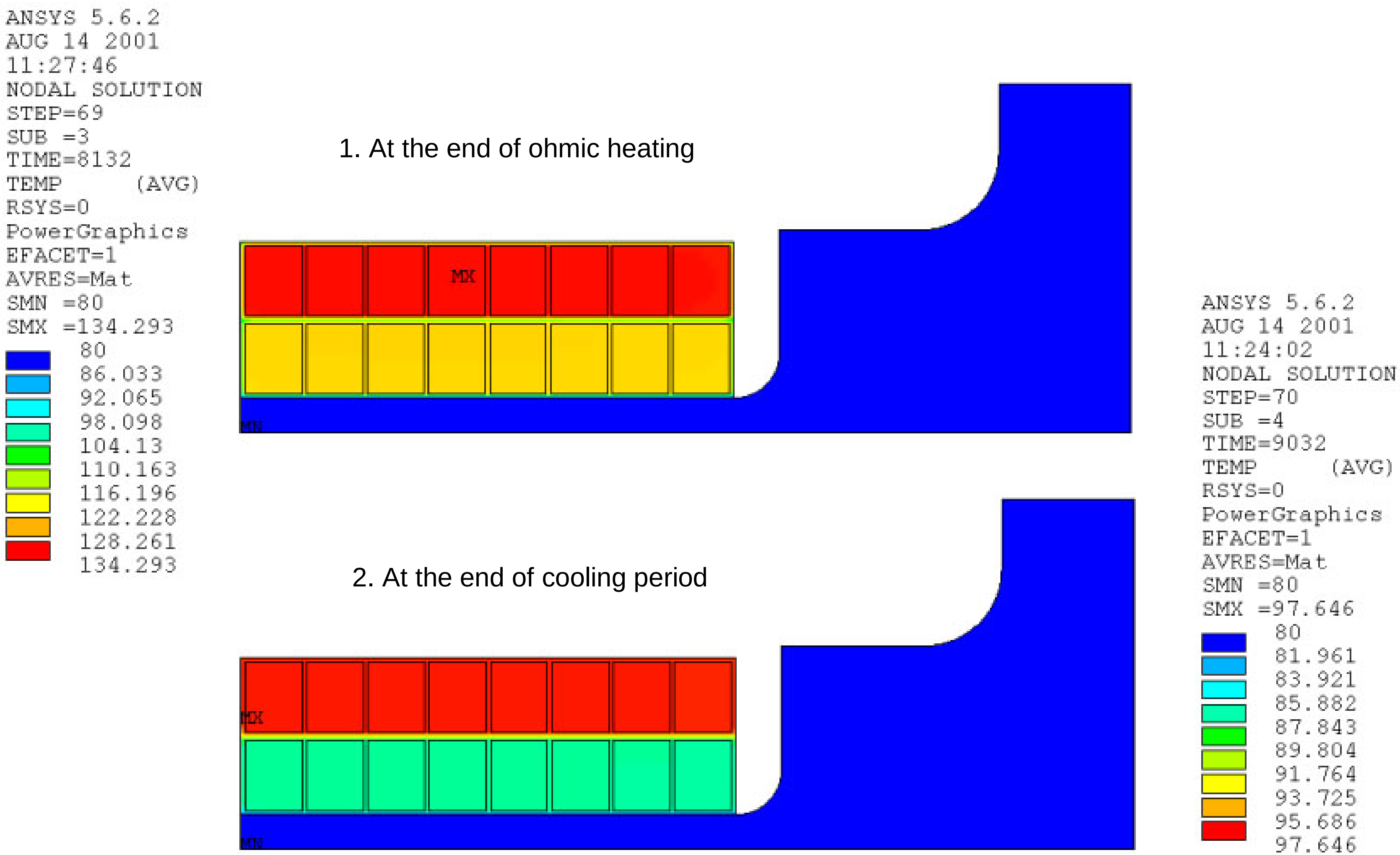




Temperature Constraint on Center Line of T-Shape Coil Structure (3)



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



Temperature vs. Time on Selected Nodes (3)