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1 Introduction

This document outlines the design considerations and calculations made for Gaucho Racing's Pre-preg oven.

2 Design Requirements

2.1 TC350-1 Curing Requirements

Toray TC350-1 has two available cure cycles: Cure A and Cure B.

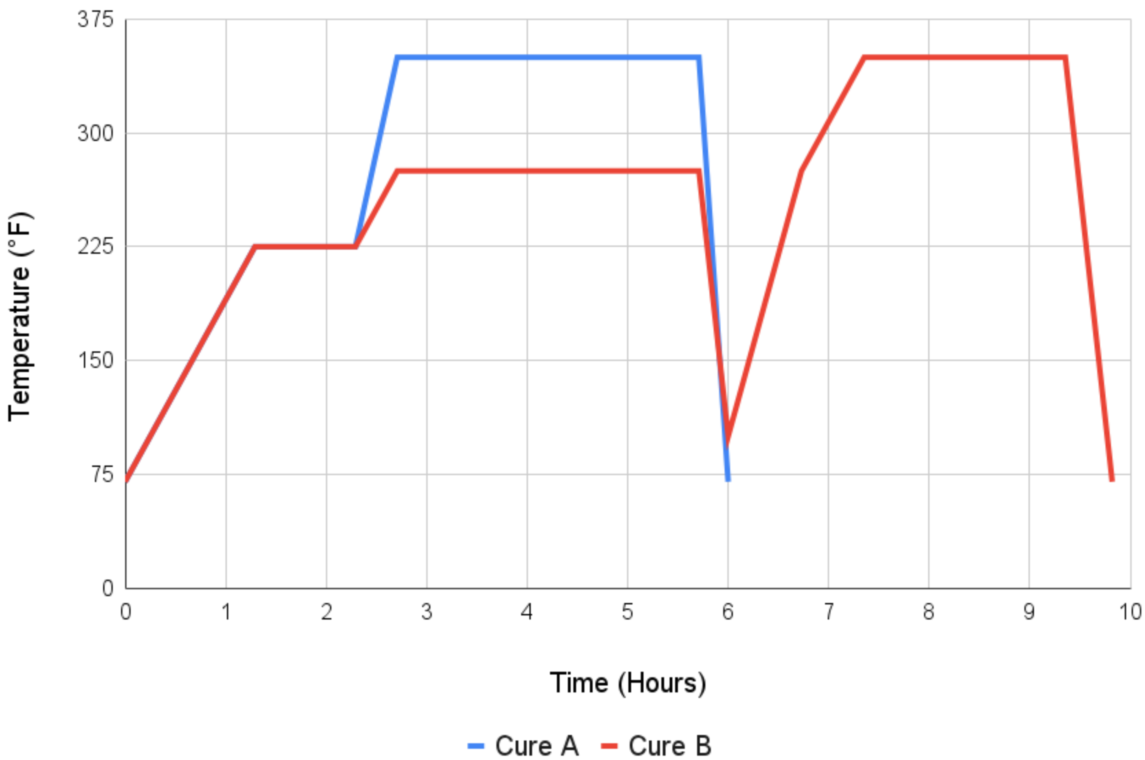


Figure 1: Curing Options for TC350-1 Pre-preg Carbon Fiber

Cure B partially cures the carbon fiber at a maximum of $275^{\circ}F$ at which point the tooling can be removed for the final cure to $350^{\circ}F$. For this reason, Cure B will be chosen to allow for cheaper tooling material.

- Withstand temperatures upwards of $350^{\circ}F$ for at least 10 hours.

- Be able to increase inner air temperature at a rate of $2^{\circ}F$ per minute.
- Be able to reduce inner air temperature at a rate of $10^{\circ}F$ per minute.
- Control chamber air temperature such that any point in the chamber is within $\approx \pm 5^{\circ}F$ of the target.

2.2 Size Requirements

The largest aerodynamic element currently designed for GR24 is the nosecone, which is approximately 3.5' x 2' x 2'. Adding an extra 6" on either side to ensure proper air circulation and allow space for the mold defines the minimum chamber dimensions. GR does not have enough storage space to store such a large footprint which requires the the oven to be able to be disassembled into panels for storage and transport.

- Chamber must be at least 4' x 2.5' x 2.5'.
- Panels must come apart.

2.3 Safety

- Outside panel temperature should not exceed $100^{\circ}F$.
- Clear identifiable kill switch
- Control logic so that the heating coils are turned off and an audible and visible alarm goes off if
  - The inner temperature exceeds $375^{\circ}F$.
  - The electronics box temperature exceeds $100^{\circ}F$.
  - There is no airflow.
- Control logic that cuts all power should any of the previous conditions persist for longer than a minute.
- Panels must not come apart during operation.

3 Design

3.1 Panel Design

Each oven panel will consist of a frame made out of 3 5/8" galvanized steel track and 3 5/8" galvanized steel studs. For insulation, we will be using R-15 Rockwool batt insulation, 23" x 47" x 3.5", see fig 4. The frame will be covered with 22 ga 1008 cold rolled steel on the inside and 22 ga A653 galvanized steel on the outside. In between the frame and both sheet steel skins will run fiberglass tape to

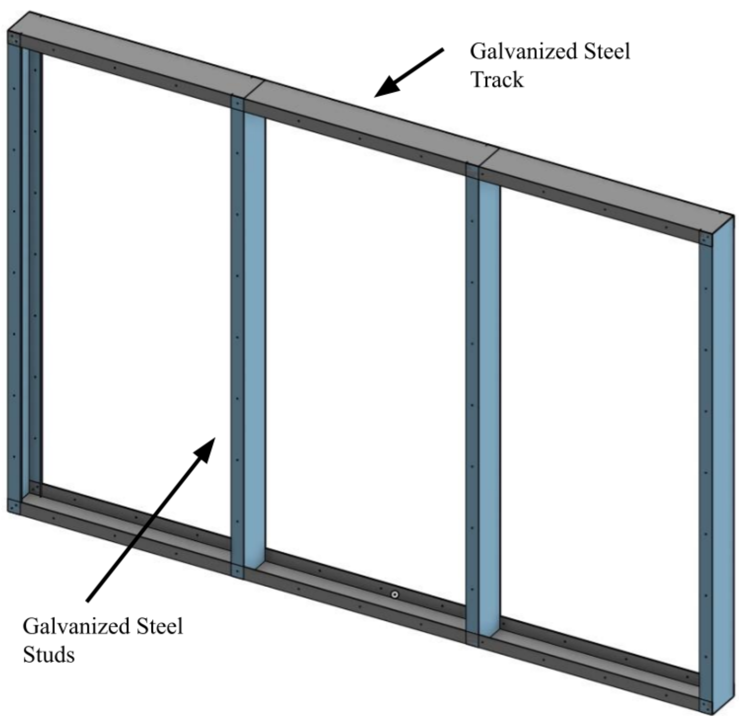


Figure 2: Panel Frame

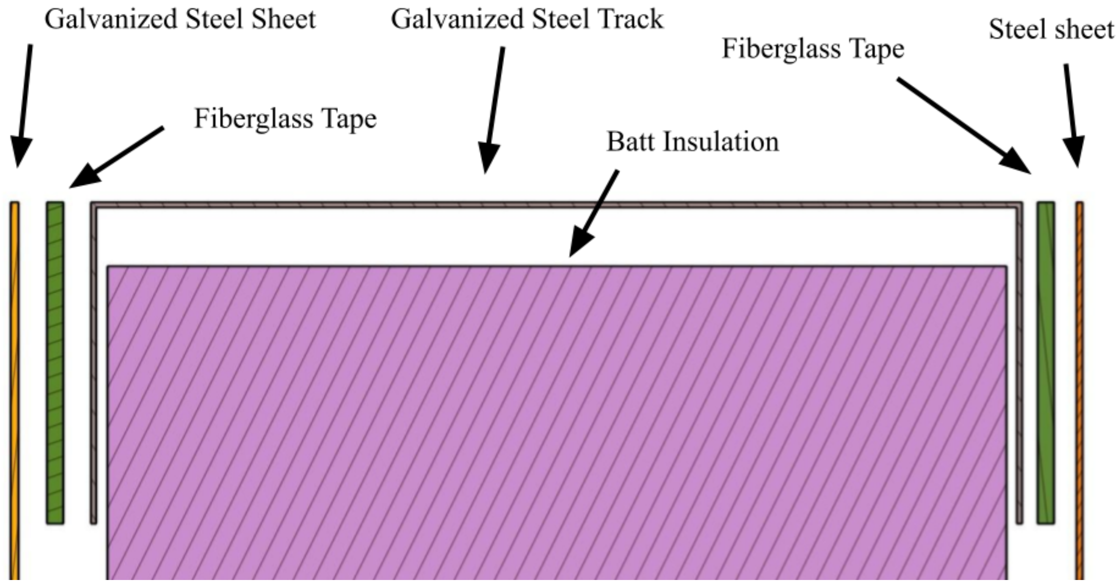


Figure 3: Panel Cross Section

reduce heat conduction, see fig 3. The inside sheet metal skin will be riveted to the frame through the fiberglass tape using 18-8 stainless steel blind rivets, the outside will be fastened using sheet metal screws. Using the dimensions of the batt insulation as a guideline we can find the dimensions of the inner chamber, which work out to be 5.75' x 3.9' x 3.3'.

3.2 Air Circulation

The oven will recirculate the air in the chamber to reduce energy consumption. This will be accomplished using a 1/45 hp blower fan rated for a temperature up to $450^{\circ}F$ which moves 96 cfm. The fan will be mounted to one of the small side panels near the top of the chamber and feed into a channel going to the bottom of the chamber. To approximate air velocity in the chamber we can divide the volumetric airflow by the small side panel cross-section of the chamber.

$$
\begin{aligned}
v &\approx \frac{96ft^3/min}{12.87ft^2} = 7.61\frac{ft}{min} \\
v &\approx 0.039m/s
\end{aligned}
$$

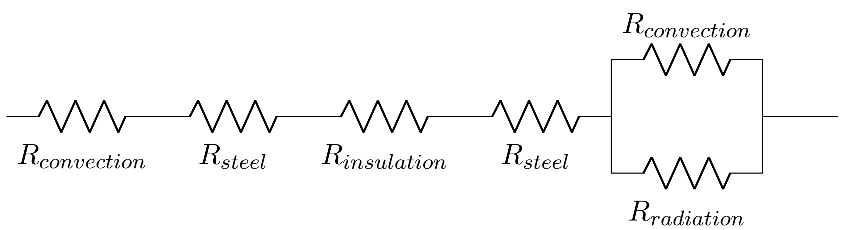
3.3 Heat loss

3.3.1 Thermal conductivity of insulation

$$
\begin{aligned}
R &= \frac{l}{\lambda} \\
\lambda &= \frac{l}{R} \\
\lambda &= \frac{0.0889m}{15R(SI)} \\
\lambda &= \frac{0.0889}{2.6415R(metric)} \\
\lambda &= 0.033\frac{W}{m^2K}
\end{aligned}
$$

3.3.2 Through Panel Insulation Cross Section

- $T_i = 450K$
- $h_i = 10\frac{W}{m^2K}$
- $h_\infty = 7\frac{W}{m^2K}$
- $k_{steel} = 48\frac{W}{mK}$
- $k_{rockwool} = 0.033\frac{W}{mK}$
- $h_{steel} = 0.0007m$
- $h_{insulation} = 0.0889m$
- $\mathcal{E}_{steel} = 0.5$



Outside radiation:

$$
\begin{aligned}
h_{rad} &= 4\mathcal{E}_0 T_m^3 \\
T_m &\approx 375K \\
h_{rad} &= 0.5 \\
h_{rad} &= 5.98\frac{W}{mK}
\end{aligned}
$$

Resistance equation:

$$\begin{aligned}
R_{tot} &= R_{convection} + R_{steel} + R_{insulation} + R_{steel} + \frac{1}{R_{convection} + R_{radiation}} \\
R_{tot} &= \frac{1}{h_1} + \frac{h_{steel}}{k_{steel}} + \frac{h_{insulation}}{k_{insulation}} + \frac{h_{steel}}{k_{steel}} + \frac{1}{h_2 + h_{rad}} \\
R_{tot} &= \frac{1}{10} + \frac{0.0007}{48} + \frac{0.0889}{0.033} + \frac{0.0007}{48} + \frac{1}{7 + 5.98} \\
R_{tot} &= 2.871\frac{m^2K}{W}
\end{aligned}$$

$$\begin{aligned}
q &= \frac{\Delta T}{R_{tot}} \\
q &= \frac{450K - 295K}{2.871} \\
q &= 53.99\frac{W}{m^2}
\end{aligned}$$

Outside skin temperature:

$$\begin{aligned}
\Delta T &= q * R_{OutsideWall} \\
\Delta T &= 53.99 * 2.79 \\
\Delta T &= 150.63K \\
T_{outside} &= 450K - 150.63K \\
T_{outside} &= 79.20^{\circ}F
\end{aligned}$$

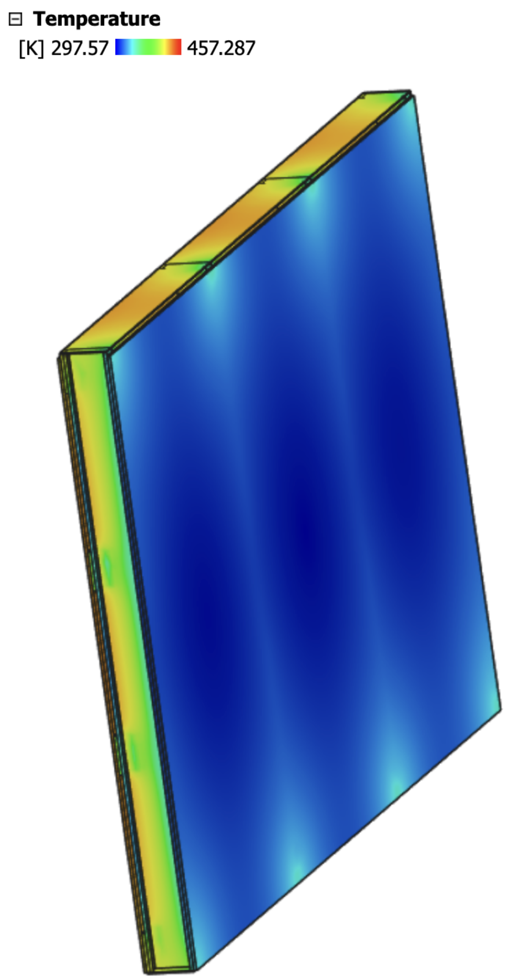


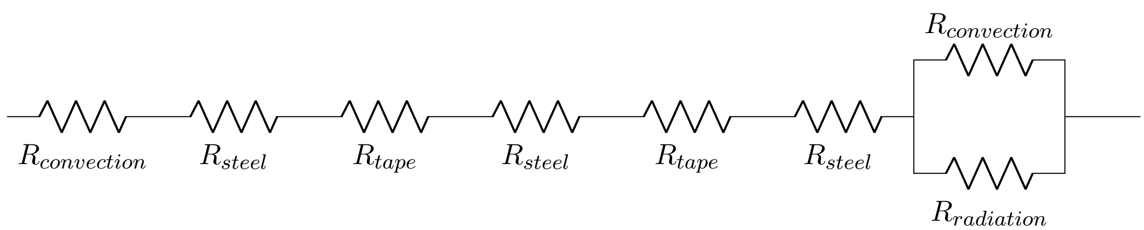
Figure 4: Frame Panel Thermal Simulation

Heat dissipation through insulated cross-sections of all panels:

$$
\begin{aligned}
Q &= qA \\
Q &= 53.99\frac{W}{m^2} * 10.08m^2 \\
Q &= 544.2W
\end{aligned}
$$

3.3.3 Through Panel Stud Cross Section

- $T_i = 450K$
- $h_i = 10\frac{W}{m^2K}$
- $h_\infty = 7\frac{W}{m^2K}$
- $k_{steel} = 48\frac{W}{mK}$
- $k_{tape} = 0.05\frac{W}{mK}$
- $h_{steel} = 0.0007m$
- $h_{tape} = 0.0032m$
- $h_{stud} = 0.0889m$
- $\mathcal{E}_{steel} = 0.5$
- $h_{rad} = 5.98\frac{W}{mK}$



Resistance equation:

$$
\begin{aligned}
R_{tot} &= R_{convection} + R_{steel} + R_{tape} + R_{steel} + R_{tape} + R_{steel} + \frac{1}{R_{convection} + R_{radiation}} \\
R_{tot} &= \frac{1}{h_1} + \frac{h_{steel}}{k_{steel}} + \frac{h_{tape}}{k_{tape}} + \frac{h_{stud}}{k_{steel}} + \frac{h_{tape}}{k_{tape}} + \frac{h_{steel}}{k_{steel}} + \frac{1}{h_2 + h_{rad}} \\
R_{tot} &= \frac{1}{10} + \frac{0.0007}{48} + \frac{0.0032}{0.05} + \frac{0.0889}{48} + \frac{0.0032}{0.05} + \frac{0.0007}{48} + \frac{1}{7 + 5.98} \\
R_{tot} &= 0.207\frac{m^2K}{W}
\end{aligned}
$$

$$
\begin{aligned}
q &= \frac{\Delta T}{R_{tot}} \\
q &= \frac{450K - 295K}{0.207} \\
q &= 748.8\frac{W}{m^2}
\end{aligned}
$$

Outside skin temperature

$$\begin{aligned}
\Delta T &= q * R_{OutsideWall} \\
\Delta T &= 748.8 * 0.13 \\
\Delta T &= 97.3K \\
T_{outside} &= 450K - 97.3K \\
T_{outside} &= 173.93^{\circ}F
\end{aligned}$$

Heat dissipation through all stud cross-sections

$$\begin{aligned}
Q &= qA \\
Q &= 748.8\frac{W}{m^2} * (22studs) * (1.03in^2) \\
Q &= 748.8\frac{W}{m^2} * 0.015m^2 \\
Q &= 11.23W
\end{aligned}$$

This value is insignificant and leads to the conclusion that the hot spots on the stud cross-sections would be barely higher in temperature compared to the temperature of the rest of the steel skin.

3.3.4 Total Heat Loss

From these calculations, we have a total heat loss through the oven at $350^{\circ}F$.

$$\begin{aligned}
Q_{tot} &= Q_1 + Q_2 \\
Q_{tot} &= 555.43W
\end{aligned}$$

3.4 Heating Air

The energy required to heat the air can be calculated using the specific heat of air and the specific heat of our tooling and carbon fiber. The oven panels are not sealed so the system is isobaric. We will assume that we are using MDF tooling. At $350^{\circ}F$:

$$\begin{aligned}
{C_{p(air)}}^1 &= 1.022\frac{kJ}{kgK} \\
{C_{p(carbonfiber)}}^2 &= 1.20\frac{kJ}{kgK} \\
{C_{p(MDF)}}^3 &= 2.00\frac{kJ}{kgK}
\end{aligned}$$

We will overestimate the amount of tooling material and carbon fiber, assigning 20kg of MDF and 10 kg of Carbon fiber. With no change in air volume. The energy required to heat the entire oven chamber from $70^{\circ}F$ to $350^{\circ}F$ can be found as follows:

$$
\begin{aligned}
Q &= \Delta T(m_{air} * c_{air} + m_{MDF} * c_{MDF} + m_{CF} * c_{CF}) \\
Q &= 155.6 * (2.10m^3 * 1.3\frac{kg}{m^3} * 1.022 + 20kg * 2 + 10kg * 1.2) \\
Q &= 8525.3kJ
\end{aligned}
$$

To fulfill our requirement of increasing inner air temperature at a rate of $2^{\circ}F$/min we would require:

$$
\begin{aligned}
P &= \frac{Q}{t} \\
P &= \frac{8525.3kJ}{8400s} \\
P &= 1.015kW
\end{aligned}
$$

3.5 Power Requirements

We have calculated values for the energy required to heat the inner chamber to $350^{\circ}F$ and maintain that temperature. We can approximate our power requirements by summing those two together:

$$
\begin{aligned}
P_{tot} &= P_{heating} + P_{losses} \\
P_{tot} &= 1.015kW + 0.555kW \\
P_{tot} &= 1.57kW
\end{aligned}
$$

Electric resistance heating is 100% efficient but there will be losses through the circuit and wiring so we will assume a 90% efficiency.

$$
\begin{aligned}
P_{required} &= \frac{P_{tot}}{0.9} \\
P_{required} &= 1.74kW
\end{aligned}
$$

We are planning on using two 1,440 W heating elements:

$$
P_{available} = 2.88kW
$$

[1]https://www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html?vA=350&degree=F&pressure=1bar
[2]https://www.matweb.com/search/datasheet.aspx?matguid=39e40851fc164b6c9bda29d798bf3726&ckck=1
[3]https://www.researchgate.net/publication/270918141_On_Determining_Density_and_Specific_Heat_of_New_Zealand_Medium_Densit

3.6 Maximum Temperatures

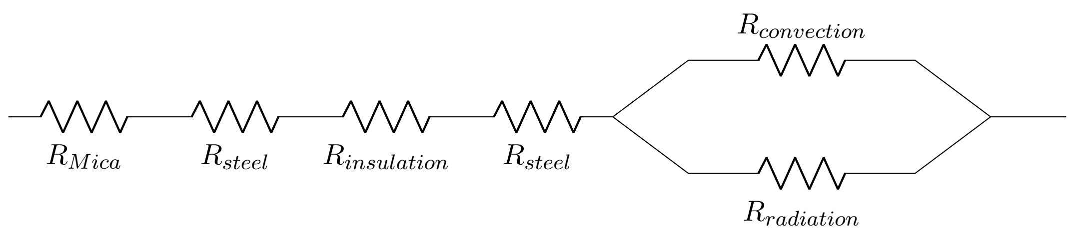
3.6.1 Temperature of Panel Behind Heating Elements

- $Q_{in} = 2.88kW$
- $\rho = 0.6\frac{kg}{m^3}$
- Isobaric Air flow $T_\infty = 22C = 72F$
- $\dot{V} = 96\frac{ft^3}{min} = 0.0453\frac{m^3}{s}$
- $C_{air} = 1.007\frac{kJ}{kgK}$

As the oven reaches its maximum temperature, the air being drawn into the heating element will be around 350F (176.7C), and must enter the oven at an elevated temperature carrying energy from the source. Let the energy input be the maximum energy of the source.(kW).

$$\begin{aligned} Q &= \rho\dot{V}C_{air}(T_{out} - T_{in}) \\ T_{out} &= T_{in} + \frac{Q}{\rho\dot{V}C_{air}} \\ T_{out} &= 176.6 + \frac{2.87}{0.0453 * 0.6 * 1.007} \\ T_{out} &= 282°C \end{aligned} \tag{1}$$

Let this $282°C$ be the driving temperature of heat transfer, and now we can find the temperature of the outer wall.



$$R_{Mica} = \frac{0.15mm}{0.3\frac{W}{mK}} = 0.0005\frac{Km^2}{W}$$

$$R_{steel} = \frac{0.5mm}{60\frac{W}{mK}} = \ negligible$$

$$R_{ins} = \frac{0.0889m}{0.033\frac{W}{mK}} = 2.69\frac{Km^2}{W}$$

$$R_{conv} = \frac{1}{7\frac{W}{m^2K}} = 0.143\frac{Km^2}{W}$$

$$R_{rad} = \frac{1}{0.6(4)(5.67\times10^{-8})(313K)^3} = 0.239\frac{Km^2}{W}$$

$$R_{tot} = 0.0005\frac{Km^2}{W} + 2.69\frac{Km^2}{W} + 0.0895\frac{Km^2}{W} = 2.779\frac{Km^2}{W}$$

$$q = \frac{T_{out}-T_{\infty}}{R_{tot}} \implies q = 94\frac{W}{m^2}$$

$$q = \frac{T_{out}-T_{wall}}{2.69} \implies T_{wall} = 30.3C \approx 87F$$