Fermi National Accelerator Laboratory
PPD / Mechanical Support / Engineering Analysis

The Effect of Hot Chase Shielding Blocks on Horn 1 Strip Line Temperatures at 1MW

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There is a concern that during a power outage, when active cooling of the target chase has stopped, the hot shielding blocks will heat the strip lines, exceeding 100C, and induce unpredictable degradation of strength properties of aluminum material. We make this finite element model to simulate the thermal process after active cooling is cutoff, to see how the temperature of strip lines changes with time.

An estimate of the steady state blue block temperatures was achieved by extrapolating temperatures from the NOvA 700kW analysis, and utilizing actual thermocouple measurements on chase blocks in NuMI for verifying those assumptions. The 700kW analysis, and subsequent initial block temperatures for 1MW, are believed to be accurate since the measured blue block surface temperature corresponds to within ~5% of the value shown in the NOvA analysis. Steady state 700kW block temperatures can be seen in figure 1 for reference.

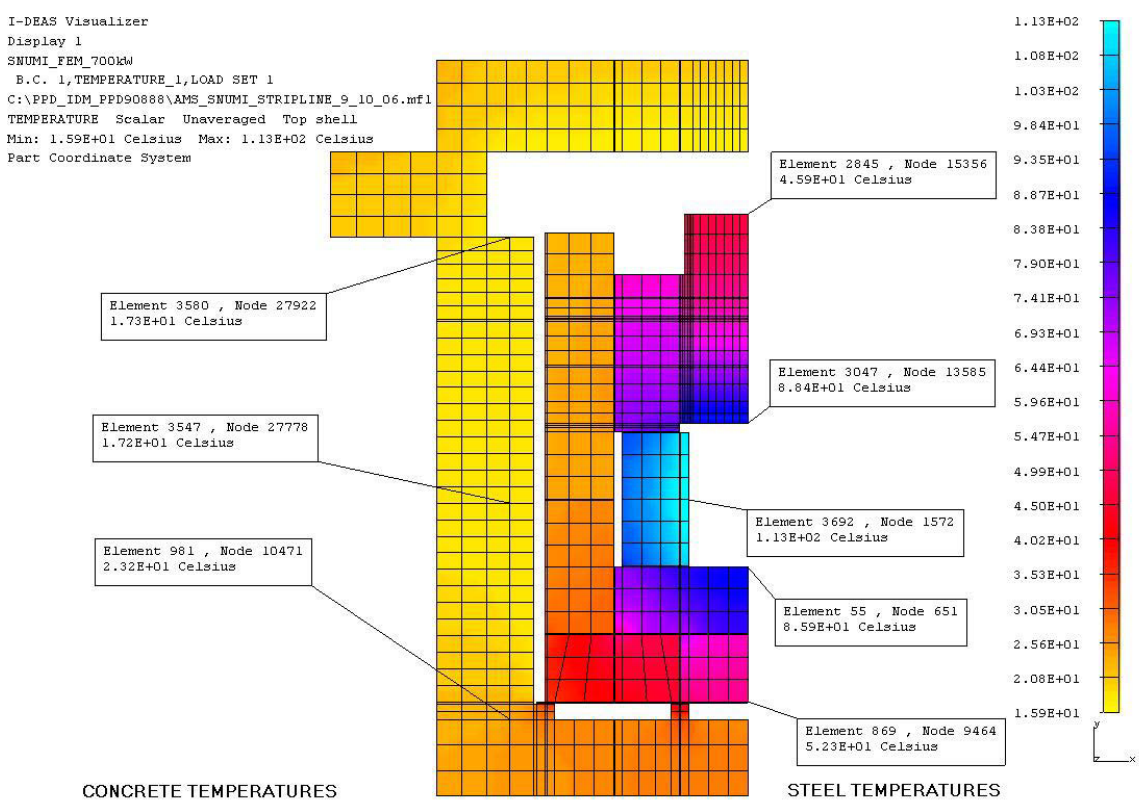

Figure 1. 700kW Steady State Shielding Temperatures at D.S. End of Horn 1 Stripline.

The components of the 1MW model are shown in Figure 2, and initial conditions are assumed to be steady state temperatures during 1MW operation. The thickness of the model is about 1.33m. We assume there is no significant temperature change in thickness direction, and the right boundary is symmetric. Their material properties used in the model are listed in Table I. For simplicity, we consider only one strip line, that most close to the hot shielding blocks.

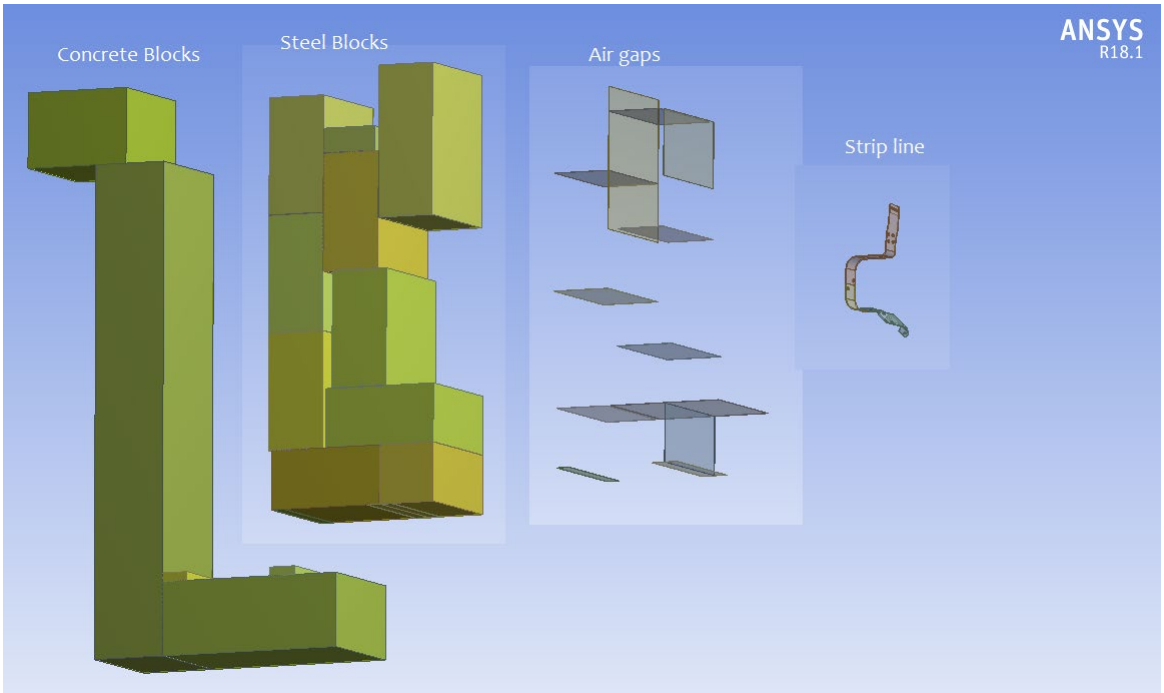

Figure 2. Components of the finite element model

Table I. Material Properties

Material	Density (kg/m^3)	Specific heat (J/kg-K)	Conductivity (W/m-K)
Concrete	2550	960	1
Steel A36	7900	470	50
Aluminum	2700	896	170
Air	1.205	1005	See below

Thermal Conductance of Narrow Air Gaps

The chase block is cast steel with rough surface. It is estimated that the average gap between steel blocks is about 1/8 inch, or 3.175 mm. In this narrow gap, the convection flow can be neglected. Here we try to estimate the effect of radiation. Radiation Heat transfer between the two surfaces of a narrow gap is basically one-dimensional, i.e. the heat transfer is in the direction across the gap. Here we try to derive a method to model it as conduction.

Radiation Heat transfer between two surfaces A_1 and A_2 can be written as (R.F. Barron, *Cryogenic Heat Transfer*, 1994, Taylor & Francis)

$$Q = F_e F_{12} A_1 \sigma \left(T_2^4 - T_1^4\right).$$

Here F_e is emissivity factor and F_{12} is geometric factor, $\sigma = 5.67\text{x}10{-}8$ w/m^2-K^4 is Stefan-Boltzmann constant, and T_1 and T_2 are temperatures at the two surfaces.

For steel block gaps, the block size is in the order of magnitude of meter, and the gap size δ is usually a few millimeters to a centimeter. Therefore the two surfaces can be considered as two infinite parallel planes. Hence $F_{12} = 1$, and $F_e = \varepsilon_1\varepsilon_2/(\varepsilon_1 + \varepsilon_2 - \varepsilon_1\varepsilon_2)$.

If we assume $\varepsilon_1 = \varepsilon_2 = 0.8$, then $F_e = 0.667$. Therefore

$$q = \left(Q / A_1\right) = 0.667\sigma\left(T_2^4 - T_1^4\right).$$

Compare with conduction heat transfer

$$q = k\left(T_2 - T_1\right)/\delta,$$

We have the effective conductance of

$$\begin{aligned}\frac{k}{\delta} &= 0.667\ \sigma\left(T_2^2 + T_1^2\right)\left(T_2 + T_1\right) \\ &= 3.78\times10^{-8}\left(T_2^2 + T_1^2\right)\left(T_2 + T_1\right).\end{aligned}$$

Let us define

$$\tilde{T} = \left(T_1 + T_2\right)/2, \quad \hat{T} = \left(T_1 - T_2\right)/2,$$

They are the average temperature and half the temperature difference, respectively. Then above equation can be written as

$$\frac{k}{\delta} = 3.78\times10^{-8}\, 4\tilde{T}^3\left(1 + \left(\hat{T}/\tilde{T}\right)^2\right).$$

In our problem,

$$\tilde{T} \sim 400\text{K}, \quad \hat{T} < 40\text{K}, \quad \text{so } \left(\hat{T}/\tilde{T}\right)^2 < 0.01.$$

Therefore the second term can be neglected compared with the first term. In following we omit the tilt above the average temperature. If the temperature is given in C instead of K, we have

$$\begin{aligned}\frac{k}{\delta} &= 15.12\times10^{-8}\left(273 + T\right)^3 \\ &= 3.077 + 3.381\times10^{-2}T + 1.238\times10^{-4}T^2 + 1.512\times10^{-7}T^3.\end{aligned}$$

Air conductivity can be approximately written in the temperature range of 0~200C as

$$k_{air} = 2.4\times10^{-2} + 0.0075\times10^{-2}T.$$

If we assume that the gap size is $\delta = 3.175$ mm, we have the conductance of

$$\frac{k_{air}}{\delta} = 7.56 + 0.0236\,T.$$

The total conductance due to conduction and radiation is therefore

$$\frac{k_{total}}{\delta} = 10.637 + 5.741\times10^{-2}T + 1.238\times10^{-4}T^2 + 0.1512\times10^{-6}T^3.$$

These conductances are plotted in the Figure.2.

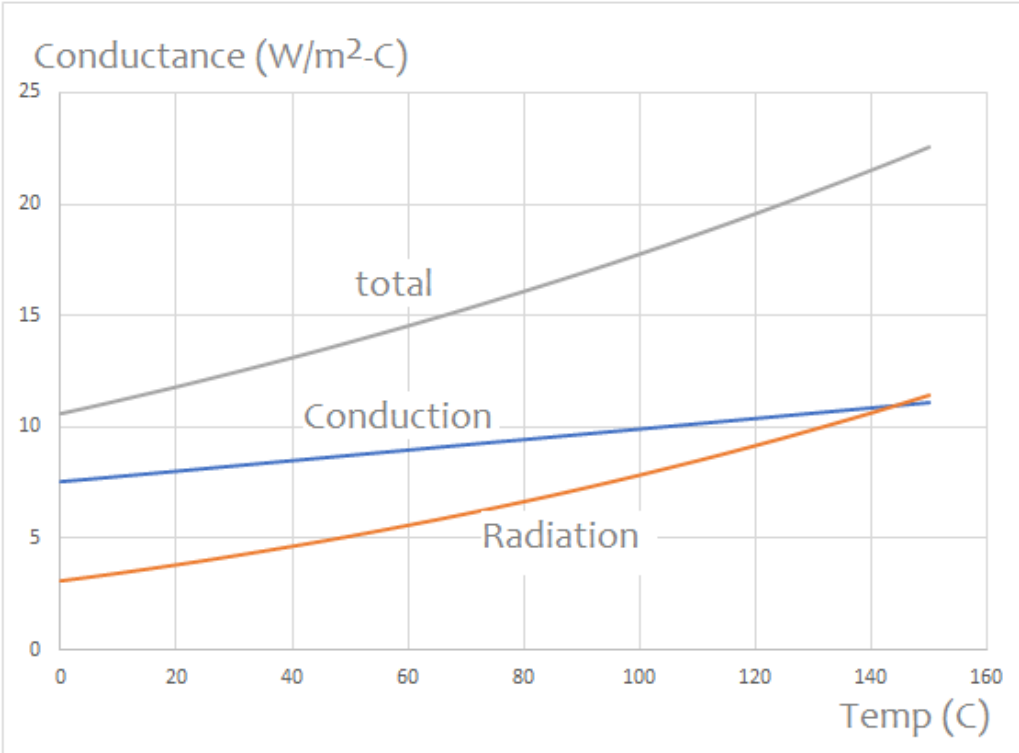

Figure 3. Conductance across 1/8 inch air gap

Initial Temperatures

The initial temperature distribution is plotted in Figure 4 on the following page.

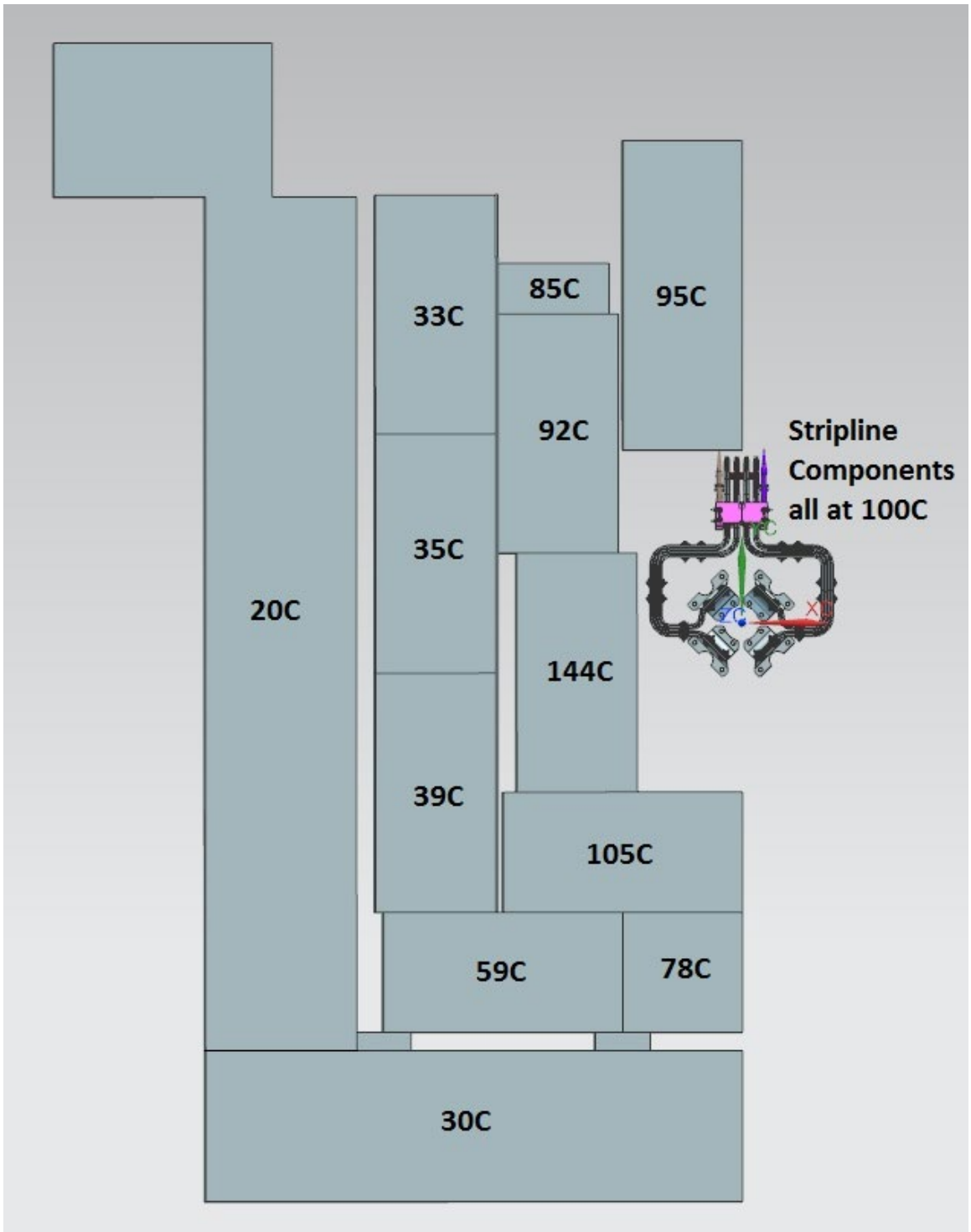

Figure 4. Initial temperature

Boundary Conditions

Boundary conditions are plotted in Figure 5. For conservative purpose, we specify the free convection cooling only on one surface of the strip line. The radiation effect is included in conduction for those narrow air gaps. For the open cavities, the surface radiation is specified. The free convection cooling is also specified on the open surfaces.

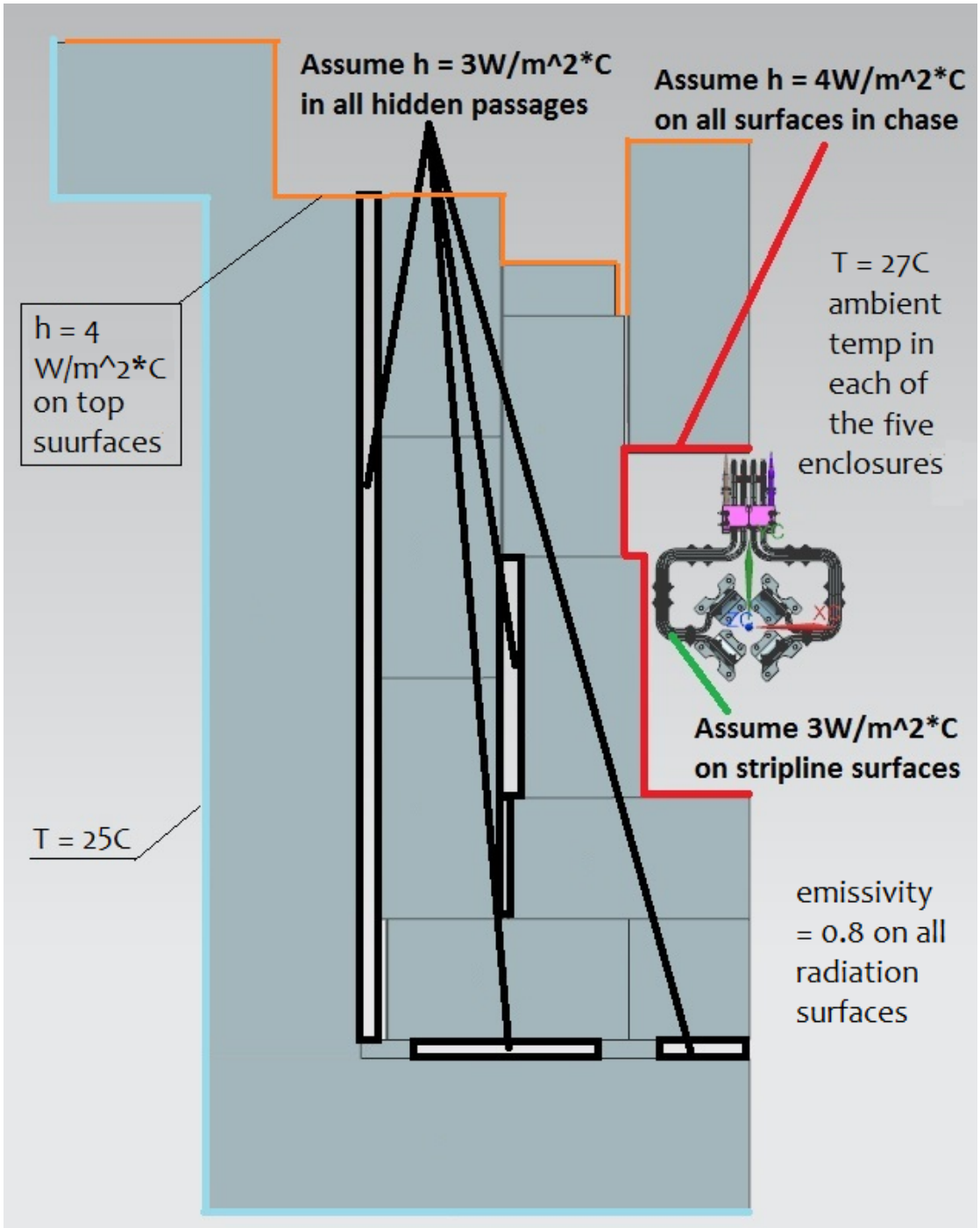

Figure 5. Boundary conditions applied to the model

Results

The temperature at the end of 1 hour, 5 hour and 24 hour is shown in Figures 6~8. Figures 9~11 show strip line temperature change with time. We see that the temperature of strip line will not exceed 100C. Figure 12 plotted stripline temperature with different film coefficient on the stripline surface.

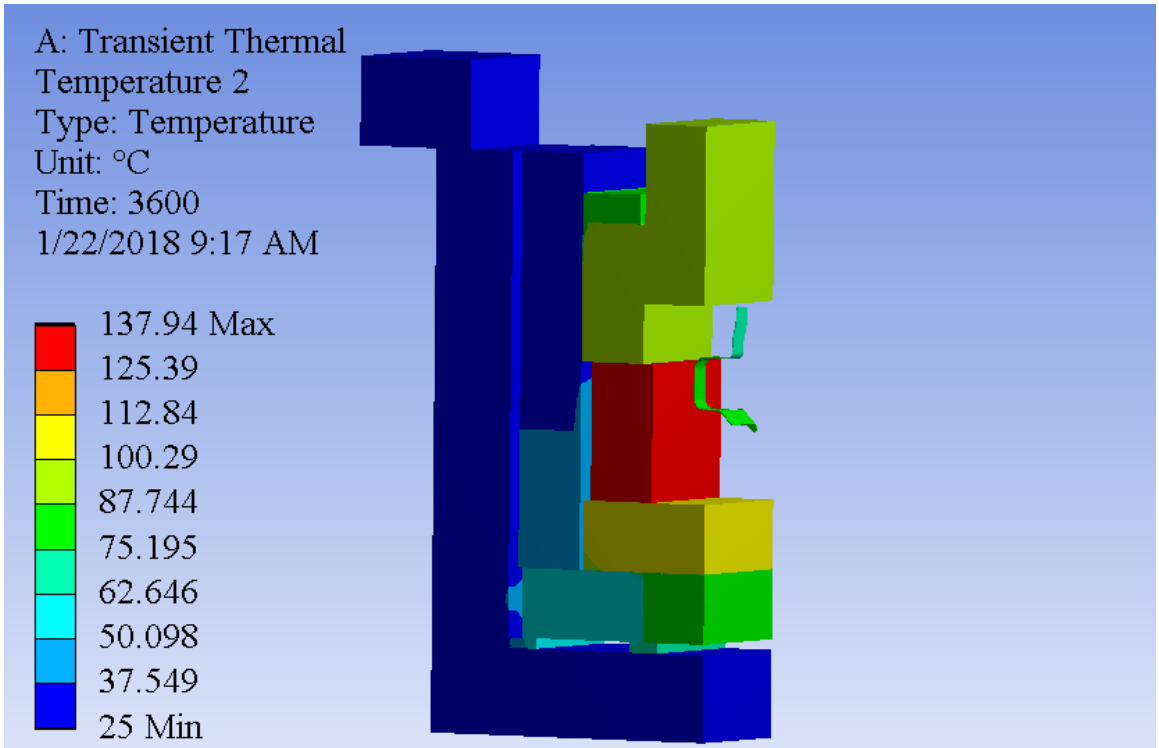

Figure 6. Temperature at the end of 1 hour

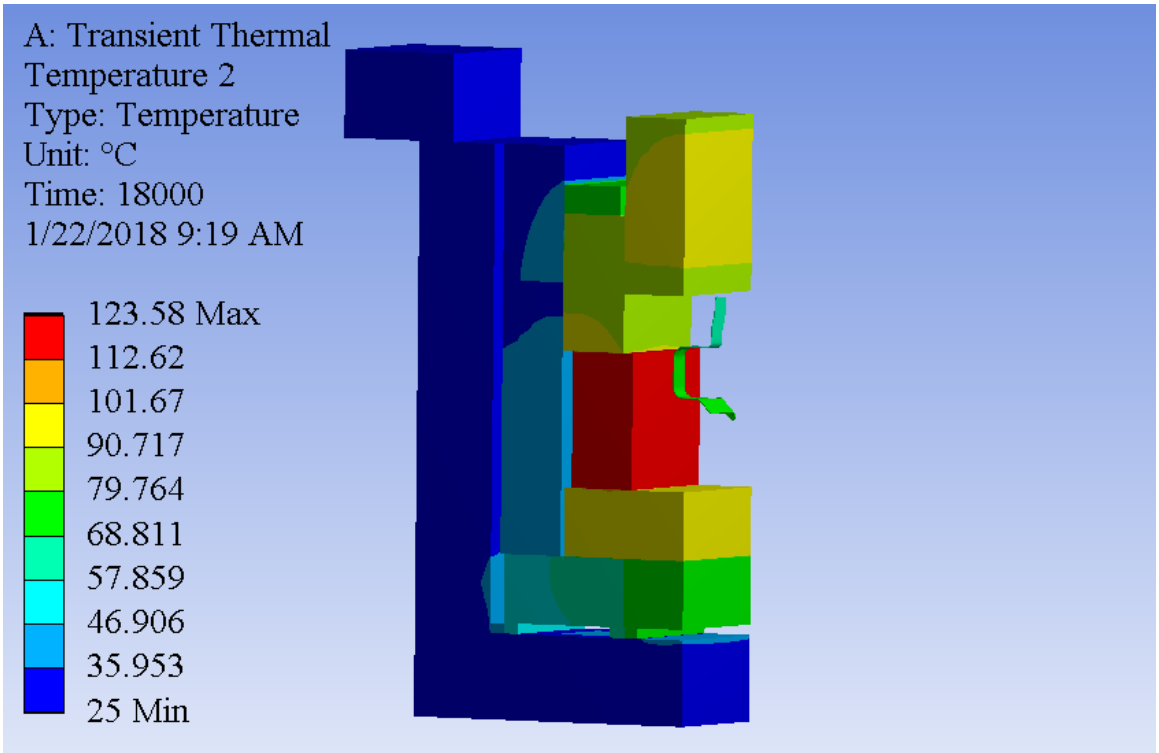

Figure 7. Temperature at the end of 5 hours

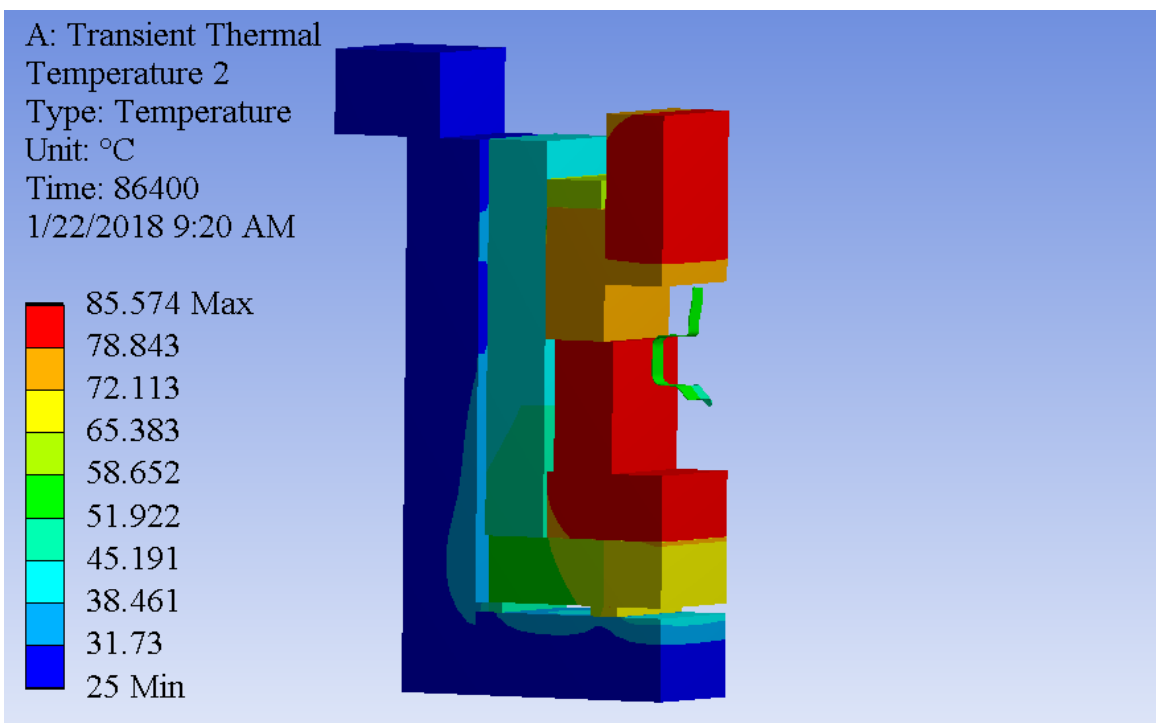

Figure 8. Temperature at the end of 24 hours

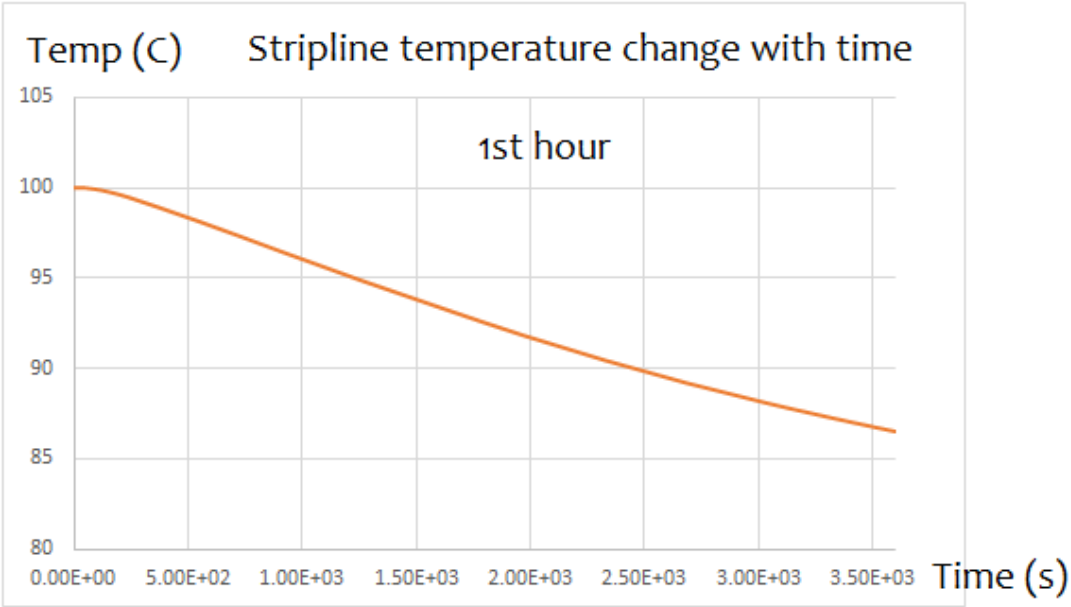

Figure 9. Strip line temperature in 1st hour

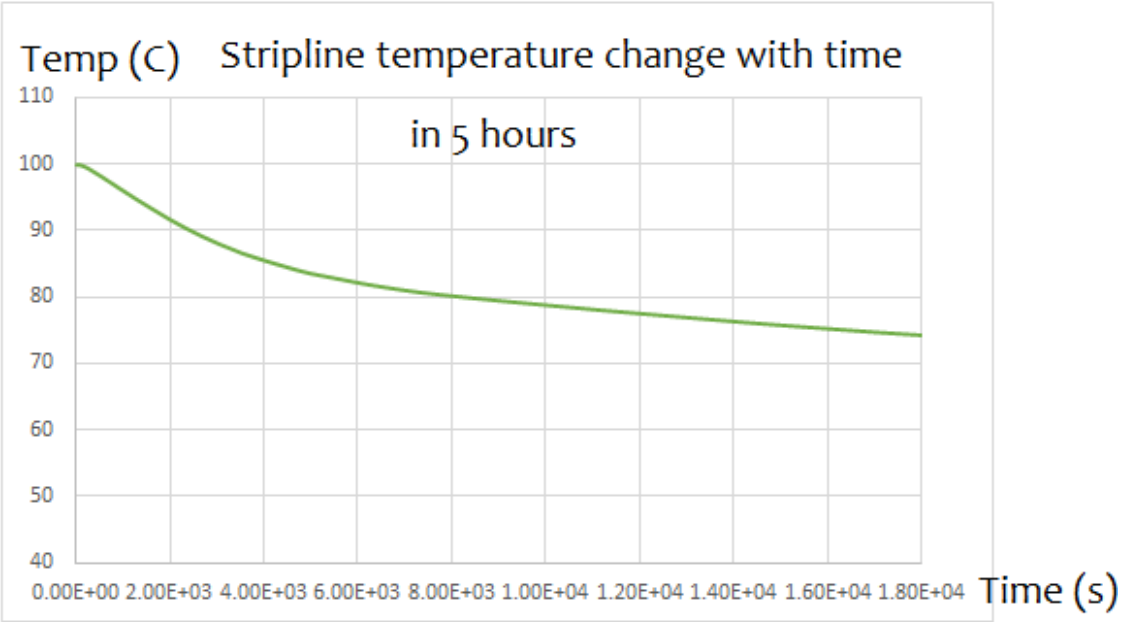

Figure 10. Strip line temperature in first 5 hours

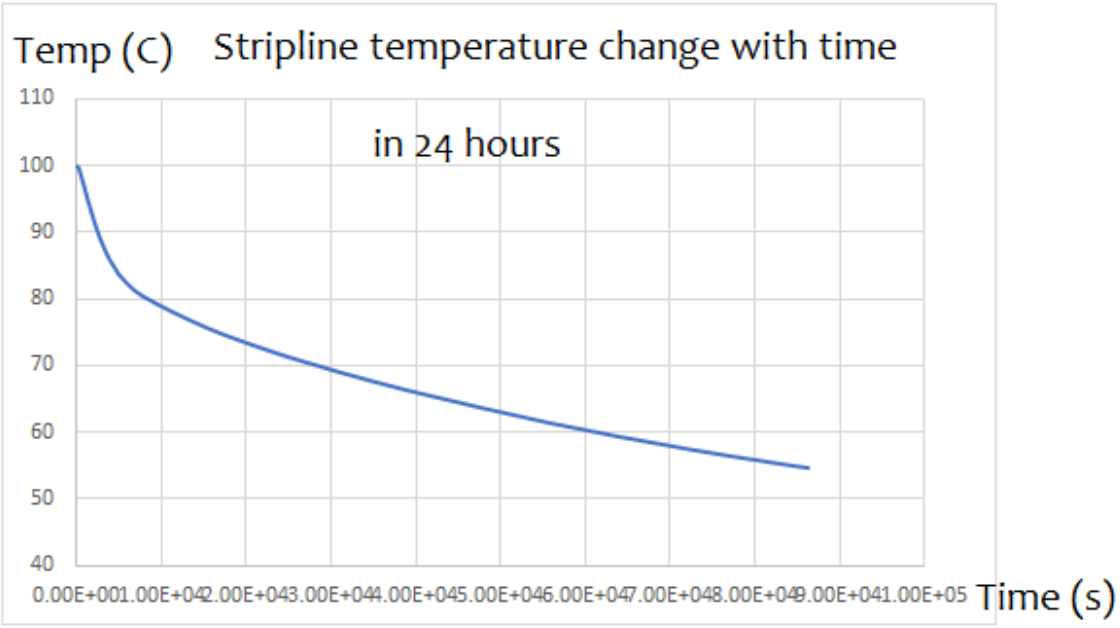

Figure 11. Strip line temperature in first 24 hours

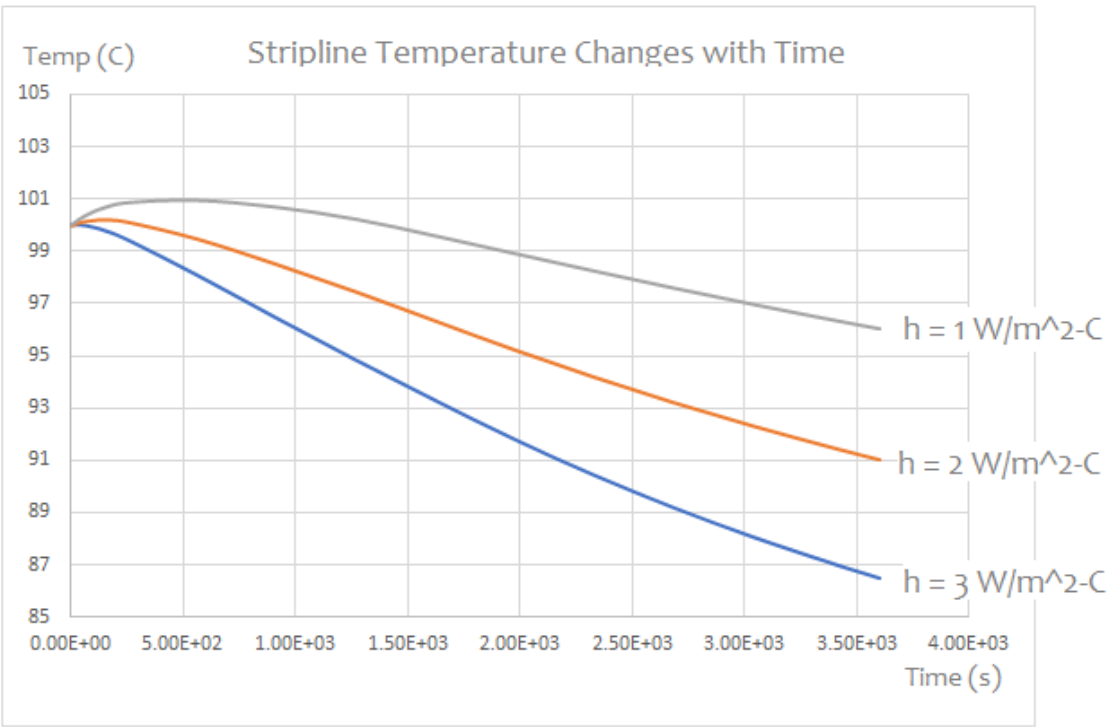

Figure 12. Stripline temperature with different free convection efficiency