# Reflow Oven

MENG 4352: Thermo-Fluid Design

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By:

Hunter Creery

Peyton Creery

Kevin Wong

Tyler Yada

Purchaser:

(Lucas Creery)

Sponsors:

(Hand Industrial)

Submitted To:

Dr. Roy J. Issa

Department of Engineering, Computer Science and Mathematics

West Texas A&M University

# Executive Summary

With the rapid advances in technology and the increase of hobbyists making their own electrical components, there is a need for a more efficient manner of effectively soldering electrical components. With the use of solder reflow ovens in-place in mass production companies, the desire for a reflow oven that a hobbyist can build and use also arises. This project began by an individual who had reached out and was interested in owning a reflow oven that could operate efficiently and had a price competitive in todays' market. After research, it was determined that a hobbyist with a budget around $500.00 could design and build their own reflow oven. With the help of some individuals, the group was able to reuse some parts and recycle some material that benefited the cost of production. It was determined that the insulation material for the reflow oven could be obtained from a recycled home oven which was composed of ceramic fiber. The wall material for the oven was donated by Hand Industrial which was expected to be the highest expense of the design budget. Having Hand Industrial donate the stainless steel that was used for the walls allowed the group to focus on buying the correct heating elements and electrical components for the oven. After testing the oven at the appropriate time versus temperature profile, the outer wall of the oven was found to be 99˚F. By OSHA standards this temperature would allow the user to safely operate the oven with little concern of physical harm to the individual in the environment the oven would be placed in.

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# Nomenclature

| Symbol | Units | Definition |
|---|---|---|
| f | | Ratio of rigid wall thickness to overall thickness for freezer wall |
| k | W/(m*K) | Thermal conductivity coefficient |
| A | $m^2$ | Average area of wall |
| $\Delta T$ | K | Change in temperature |
| $E_{flex}$ | GPa | Flexural modulus of selected material |
| t | Inches | Thickness |
| K | | Coefficient for shear factor |

# Objectives

The main objective was to design and build a solder reflow oven within a given timeframe that would not exceed the set budget while meeting the expectations of the customer. This project was meant to utilize and showcase the groups' knowledge of thermodynamics and fluid mechanics. By properly designing and analyzing the oven, this would allow the customer to be satisfied with their machine. The intent of this oven was to be used for academic and personal projects by a hobbyist. The oven utilizes thermal radiation of a quartz heating element for reflow soldering electronic surface components to a printed circuit board. Most reflow ovens cost upwards of $1,000, so we set our objective to reduce the price by half by scraping material.

# 1 Introduction

As technology progresses and gets more advanced, the footprint of circuit components enlarges and is becoming more relied on in everyday life. The reflow oven presented in this report has the capability to reflow solder electronic components on a printed circuit board using leaded and non-leaded solder paste. The oven is composed of stainless-steel inner and outer walls while being insulated with ceramic wool to minimize heat loss. A PID, proportional-integral-derivative, equation-based controller is used to regulate the temperature given off by quartz heating elements.

## 1.1 Design Process

To begin the design process identification of need is required, which in this case is to solder electronic surface mounted components to a printed circuit board. The next step is the definition of problem which addresses the need with a solution. To contact the electronic components to the circuit board using solder paste, a reflow oven will be constructed. Since this design will be utilized for academic or personal projects, a reasonable budget and design must be developed. In the synthesis step various design concepts are presented and a cumulative solution is decided upon. Analysis and optimization are where academic knowledge of heat transfer is applied to show that the design works as intended. The evaluation process involves testing the machine and redesigning if necessary. Optimization may also occur in this part of the process. Lastly, presenting all aspects of the design will help others, like potential customers, understand how the oven works and the limitations of it.

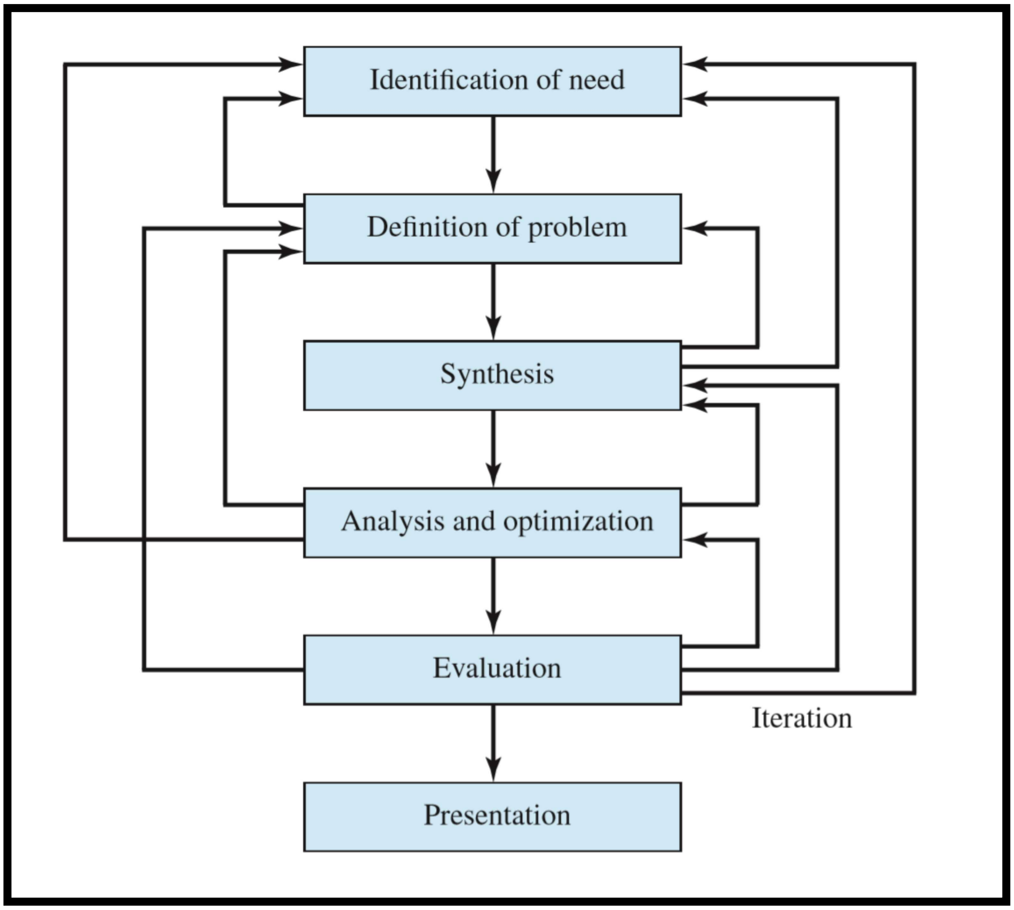


*Figure 1. Design Process Flowchart*

## 1.2 General Design Requirements

Engineers need to satisfy everchanging policies, codes, economic standards, and exceed levels of safety and liability. There are many other design aspects to examine such as corrosion, sustainability, marketability, noise, and so on. A general mechanical design needs to meet or exceed the expectation of all of these while providing a product that is very functional and reliable. Functionally the reflow oven needs to reach a maximum temperature of 400°F for a short period of time. This temperature is hot enough to allow leaded and non-leaded solder paste apply the electronic components to the circuit board. There will not be any need for an exhaust system since the oven will be designed to handle small loads. This reflow oven will not be built for commercial use. The budget set for the oven is $500 which is very reasonable as the costliest materials will be reused from scrap. An example of this is the ceramic wool insulation that will be reused from a small, older kitchen oven to minimize heat loss and provide safety to the customer. “Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.” [1]

## 1.3 Problem Definition

### 1.3.1 Scope

The problem that this group is solving is creating a design for a reflow oven that any hobbyist could make on their own time. Core components of the problem involved analyzing and designing a reflow oven that met the performance, reliability, and safety of current models in production at a more average consumer cost. A small reflow oven cost starts at $800 and becomes more expensive from there. Being cost effective while maintaining the same, or better, performance of other reflow ovens on the market is an area that is going to be addressed.

### 1.3.2 Technical Review

The customer would like a reflow oven built for small projects at a low cost while maintaining stellar performance. The dimensions for the reflow oven will depend upon the projects the customer will be doing. Projects would include anything from the circuit board used for a key fob to the motherboard for a fifteen-inch laptop. The most safe and efficient way of creating contact between the circuit board and the electrical surface components is to apply solder paste to the board, lay the electrical components on top of the paste, then put all components into a reflow oven. The oven will produce enough energy to allow the solder paste to melt while not damaging any additional components. Natural convection will allow the solder to harden for good contact between parts. An individual could argue that a kitchen oven would work, but that person would be incorrect because a household oven does not reach the desired temperature fast enough. We purposely made the feet of the oven have a metal contact that way the oven will be grounded. This will ensure that the PCB board will not be affected by any electrostatic discharge. As a group, the goal is to produce a safe, reliable, and cost-effective machine to perform up to the needs and standard of the customer’s expectations.

### 1.3.3 Design Requirements

The most crucial goal of the design to meet is the efficiency of the oven. Two objectives rely on how efficient the oven is under operation. First, the performance of the oven is directly proportional to how efficient it is. If the processor and elements can effectively reach the temperature profile within its given time, then the solder paste being heated will have a high success to bond the components and board when melting. Secondly, how efficient the oven is will boost the sustainability of the oven. Again, directly related to the performance, the heat loss from the oven is excess energy being consumed by the oven. That energy, in the form of electricity, is lost when the oven's performance is deficient.

### 1.3.4 Constraints

Constraints set by the group while designing this project were budget, tool access and fabrication. The budget set by the customer was five hundred dollars and this group was determined to complete the project with far less than that with the help of donations and recycling. Access to tools was not a concern once the design was settled on, and the materials were chosen. The fabrication of the prototype was done through welding which was done by a group member who is a professional welder. Further, access to a CNC laser was available through the workplace of a group member. The CNC laser was used to cut components necessary to complete the build. Many of the components were found within the local area, and only minimal parts were outsourced. The ordering of these outsourced parts was done early in an attempt to gain part access early on for testing and analysis.

# 2 Concept Design

## 2.1 Ideas/Concepts Proposed

Figure 2 is a concept where the user would lift a lid and insert the PCB board into the oven. Once the PCB board has been placed inside the user would operate the oven as desired. After the operation has been completed the user would then open the clam like cover and remove the PCB board. This concept was deemed unfavorable due to the safety concern of potentially having the door that has been heated falling on the user while the user is reaching into the hot oven.

*Figure 2 Lid Concept*

Figure 3 is the drawer concept that allows the user to operate the oven by placing the PCB board on the drawer that is attached to the door. This unit slides out allowing the board to be removed from the internal part of the oven where the source of the heat is located. This concept was not used due to the door section of the drawer still being attached to the drawer and the amount of possible heat that could be within the material. This could cause harm to the user due to the door being in the way.

*Figure 3 Drawer Concept*

Figure 4 is the door concept which has a door that can move out of the way of the operator. This concept allows for the user to place a PCB board on a piece of expanded metal shelf. This concept was modeled after a simple home oven. It was determined that this concept would allow for the highest safe operation.

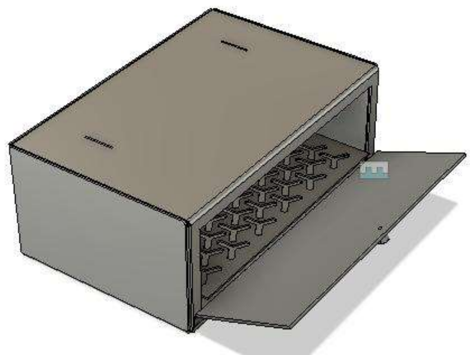

*Figure 4 Door Concept*

## 2.2 Selection of Design Concept

For the design that was created, three Pugh Matrices were made to evaluate what overall design was going to be used as seen in

*Table 1 through*

Table 3.

Table 1 Design Pugh Matrix

| Pugh Matrix Design | | Drawer | Lid style | Door Style |
|---|---|---|---|---|
| Ease of Use | 3 | 0 | -1 | 1 |
| Safety | 4 | 0 | -1 | 1 |
| Ease of Manufacturing | 2 | -1 | 0 | 1 |
| Ability to heat | 1 | -1 | 0 | 1 |
| Total | | -7 | -6 | 13 |

*Table 2 Design Shell Material Pugh Matrix*

| Pugh Matrix Materials | | Stainless steel | Aluminum | Low Carbon Steel |
|---|---|---|---|---|
| K Value | 5 | 1 | -1 | 0 |
| Cost | 1 | -1 | 0 | 1 |
| Embodied Energy | 4 | -1 | 1 | 1 |
| Co2 | 3 | -1 | 1 | 1 |
| Max Temp. | 2 | 1 | -1 | 0 |
| Total | | -1 | 0 | 8 |

*Table 3 Design Insulation Pugh Matrix*

| Pugh Matrix Insulation | | Ceramic Fiber | Air | Expanding Foam |
|---|---|---|---|---|
| Max Temp | 3 | 1 | 0 | -1 |
| Availability | 1 | 0 | 1 | -1 |
| K- Value | 2 | 1 | -1 | 0 |
| Total | | 5 | -1 | -4 |

### 2.2.1 Criteria and scaling

For the Pugh Matrices a scaling was applied that gave the higher priority a larger value. This scaling system was then applied to the remaining constraints accordingly. The components that where being evaluated where then given a rank of -1, 0, or 1. The scale system is used to determine how the components fit the constraints for the design. If the component did not meet the constraint it was given a rank of -1, if it met the constraint it was given a rank of 0, and if the component exceeded the constraint it was given a scale of 1. After all the components had been evaluated with the constraints, the score was calculated by multiplying the rank by the scale of each constraint, then the sum of the values was compared. The component with the highest score would be the components used in the design.

### 2.2.2 Design/Pugh Matrix

When looking at the final design concept compared to other concepts, the design has a function that allows for the user to have a safe operation feature. This is shown by the platform that the PCB board sits on. The platform has the concept of a traditional home oven where a grate is used for the circuit board to lay. This ensures that the user will have a small chance of ever encountering any surface that is hot enough to cause permanent damage to the user in the form of burns. With the door of the oven latched with a simple locking system, and open and close with the use of hinges, this allows the user to have an easy time operating the oven with consistency. The design of the oven was done with the notion of making it as easy as possible to construct. This was done by designing the oven in a way that only a few simple tools would be necessary to construct the oven if anyone wanted to reproduce the design on their own. Due to the orientation of the heating elements in the oven, it allows for a consistent heating of the PCB board for multiple attempts. The heating elements have been placed on the ceiling of the inner shell giving the PCB board direct heat resulting in a faster heat up time and resulting in the oven being able to produce more than one soldered board in a day.

# 3 Design Description

## 3.1 Component Design:

The key factors for this design are the insulation of the oven and the structural strength of the enclosure. Through calculations the optimal material thickness combined with insulation thickness can be found for an optimal efficiency for the design of the reflow oven.

### 3.1.1 Oven Wall Material Selection

The first and obvious design that the group needed to know was the materials and thickness of the oven wall. With the limited selection of materials as the constraint for the project, the group began to analyze the oven walls. Several combinations of wall and insulation pairs were created to find which would be most thermally efficient all while being structurally sound. The combined thermal conductivity can be represented as a function shown in Equation (1), from [2].

$$k_{eff}\left(k_{wall}, k_{core}, f\right) := \left(\frac{f}{k_{wall}} + \frac{1-f}{k_{core}}\right)^{-1} \tag{1}$$

with $f$ representing the ratio of wall thickness to overall thickness

$$f = 2\,\frac{t}{d} \tag{2}$$

Similarly, the effective Flexural Modulus of the composite material, referenced from Eq. 11.18 in [3], can be represented as the following,

$$\frac{1}{E_{flex}} = \frac{1}{12} \cdot \frac{1}{E_f \cdot \left(\left(1-(1-f)^3\right) + \frac{E_c}{E_f} \cdot (1-f)^3\right)} + \frac{B_1}{B_2} \cdot \left(\frac{d}{L}\right)^2 \cdot \frac{1-f}{G_c} \tag{3}$$

Since the group is only concerned with bending per unit length for the optimization, the term quantifying length ($L$) and Shear Modulus ($G_C$) of this equation can be eliminated. The insulation modulus of Elasticity can be assumed to be zero and any scaling of the equation will render no change to the comparison. In result, the equation for Flexural Modulus in this case is

$$E_{flex}\left(E_f, f\right) := \left(1-(1-f)^3\right) \cdot E_f \cdot K \tag{4}$$

Graphing four different combinations of Aluminum, Stainless Steel, Ceramic, and Flexible Foam, yielded the following graph.

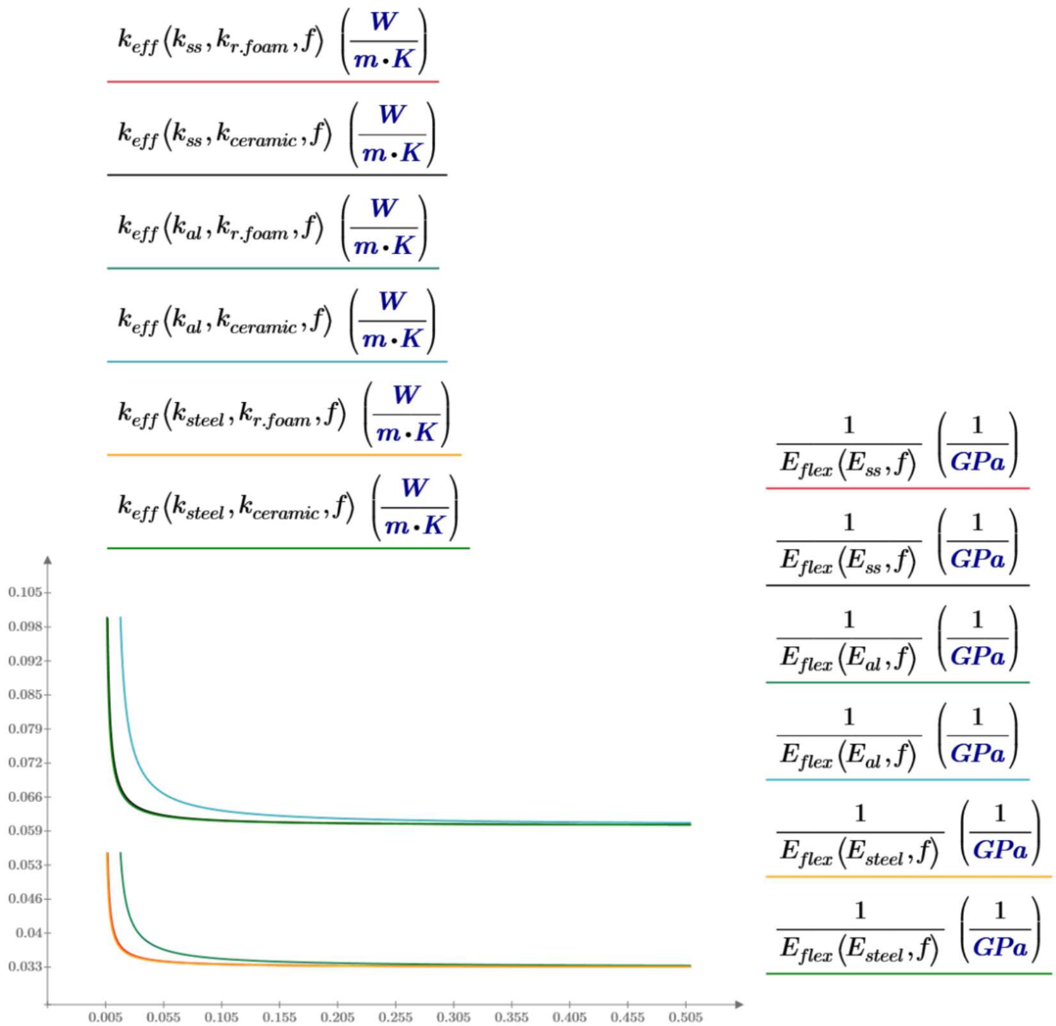


*Figure 5 Component Version Comparison*

The closest value to the origin of this plot represents the greatest value of thermal insulation and strength. From Figure 5 the stainless steel combined with the ceramic wool gives the closest value to the origin of the graph. This concluded that the combination of Stainless steel and Ceramic wool would be the best pick for the oven.

### 3.1.2 Oven wall thickness ratio

To further expand on this analysis, the ratio of these materials that has the greatest value of thermal insulation and strength can be determined. A function can be created to determine the effective thermal conductivity combined with Flexural modulus for the selected materials.

$$F(f) := \frac{1}{E_{flex}(E_{ss}, f)} \cdot k_{eff}(k_{ss}, k_{ceramic}, f) \cdot (1 \cdot 10^{14}) \tag{5}$$

This function is multiplied by a large number to scale it for calculation accuracy. The number that this function represents is smallest when thermal conductivity is the least and flexural modulus is the greatest. This can be plotted with respect to wall thickness ratio to create the following graph.

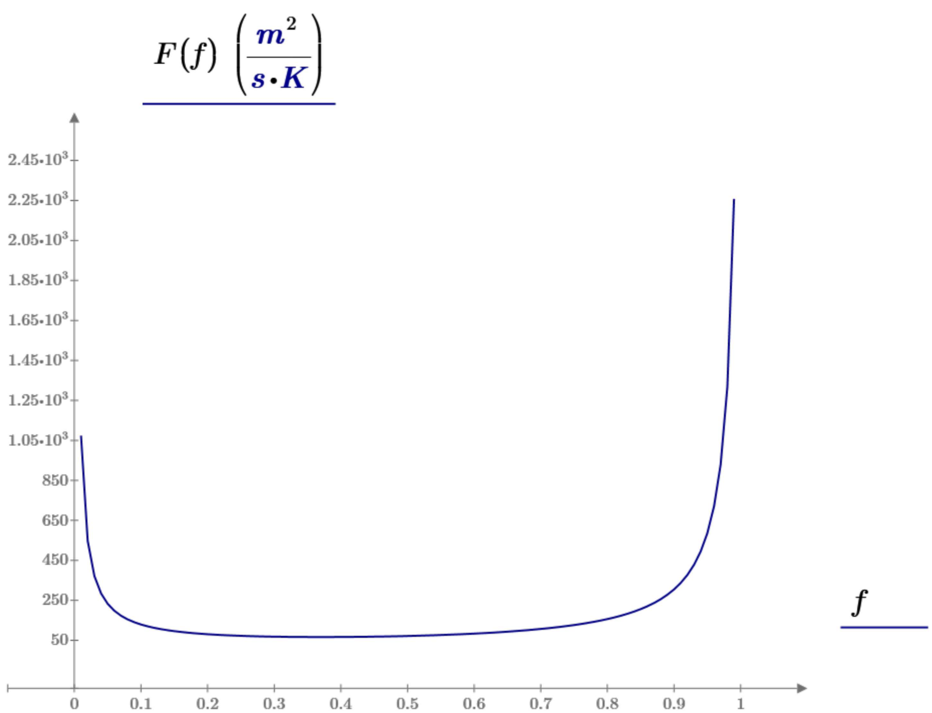


*Figure 6 Thermal Conductivity with Flexural Modulus*

From this graph, it is seen that the ideal wall to thickness ratio lies somewhere between 0.1 and 0.9. Computer tools are then utilized to find the minimum value of F.

Guess Values

$$f := 0.1$$

Constraints

$$f < 0.9 \qquad f > 0.1$$

Solver

$$f_{min} := \mathbf{Minimize}(F, f) = 0.371$$

*Figure 7 Wall Thickness Ratio*

### 3.1.3 Oven Insulation Thickness

The group decided to base the thickness of the insulation on setting a constraint at the surface temperature of the oven at steady state conditions. According to IEC's 60950-1, the recommended temperature for metal surfaces should remain at or below 140°F. The reason for this is that the average person can touch a 140°F surface for up to five seconds without sustaining irreversible burn damage, [4].

Using the resistance method for one dimensional steady-state conduction, convection, and radiation, eq. 3.17 of [2], heat transfer through the wall can be found.

$$q_{ceramic}(w) := \frac{T_0 - T_\infty}{\dfrac{1}{h_i \cdot A_i} + \dfrac{w_{ss.i}}{k_{ss} \cdot A_i} + \dfrac{w}{k_{ceramic} \cdot \dfrac{(A_i + A_o)}{2}} + \dfrac{w_{ss.o}}{k_{ss} \cdot A_o} + \dfrac{1}{h_o \cdot A_o}} \tag{6}$$

This equation is under the assumption that the internal wall, made of polished stainless steel, is ideal and completely reflects any radiation, thus greatly simplifying the equation and eliminating further assumptions. The convection heat transfer coefficient for inside and outside the box also has an assumption of a constant film temperature. Once the heat transfer is found, it then can be plugged back into the steady-state conduction equation, without external convection, to find the surface temperature, at a given thickness, *w*.

$$T_{s2.ceramic}(w) := -\left(q_{ceramic}(w) \cdot \left(\frac{1}{h_i \cdot A_i} + \frac{w_{ss.i}}{k_{ss} \cdot A_i} + \frac{w}{k_{ceramic} \cdot \frac{(A_i + A_o)}{2}} + \frac{w_{ss.o}}{k_{ss} \cdot A_o}\right) - T_0\right) \quad (7)$$

This is then plotted to find the ideal wall thickness that allows for a surface temperature that permits human touch. Since this equation has assumptions, and the IEC's 60950-1 [4] is the maximum limit of recommended temperature, the group decided to shoot for an insulation thickness that would give a temperature below suggested. Figure 8 shows surface temperature of ceramic wool insulation (brown line) at different thicknesses, w, alongside an insulation of just air (blue line).

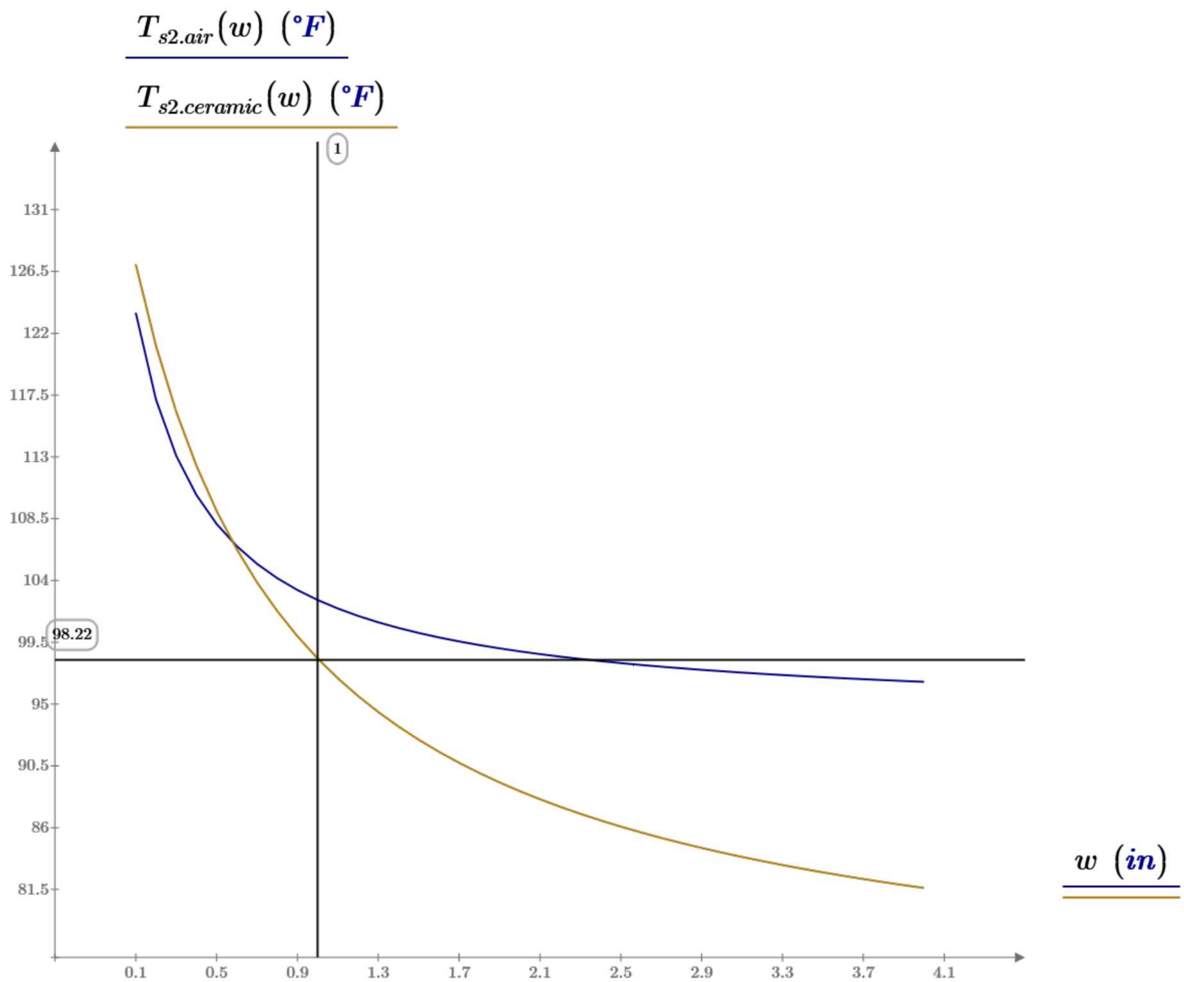


*Figure 8, Surface Temperatures of oven at different insulations and thicknesses*

From Figure 8, we can see that the ceramic wool (brown line) at one inch gives an approximate temperature of 99˚F, which makes the outer surface safe to touch for the user.

We can then plug this value back into the definition of $f$, Equation (2), to find the ideal wall thickness with respect to the determined insulation thickness of one inch.

$$\frac{f_{min} \cdot 1.\ in}{2} = 0.186\ in \tag{8}$$

### 3.1.4 Transient Conduction

Once the thickness is found then, for an extra measure, we were able to plot the one-dimensional transient conduction of the wall on a three-dimensional graph. There are many methods of deriving and implementing the equation for transient conduction. Our initial method of solving was the Forward Euler method. To briefly explain, this method utilizes either a forward or backward point and derivative of time to numerically solve the next plot with a given derivative equation. We apply the heat equation derivative given that includes transient conduction to the method to solve for the temperature gradient across the insulation with respect to time.

$$k \cdot \frac{d}{dx}\left(\frac{d}{dx} T\right) + q = \rho \cdot c_p \cdot \frac{d}{dt} T \tag{9}$$

This method accuracy is limited and with a high diffusion number, a function of $\Delta t$, $\Delta x$, and material properties, the results are numerically instable. Another method that is most accurate is the Crank Nicholson Method which is a combination of both the forward and backward Euler method but is not the average of both. The results of this method are shown below with the Z-axis (pointing left) being the thickness, the X-axis (pointing right) is the time, and the Y-axis (vertical) as the temperature.

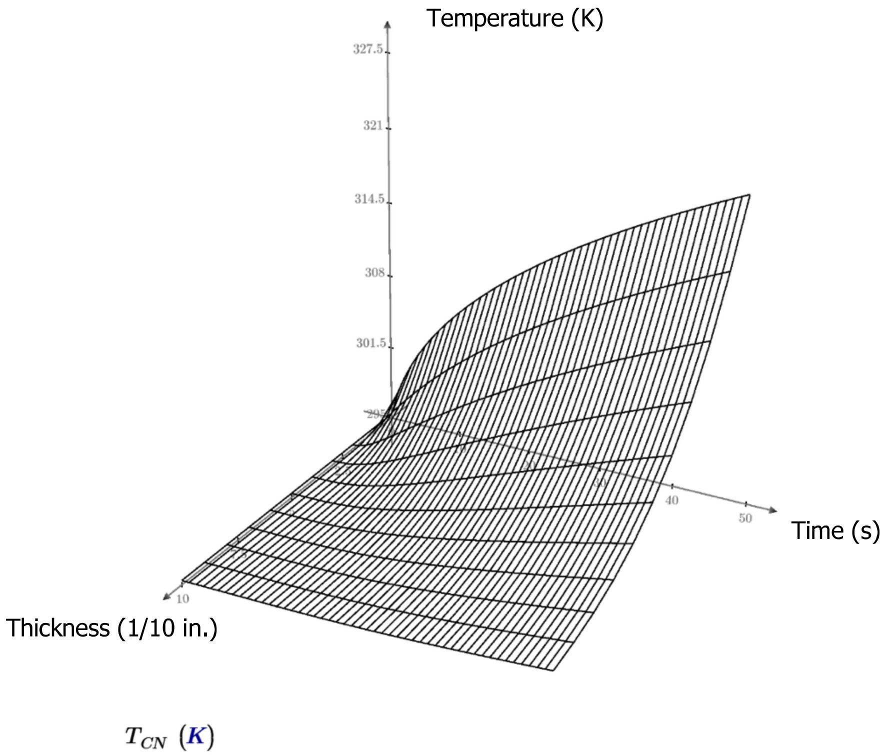


*Figure 9 Transient Conduction*

Figure 9 plots the temperature gradient of one-inch ceramic fiber insulation over one minute.

### 3.1.5 Circuit Layout

The central brain of the reflow oven is a Raspberry Pi equipped with Wi-Fi. The oven monitoring utilizes a Thermocouple attached to a MAX31855 "analog-to-digital" breakout board for the raspberry pi to comprehend. The picoReflow software on the pi then reads the input and controls the output based on the desired temperature. To output, the pi is hooked to a solid-state relay, that is then what switches the heaters on and off accordingly as seen in Figure 10.

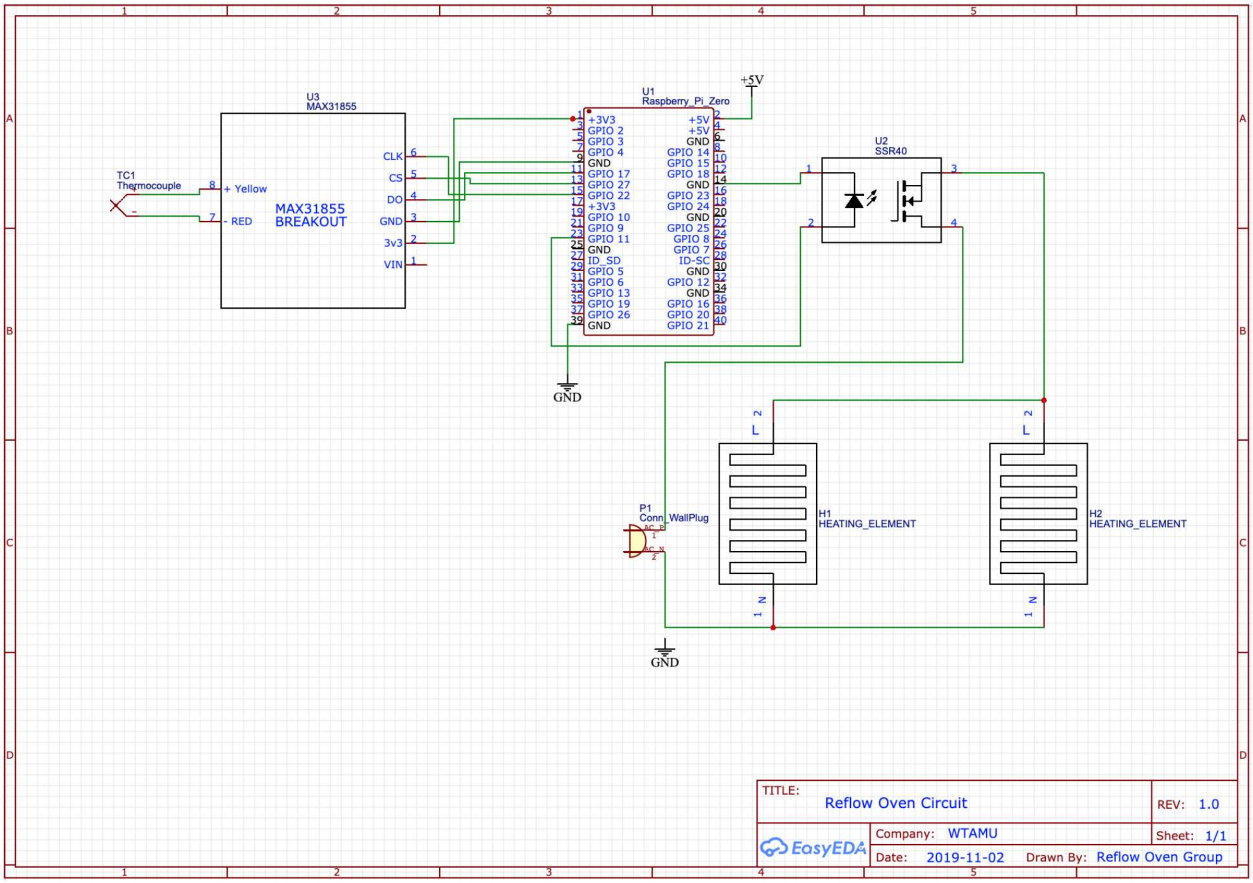


*Figure 10 Circuit Diagram*

## 3.1.6 Life Cycle Assessment

As responsible engineers, we also went the extra measure to perform an LCA (Life Cycle Assessment) in order to further provide a foundation for material selection. For our LCA, we compared the same materials as in 3.1.1 (Material Selection), a combination of Stainless Steel, Carbon Steel, or Aluminum with Ceramic Fiber or Rigid Foam. After gathering material properties, energy use, and environmental impact, our group compiled a representation of comparison of materials in those fields.

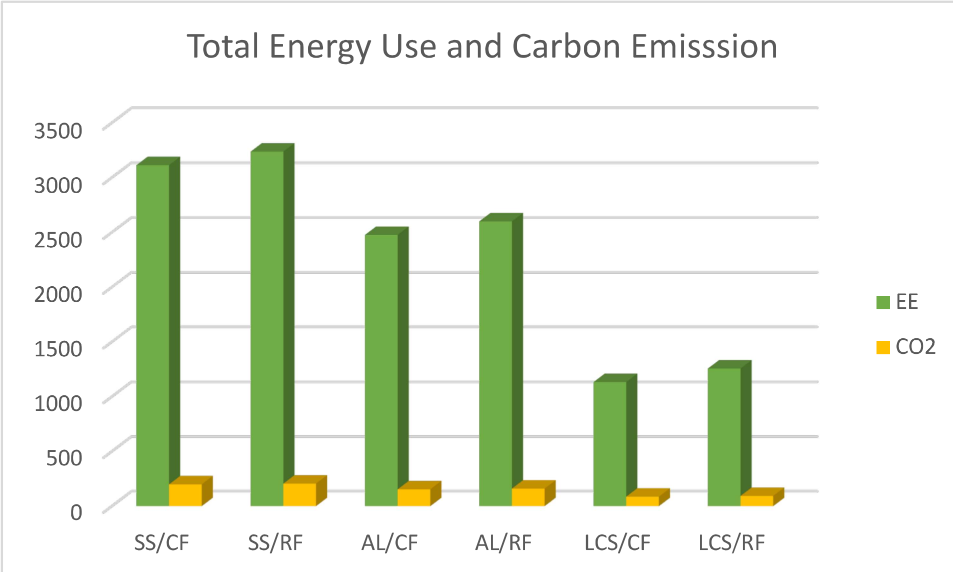


*Figure 11. Energy Use and Carbon Emission Comparison*

From this chart we can see that the Aluminum combined with ceramic fiber is the most environmentally friendly in terms of both Embodied Energy and Carbon Dioxide emission. Although our material has already been selected, this chart can be used as another means of material selection. The LCA of our material can be further broken down into four major categories, Material gathering, Material Processing, Use, and End of Life energy.

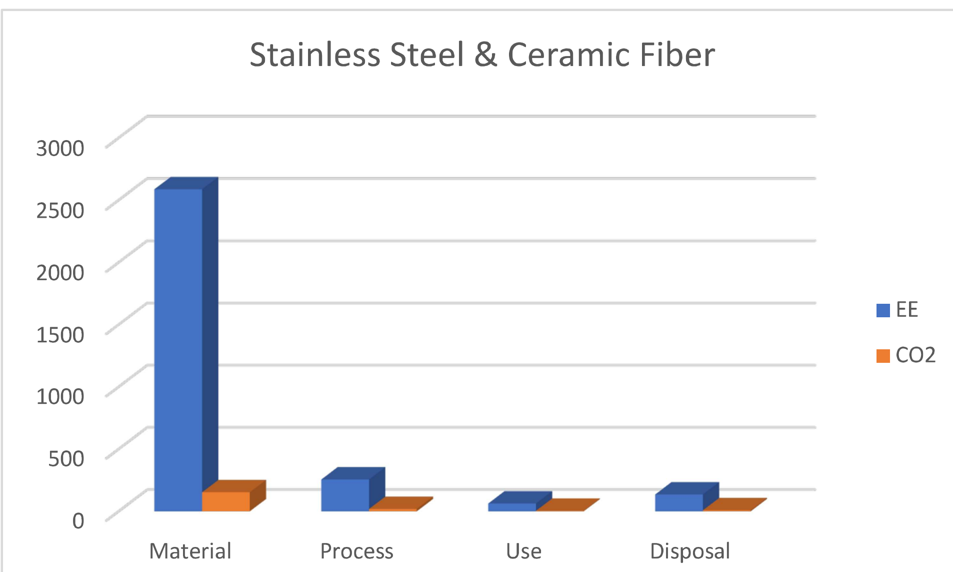


*Figure 12 LCA of Stainless Steel and Ceramic Fiber*

From this chart, the reader can see that that material gathering of theme materials has a large impact on the Embodied Energy (energy use) out of the four phases.

## 3.2 Dimensioning and Assembly

The inside dimensions of the reflow oven were designed to accommodate a large circuit board, such as a motherboard for a laptop. The inside dimensions chosen were 18 inches wide, 12 inches deep, and 6 inches tall. Ideal thickness for ceramic fiber insulation for the oven was found to be 1 inch and the optimal thickness of the stainless-steel walls was found to be 0.186 inch. Since at 0.186-inch-thick sheet of steel is not standard in the industry, a 0.125-inch stainless steel sheet was used for the walls. The dimensions of the geometry from the front view are shown in Figure 13.

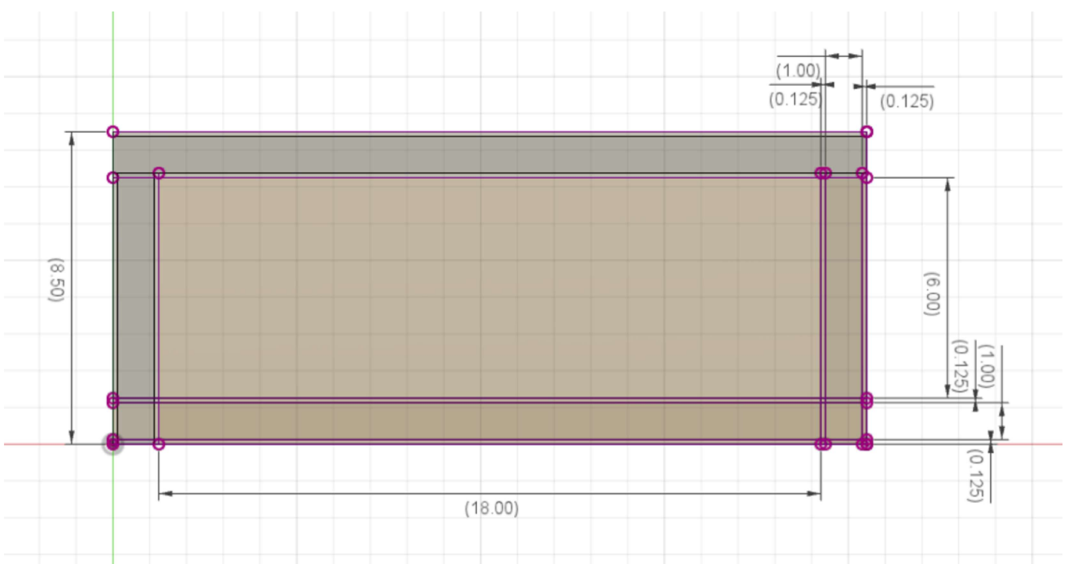


*Figure 13. Front View Dimensions of Reflow Oven. (Units: Inches)*

A bottom view with dimensions of the oven is given in Figure 14.

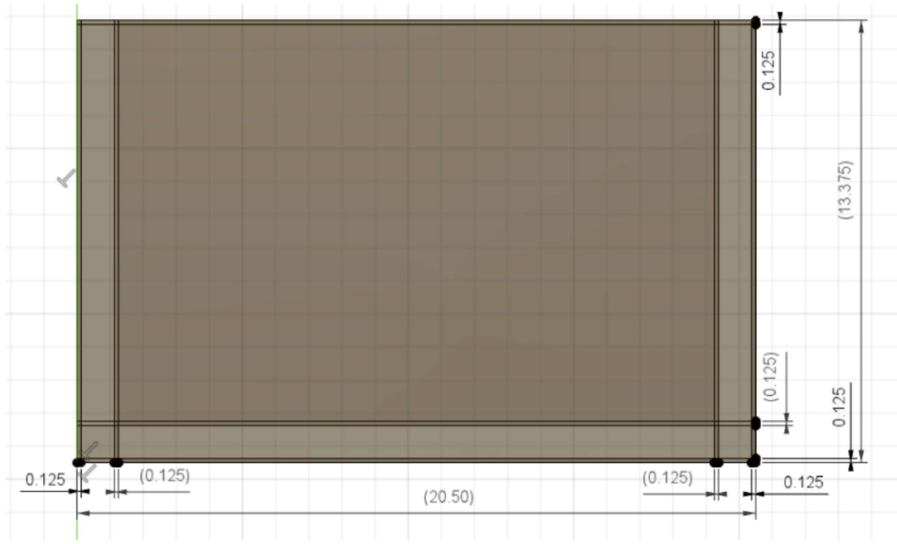

*Figure 14. Bottom View Dimensions of Reflow Oven. (Units: Inches)*

A side view is shown in Figure 15 with width and height dimensions.

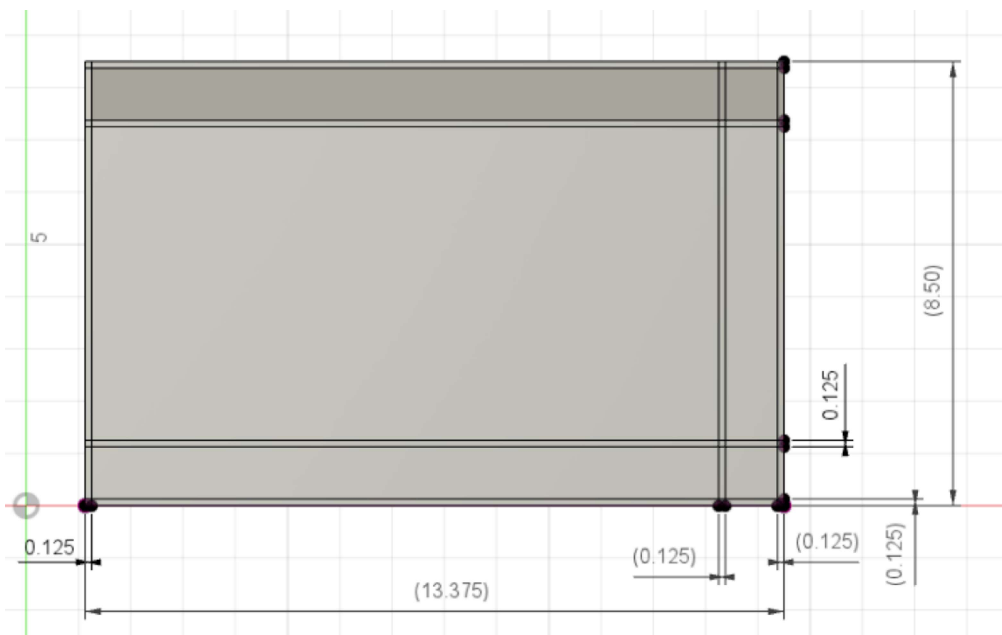

*Figure 15. Side View Dimensions of Reflow Oven. (Units: Inches)*

Figure 16 shows the length and width dimensions for the 12-gauge thick grate that the PCB board will be set on while inside the reflow oven.

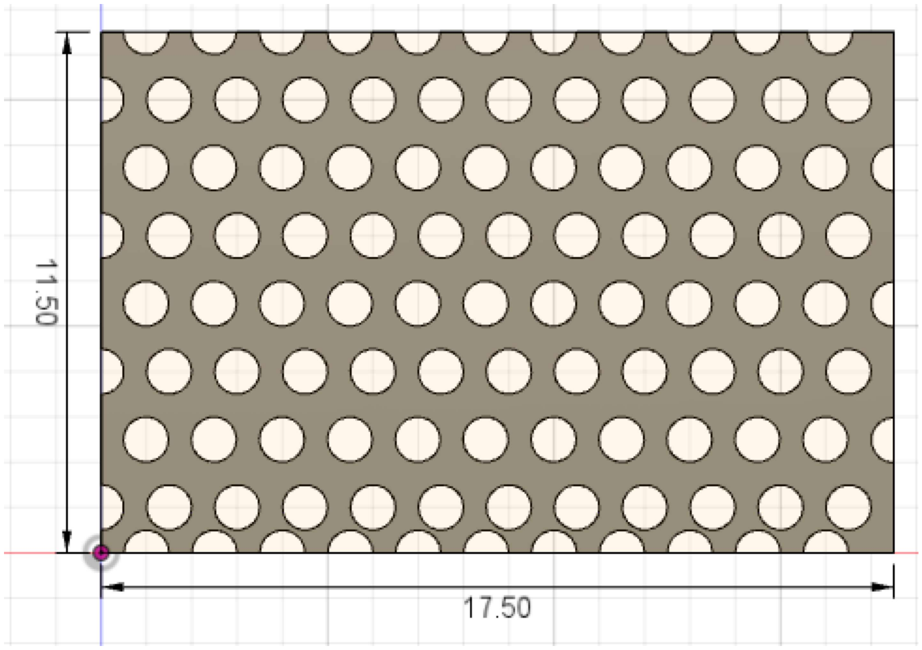


*Figure 16. Grate for PCB Board to Lie On. (Units: Inches)*

## 3.3 Working Principles of Design

When operating the oven, the user will plug the device into a power source before turning the oven on. The user will then use the toggle switch on the top of the box to provide power to the electrical components of the oven. The user will then open the door to the oven and insert the screen that holds the PCB board at a distance that is set to ensure the solder is able to heat as efficiently as possible seen in Figure 17. The user will then open the program that controls the operation on an internet connected device and adjusts the controls from a webpage. Depending on the type of solder that is used and the size of the job, the user will load a predetermined cycle from testing that will allow for the solder to complete the bonding between the PCB board and the components. Once the program has been run and the soldering process is complete the user will then open the door of the oven to check the PCB board. The user will then remove the screen and PCB board from the oven using safety equipment to ensure no burn injury occurs to the user.

*Figure 17 Holding Screen*

## 3.4 Use of Advanced tools for Optimization

During this project the group used advanced tools to assist in the optimization of the reflow oven design such as Fusion 360, Mathcad, and picoReflow [5]. The group first used Fusion 360 to aid in the design of the oven by designing multiple concepts that allowed a visual aid when completing the Pugh Matrices to determine which concepts would be the more feasible design. After determining the concept that was going to be used for the design, a program called Mathcad was used. Mathcad is an advanced computer program that allows a user to create and solve complex mathematical equations along with the variables associated with the equation. This program is a very useful tool that allows users to keep track of the units and proper operations for any equation that is used for project calculations. Software that drives the reflow oven is named “picoReflow.” Variables have the ability to be adjusted within the software for fine tuning, such as the reflow graph, max temperature, time variables and the controller constants that determine the accuracy of the reflow process. This type of controller is called a PID controller, a Proportional Integral Derivative system. The PID controller is an equational method of minimizing the error in the heating system by controlling the input and monitoring the output to match a desired specification. A graphical representation of the equation is shown below.

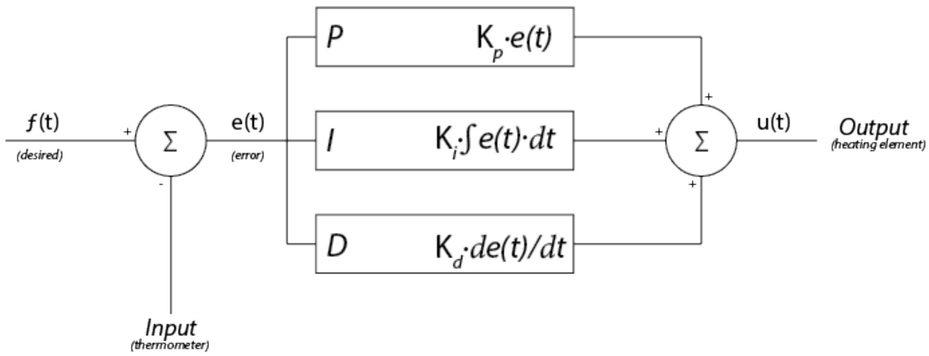

*Figure 18 PID Equation*

It uses an integral that keeps a running total of the input error during the operation, which can be simplified as a memory of the total number of errors over time. The integral works with the proportional path of the controller to drive the error in the system down to zero making the system operate closer to the desired output. The PID system also utilizes a derivative function that helps predict the error in the system, this is done by getting a negative error in the system. The negative error aids in the controller by adjusting for overcompensation in the system and shows the controller when it has gone past the desired output. This can be summed as the rate of change in the system. This system uses a present error, past error, and a prediction of the future error to calculate the appropriate commands for the system. Each of the three branches contribute an amount to the overall output of the controller. As a designer we dictate the amount of each branches contribution to the system and they are dependent on the system. This is done by adjusting the gain term in each branch "tuning the controller" changing the value of the constants (K) of each branch so it is calibrated for best performance to the Reflow Oven. Minor programming was done to create the hotspot and webpage for controlling the reflow oven.

# 4 Construction and Evaluation

## 4.1 Prototype Building

### 4.1.1 Bill of quantities

For the design and operation of the reflow oven, the client was contacted to verify the parts needed for the assembly of the oven. Table 4 shows all the components that are needed for the assembly and operation of the oven. After meeting with the client, they advised us that they would purchase the electrical parts for the oven such as the relays and the raspberry pi. Hand Industrial was generous enough to donate the material that was used to construct the inner and outer shell of the oven. They had material that was deemed as scrap by the company allowing us to recycle the material. Having the material that constructs the inner and outer shells of the oven allowed us to keep the budget very low as compared to the initial budget of $500.00.

*Table 4 Design Bill of Materials*

| Parts | Price |
|---|---|
| Ceramic wool insulation | Recycled |
| Stainless Steel | Donated/Scrap |
| Door Latches/ hinges | $4.00 |
| Quartz Heating elements | $40.00 |
| Wire and Connectors | Recycled |
| Solid State Relay | $10.00 |
| Controller (Raspberry Pi Zero W) | $10.00 |
| MAX 6675 Cold-Junction K-Type Thermocouple | $5.00 |
| | |
| Total | $69.00 |

### 4.1.2 Manufacturing Process:

Manufacturing of the reflow oven began soon after completion of the analysis and design. The bill of quantities listed in Table 4, and all the parts and components were purchased by the customer. The initial plan was to reuse and recycle as many parts as possible to keep the cost of the oven to a minimum. The group decided to use this concept with the idea that it would make it possible for anyone making PCB boards as a hobby, to construct their own oven. The group designed an initial drawing to have a concept that would allow for the operation of the oven to be as user friendly as possible. After obtaining access to a fabrication shop and a welder, the options of what type of construction method and materials increased, as well as options for completing the construction of the oven.

The group used Fusion 360 to draw and design the oven and the components of the oven. This allowed the group to design and aid in the optimization of the oven. With the fabrication shop of Hand Industrial being available to the group, it was decided to utilize the CNC fiber laser at the shop. The laser allowed for a higher accuracy with the construction of the oven walls and to utilize as much of the raw materials as possible to eliminate waste.

Once all the materials that made up the inner and outer walls of the oven had been made. The components had been assembled using a TIG welder as seen in Figure 19 to complete the construction of the walls. The internal parts including the ceramic wool fiber insulation and electrical components were then placed in the oven, then the oven was sealed using a welder.

*Figure 19 TIG Welding of Design*

The insulation was placed between the inner and outer wall of the oven during the welding process as seen in Figure 20. The wool was recycled from a broken residential oven. The oven was going to be recycled allowing us to obtain the ceramic wool insulation that all home ovens have.

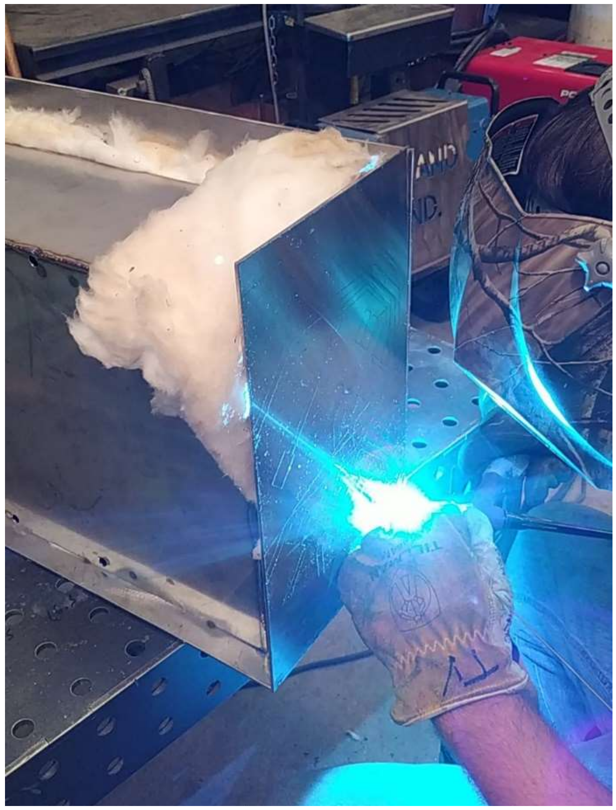

*Figure 20 Insulation Inserted During Assembly Process*

The electrical components were a mixture of purchased and recycled parts. A majority of the materials that were able to be recycled was the wire and the parts for the connectors. The Raspberry Pi and relays had to be purchased. The purpose of the raspberry pi and the relays made it difficult to find ones to recycle because of the unique purposes that we are using them for. After completing the welding process and the assembly of the electrical components, a protective box was used to house the Raspberry pi and solid state relay on top of the oven seen in Figure 21 to minimize the amount of wire needed between the heating elements and the controllers. This also allowed for protection of the complex electrical equipment.


*Figure 21 Completed Prototype*

### 4.1.3 Challenges

There were several challenges faced during the conception and completion of this project in both the design phase as well as in the manufacturing phase. The design challenge was determining the best design to construct the design allowing for ease of use and safety of the operator. After calculating the material that would be a great choice for the material and having to settle with using stainless steel as the inner and out shell of the oven. We then had to determine the proper welding application that was going to be used for the design. Because a group member had the knowledge and experience as a professional welder, the group chose to use the TIG method (Tungsten Inert Gas). We felt that this method would allow for the strongest welds for the application, while ensuring that the insulation and heat transfer from the inner to outer wall would be as uniform as possible. This method allowed us to use a more pin pointed welding application and not cause damage to any of the internal components of the oven

### 4.1.4 Optimization

One of the most obvious issues that the group faced was how to safely open the door of the oven to ensure that the user would not be harmed. To overcome this obstacle, the group decided to attach a handle on the door that had a spring wrapped loosely around the handle, this would minimize the amount of heat conducted from the inside of the oven to the handle resulting in a safe manor to open and close the door of the oven. This concept was utilized from the styles of handles that are used on some wood burning stoves.

The group also had to solve the issue of securing the door to the oven differently from that concept design. The group decided to fasten a pivot clip style latch. This device was bought from a local hardware store by the client at our request. The style of latch ensures a tight secure fit to the oven. The door was secured to part of the oven by hinges that allowed the door to open and close without being fully removable. The group had to find a way to optimize the design to accommodate the wiring and possibility of the oven needing to be repaired and anytime. Access to the wiring would be limited with the original design, to solve this challenge it was determined that making the wires pass through a hole at the top of the box would allow them to be easily replaced if needed. Doing such with the wires would allow for a person to simply snake the wires (attach a replacement wire to the old and pull the new wire through the current wire path). This would minimize the destruction and packing of the insulation changing the insulating efficiency causing the outer shell to possibly fall outside the safe operating temperature.

## 4.2 Testing and Results

### 4.2.1 Design requirement

The overall design needed to fall within parameters of being able to operate effectively while still maintaining a safe process that would minimizing the chances of burning the operator. Some of these requirements were given by OSHA and client preference or need. Due to the concept being used to heat material at a high temperature it was necessary to determine the safe temperature that the outside of the box could be. The temperature of the outside of the box was determined to be approximately 99˚F. OSHA states that the max temperature that a human hand can be exposed to before experiencing any severe harm is 140 ˚F for five seconds. Another parameter to work with was finding a material that would allow for a sustainable design that was determined through calculations. The best material choice was found to be aluminum. Although that material that was used for the design was stainless steel, it was determined that this would be acceptable due to the high corrosion resistance of the material, and that the material was donated by Hand Industrial.

## 4.2.2 Testing Methodology

After assembly of the oven was completed, tests were run to calibrate the heating elements. The tests were run using a computer software that showed a live Time versus Temperature graph seen in Figure 22. A trial and error method had been used to find the optimal time to reach 400°F. Once an appropriate Time versus Temperature profile was finalized a test was run taking a PCB board, applying solder paste to the board, mounting electrical components, then using the oven for its designed purpose.


*Figure 22 PID software*

For the testing of our oven, for our initial condition we designed the device to operate within in a time frame for heating that a person that was using the oven for their project. A PCB board was then placed into the oven after the components had been inserted into the board and the solder was applied. During the process of heating the PCB board and melting the solder continuously measured the outside and inside temperature of the oven to ensure that it would not reach an external temperature that was unsafe for the user. We also monitored the internal temperature of the oven using a thermistor. This also was used for the operating program controlling the heating elements. After the process of soldering the board was complete, we tested the safety of opening and removing the PCB board from the oven. To do this we used proper PPE (personal protective equipment) to remove the contents. This involved using a protective glove that acted as a bearer between the hot components and the user's hand.

### 4.2.3 Results and discussion

During the testing we found that the device was able to safely complete the process of soldering all components to the PCB board. The testing of safely removing the PCB board from the oven was determined to be safe if a person did not reach in the oven with a bare hand to remove the parts. After testing the operation of removing and replacing the components of the oven in the event of a repair, it was found that the top lid of the oven allowed for enough room for a person's hands and to still have a clear view of the components when working. The group felt overall that the operation and repair aspect of the oven design was adequate for a person that had the intent of using the oven for a hobby.

## 4.3 Assessment

After building and testing our design, it was made apparent that a major weakness in our design came from the overall weight of the oven. Based on the budget and availability of the material this could be changed to minimize the overall weight of the oven. While the operation of the oven and the repair simulation of the oven was acceptable. We felt that a different assembly process of the inner and outer wall of the oven would allow for better access to all the components of the oven. We also felt that if there was a way that the user could see into the oven during to process, that would allow for the user to better observe the operation of soldering the components to the PCB board. The group also thought that a different insulation material could be used depending on the budget for the project.

# 5 Conclusion and Recommendation

## 5.1 Summary of results

The project was able to heat to a temperature that would allow for leaded and non-leaded solder paste to melt and complete the bonding process between the electrical mounting components and the PCB board. Based on the calculations of the outside temperature that the reflow oven reached, the values were acceptable. However, we feel that with a more generous budget the outer temperature of the oven could be reduced with better materials. The material that was used for the inner and outer shells of the oven, which was donated by Hand Industrial, could not have the optimal thickness of the walls, so the inner walls retain as much heat during the reflow process. After testing we discovered that the inner walls of the oven began to warp causing a change in the heat transfer from the inner to outer surface to change and be less efficient. We considered adding a type of stiffener to the inner shell of the box making it harder for the shell to warp and change the efficiency of the oven. After talking to the client and consideration of the process of fixing the issue, we decided that the box would remain as is. This was done for fear of damaging the insulation that was used in the box or the electrical components of the oven.

## 5.2 Recommendations

If the design was to be improved upon, we feel that if someone changed the orientation of the quartz heating elements or added longer brackets so the heating element was farther from the walls it would help reduced the amount of deformation. We also feel that if the ceiling of the oven was to be reinforced in a manner that would not add weight to the oven, this would be beneficial to the design and operation of the oven, extending the number of times of use and life. A perfect replacement for the stainless steel would Aluminum, that would greatly reduce weight and the environmental impact to produce.

# 6 Acknowledgments

In gratitude to those who contributed to the success of this project:

Ryan Fore: Hand Industrial Project Manager

Lucas Creery: Paying for the electrical components

# 7 References


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Oven Insulation: Comparison of insulation and thickness

Given:

$$k_{air} := 33.8 \cdot 10^{-3} \ \frac{W}{m \cdot K}$$

$$w_{ss.i} := 0.125 \ in = 0.003 \ m$$

$$k_{ss} := 14.9 \ \frac{W}{m \cdot K}$$

$$w_{ss.o} := 0.125 \ in = 0.003 \ m$$

$$k_{argon} := 26.8 \cdot 10^{-3} \ \frac{W}{m \cdot K}$$

$$L_o := 10 \ in \cdot 0.0254 \ \frac{m}{in} = 0.254 \ m$$

$$k_{ceramic} := 0.06 \cdot \frac{W}{m \cdot K}$$

$$L_i := 8 \ in \cdot 0.0254 \ \frac{m}{in} = 0.203 \ m$$

$$k_{foamoc} := 0.27 \cdot \frac{W}{m \cdot K}$$

$$w := 0.1 \ in, 0.2 \ in .. 4 \ in$$

$$T_0 := 200 \ °F \qquad T_\infty := 72 \ °F = 295.372 \ K$$

$$T_i := T_\infty = 72 \ °F \qquad T_f := T_0 = 366.483 \ K$$

$$T_{avg} := \frac{T_0 + T_\infty}{2}$$

Using Soldering Profile;
the temperature is a linear
gradient from Ti to Tf.

$$T_{mid} := T_{avg} = 136 \ °F$$

$$A_i := 2 \cdot 12 \ in \cdot 6 \ in + 2 \cdot 6 \ in \cdot 18 \ in + 2 \cdot 12 \ in \cdot 18 \ in = 0.511 \ m^2$$

$$A_o := 2 \cdot 14 \ in \cdot 8 \ in + 2 \cdot 8 \ in \cdot 20 \ in + 2 \cdot 14 \ in \cdot 20 \ in = 0.712 \ m^2$$

$$T_{film.i} := T_0 = 200 \ °F \qquad T_{film.o} := T_\infty = 72 \ °F$$

T film assuming perfect insulation

Convection Coefficient of Air inside and outside box

$$\alpha_i := 52 \cdot 10^{-6} \cdot \frac{m^2}{s}$$

$$\beta_i := \frac{1}{T_{film.i}}$$

$$v_i := 35.5 \cdot 10^{-6} \ \frac{m^2}{s}$$

$$Pr_i := 0.685$$

$$\alpha_o := 22.5 \cdot 10^{-6} \cdot \frac{m^2}{s}$$

$$v_o := 15.89 \cdot 10^{-6} \ \frac{m^2}{s}$$

$$Pr_o := 0.707$$

$$T_{s2} := T_\infty + 20 \ K$$

$$\beta_o := \frac{1}{T_{film.o}} \qquad T_{s2} = 108 \ °F$$

$$T_{s1} := T_0 - 0 \ K \qquad T_\infty = 72 \ °F$$

$$Ra_i := \frac{g \cdot \beta_i \cdot (T_{s1} - T_\infty) \cdot L_o^{\ 3}}{\alpha_o \cdot v_i} = 3.904 \cdot 10^7$$

$$Ra_o := \frac{g \cdot \beta_o \cdot (T_{s2} - T_\infty) \cdot L_o^{\ 3}}{\alpha_o \cdot v_o} = 3.044 \cdot 10^7$$

$$Nu_{Li} := \left( 0.825 + \frac{0.387 \cdot Ra_i^{\frac{1}{6}}}{\left( 1 + \left( \frac{0.492}{Pr_i} \right)^{\frac{9}{16}} \right)^{\frac{8}{27}}} \right)^2$$

$$Nu_{Lo} := \left( 0.825 + \frac{0.387 \cdot Ra_o^{\frac{1}{6}}}{\left( 1 + \left( \frac{0.492}{Pr_o} \right)^{\frac{9}{16}} \right)^{\frac{8}{27}}} \right)^2$$

$$h_i := \frac{Nu_{Li} \cdot k_{air}}{L_i} = 7.656 \ \frac{W}{m^2 \cdot K}$$

$$h_o := \frac{Nu_{Lo} \cdot k_{air}}{L_o} = 5.719 \ \frac{W}{m^2 \cdot K}$$

Free Convection Heat Transfer Coefficient of Gas Insulations between parallel plates

Air

$$\alpha_{air} := 38.3 \cdot 10^{-6} \cdot \frac{m^2}{s}$$

$$\beta_{air} := \frac{1}{T_{mid}}$$

$$v_{air} := 26.41 \cdot 10^{-6} \ \frac{m^2}{s}$$

$$Pr_{air} := 0.69$$

Argon

$$\alpha_{arg} := 20 \cdot 10^{-6} \cdot \frac{m^2}{s}$$

$$\beta_{arg} := \frac{1}{T_{mid}}$$

$$v_{arg} := 13.4 \cdot 10^{-6} \ \frac{m^2}{s}$$

$$Pr_{arg} := 0.669$$

$$L_c := \frac{L_o + L_i}{2}$$

$$Ra_{air} := \frac{g \cdot \beta_{air} \cdot (T_{s1} - T_{s2}) \cdot L_c^{\ 3}}{\alpha_{air} \cdot v_{air}} = 1.789 \cdot 10^7$$

$$Ra_{arg} := \frac{g \cdot \beta_{arg} \cdot (T_{s1} - T_{s2}) \cdot L_c^{\ 3}}{\alpha_{arg} \cdot v_{arg}} = 6.751 \cdot 10^7$$

$$Nu_{L.air}(w) := 0.22 \left(\frac{Pr_{air}}{0.2 + Pr_{air}} \cdot Ra_{air}\right)^{0.28} \left(\frac{L_c}{w}\right)^{\frac{-1}{4}}$$

$$Nu_{L.arg}(w) := 0.22 \left(\frac{Pr_{arg}}{0.2 + Pr_{arg}} \cdot Ra_{arg}\right)^{0.28} \left(\frac{L_c}{w}\right)^{\frac{-1}{4}}$$

$$h_{air}(w) := \frac{Nu_{L.air}(w) \cdot k_{air}}{L_c}$$

$$h_{argon}(w) := \frac{Nu_{L.arg}(w) \cdot k_{argon}}{L_c}$$

$$Nu_{L.air}(w) := 0.046 \cdot \left(Ra_{air}^{\ \frac{1}{3}}\right)$$

$$Nu_{L.arg}(w) := 0.046 \cdot \left(Ra_{arg}^{\ \frac{1}{3}}\right)$$

eq. 9.53

$$h_{air}(w) := \frac{Nu_{L.air}(w) \cdot k_{air}}{L_c}$$

$$h_{argon}(w) := \frac{Nu_{L.arg}(w) \cdot k_{argon}}{L_c}$$

$$h_{air}(1) = 1.779 \ \frac{kg}{s^3 \cdot K}$$

$$R_{air}(w) := \frac{1}{\dfrac{1}{\dfrac{w}{k_{air} \cdot \dfrac{(A_i + A_o)}{2}}} + \dfrac{1}{\dfrac{1}{h_{air}(w) \cdot \dfrac{(A_i + A_o)}{2}}}}$$

$$R_{air}(1\ in) = 0.526\ \frac{s^3 \cdot K}{kg \cdot m^2}$$

$$R_{argon}(w) := \frac{1}{\dfrac{1}{\dfrac{w}{k_{argon} \cdot \dfrac{(A_i + A_o)}{2}}} + \dfrac{1}{\dfrac{1}{h_{argon}(w) \cdot \dfrac{(A_i + A_o)}{2}}}}$$

$$q_{air}(w) := \frac{T_0 - T_\infty}{\dfrac{1}{h_i \cdot A_i} + \dfrac{w_{ss.i}}{k_{ss} \cdot A_i} + R_{air}(w) + \dfrac{w_{ss.o}}{k_{ss} \cdot A_o} + \dfrac{1}{h_o \cdot A_o}}$$

$$q_{ceramic}(w) := \frac{T_0 - T_\infty}{\dfrac{1}{h_i \cdot A_i} + \dfrac{w_{ss.i}}{k_{ss} \cdot A_i} + \dfrac{w}{k_{ceramic} \cdot \dfrac{(A_i + A_o)}{2}} + \dfrac{w_{ss.o}}{k_{ss} \cdot A_o} + \dfrac{1}{h_o \cdot A_o}}$$

$$q_{argon}(w) := \frac{T_0 - T_\infty}{\dfrac{1}{h_i \cdot A_i} + \dfrac{w_{ss.i}}{k_{ss} \cdot A_i} + R_{argon}(w) + \dfrac{w_{ss.o}}{k_{ss} \cdot A_o} + \dfrac{1}{h_o \cdot A_o}}$$

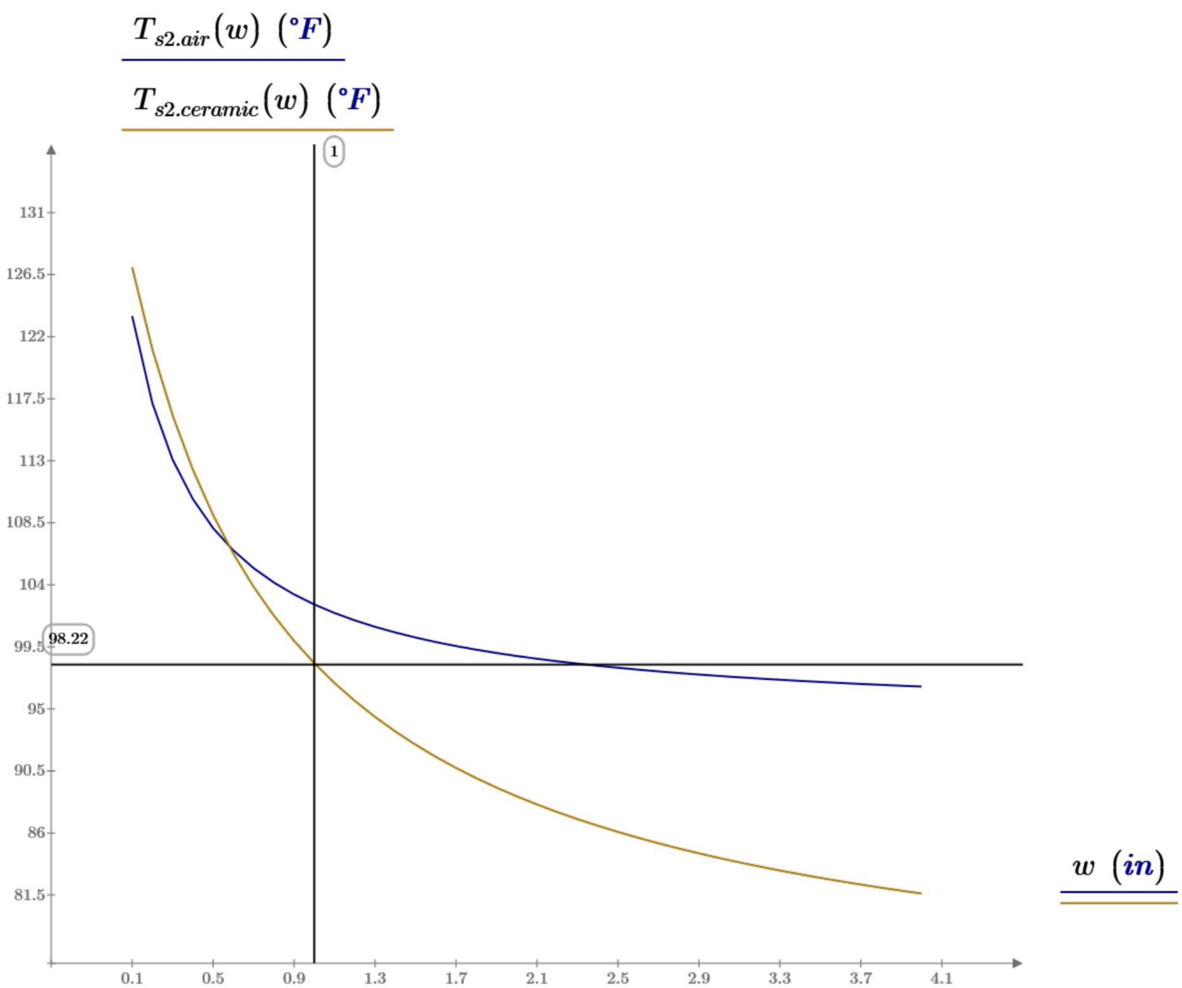
$q_{ceramic}(1\ in) = 59.556\ W$
$q_{air}(1\ in) = 69.196\ W$
$q_{argon}(1\ in) = 70.773\ W$

$$T_{s2.air}(w) := -\left(q_{air}(w) \cdot \left(\frac{1}{h_i \cdot A_i} + \frac{w_{ss.i}}{k_{ss} \cdot A_i} + R_{air}(w) + \frac{w_{ss.o}}{k_{ss} \cdot A_o}\right) - T_0\right)$$

$$T_{s2.ceramic}(w) := -\left(q_{ceramic}(w) \cdot \left(\frac{1}{h_i \cdot A_i} + \frac{w_{ss.i}}{k_{ss} \cdot A_i} + \frac{w}{k_{ceramic} \cdot \frac{(A_i + A_o)}{2}} + \frac{w_{ss.o}}{k_{ss} \cdot A_o}\right) - T_0\right)$$

$T_{s2.ceramic}(1.5\ in) = 92.404\ °F$ $T_{s2.air}(1.5\ in) = 311.027\ K$

$T_{s2.ceramic}(1.5\ in) - T_{\infty} = 11.336\ K$



Sandwich Material Thickness Optimization

Al

Aluminum (all alloys) 10.4 71.7

$$\rho_{al} := 2702\ \frac{kg}{m^3}$$

$$E_{al} := 71.7\ GPa$$

$$k_{al} := 237\ \frac{W}{m \cdot K}$$

Stainless Steel (AISI 304)

$$\rho_{ss} := 7900\ \frac{kg}{m^3}$$

$$E_{ss} := 190.0\ GPa$$

$$k_{ss} := 14.9\ \frac{W}{m \cdot K}$$

Steel

$$\rho_{steel} := 7854\ \frac{kg}{m^3}$$

$$E_{steel} := 207.2\ GPa$$

$$k_{steel} := 60.5\ \frac{W}{m \cdot K}$$

Rigid Polymer Foam

$$\rho_{r.foam} := 50\ \frac{kg}{m^3}$$

$$k_{r.foam} := 0.033 \cdot \frac{W}{m \cdot K}$$

Ceramic Wool

$$\rho_{ceramic} := 96\ \frac{kg}{m^3}$$

$$k_{ceramic} := 0.06 \cdot \frac{W}{m \cdot K}$$

Flexible Polymer Foam

$$\rho_{f.foam} := 80\ \frac{kg}{m^3}$$

$$k_{f.foam} := 0.126\ \frac{W}{m \cdot K}$$

$$f = 2\ \frac{t}{d}$$

$$k_{eff}\left(k_{wall}, k_{core}, f\right) := \left(\frac{f}{k_{wall}} + \frac{1-f}{k_{core}}\right)^{-1}$$

$$\frac{1}{E_{flex}} = \frac{1}{12} \cdot \frac{1}{E_f \cdot \left(\left(1-(1-f)^3\right) + \frac{E_c}{E_f} \cdot (1-f)^3\right)} + \frac{B_1}{B_2} \cdot \left(\frac{d}{L}\right)^2 \cdot \frac{1-f}{G_c}$$

$$K := 1$$

$$E_{flex}\left(E_f, f\right) := \left(1-(1-f)^3\right) \cdot E_f \cdot K$$

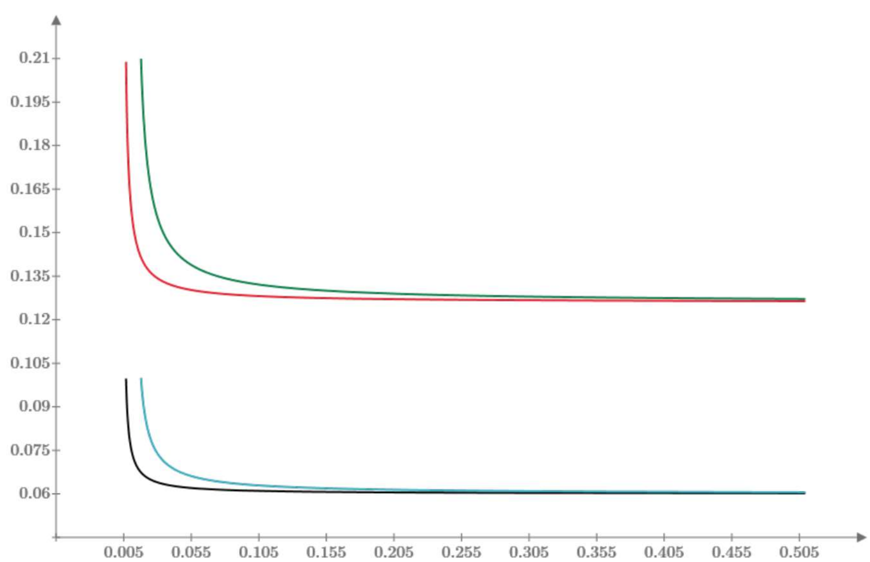
$$f := 0, 0.001 .. 0.4$$

$$k_{eff}\left(k_{ss}, k_{f.foam}, f\right)\ \left(\frac{W}{m \cdot K}\right)$$

$$k_{eff}\left(k_{ss}, k_{ceramic}, f\right)\ \left(\frac{W}{m \cdot K}\right)$$

$$k_{eff}\left(k_{al}, k_{f.foam}, f\right)\ \left(\frac{W}{m \cdot K}\right)$$

$$k_{eff}\left(k_{al}, k_{ceramic}, f\right)\ \left(\frac{W}{m \cdot K}\right)$$



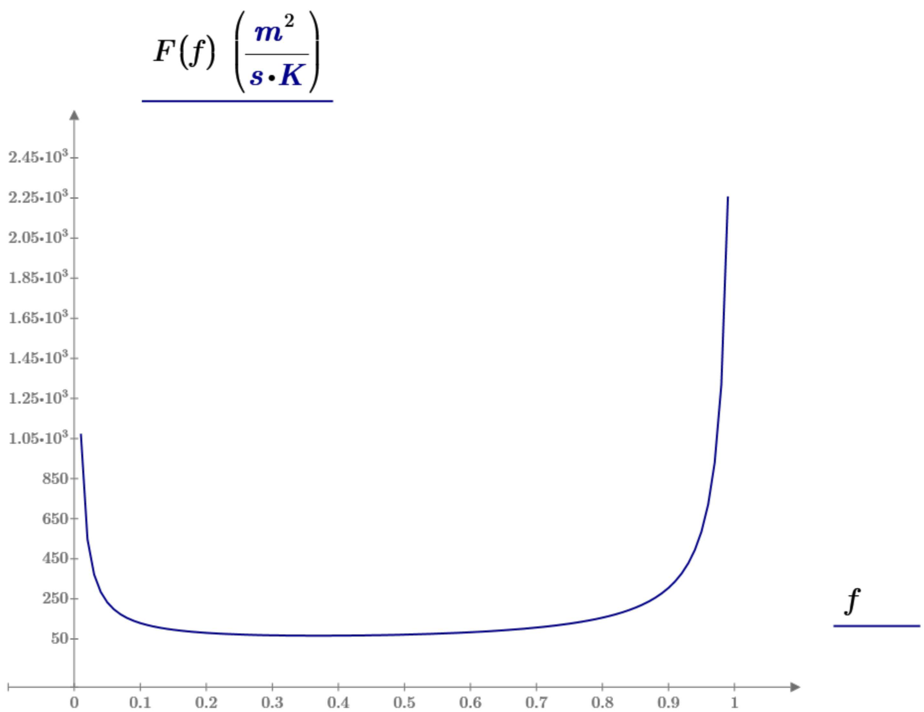

$$\frac{1}{E_{flex}\left(E_{ss}, f\right)}\ \left(\frac{1}{GPa}\right)$$

$$\frac{1}{E_{flex}\left(E_{ss}, f\right)}\ \left(\frac{1}{GPa}\right)$$

$$\frac{1}{E_{flex}\left(E_{al}, f\right)}\ \left(\frac{1}{GPa}\right)$$

$$\frac{1}{E_{flex}\left(E_{al}, f\right)}\ \left(\frac{1}{GPa}\right)$$

$$F(f) := \frac{1}{E_{flex}(E_{ss}, f)} \cdot k_{eff}(k_{ss}, k_{ceramic}, f) \cdot (1 \cdot 10^{14})$$




Guess Values

$$f := 0.1$$

Constraints

$$f < 0.9 \qquad f > 0.1$$

Solver

$$f_{min} := \mathbf{Minimize}(F, f) = 0.371$$

$$k_{eff}(k_{ss}, k_{ceramic}, f_{min}) = 0.095 \ \frac{W}{m \cdot K}$$

$$f = 2\ \frac{t}{d} \qquad \frac{f_{min} \cdot 1.\ in}{2} = 0.186\ in$$

# Oven Insulation: Plotting Transient Conduction

Given:

$$k_{air} := 33.8 \cdot 10^{-3} \frac{W}{m \cdot K}$$

$$k_{ss} := 14.9 \frac{W}{m \cdot K}$$

$$k_{argon} := 26.8 \cdot 10^{-3} \frac{W}{m \cdot K}$$

$$k_{ceramic} := 0.06 \cdot \frac{W}{m \cdot K}$$

$$k_{foamoc} := 0.27 \cdot \frac{W}{m \cdot K}$$

$$w_{ss.i} := 0.125\ in = 0.003\ m$$

$$w_{ss.o} := 0.106\ in = 0.003\ m$$

$$L_o := 10\ in \cdot 0.0254 \frac{m}{in} = 0.254\ m$$

$$L_i := 8\ in \cdot 0.0254 \frac{m}{in} = 0.203\ m$$

$$w := 0.1\ in, 0.2\ in .. 4\ in$$

$$T_0 := 400\ °F \qquad T_\infty := 72\ °F = 295.372\ K$$

$$T_i := T_\infty = 72\ °F \qquad T_f := T_0 = 477.594\ K$$

$$T_{avg} := \frac{T_0 + T_\infty}{2}$$

Using Soldering Profile;
the temperature is a linear
gradient from Ti to Tf.

$$T_{mid} := T_{avg} = 236\ °F$$

$$A_i := 2 \cdot 12\ in \cdot 6\ in + 2 \cdot 6\ in \cdot 18\ in + 2 \cdot 12\ in \cdot 18\ in = 0.511\ m^2 \qquad A := A_i$$

$$A_o := 2 \cdot 14\ in \cdot 8\ in + 2 \cdot 8\ in \cdot 20\ in + 2 \cdot 14\ in \cdot 20\ in = 0.712\ m^2$$

$$T_{film.i} := T_0 = 400\ °F \qquad T_{film.o} := T_\infty = 72\ °F$$

$$\rho_{ceramic} := 96 \frac{kg}{m^3} \qquad \rho := \rho_{ceramic} = 96 \frac{kg}{m^3}$$

$$k_{ceramic} := 0.05 \cdot \frac{W}{m \cdot K} \qquad k := k_{ceramic}$$

$$c_p := 1130 \frac{J}{kg \cdot K}$$

$$Q_{in} := 60\ W \qquad \sigma := 5.6704 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$$

$$h_o := 5.719 \frac{W}{m^2 \cdot K}$$

Derivation

$$\frac{d}{dx}\left(k\cdot\frac{d}{dx}T\right)+\frac{d}{dy}\left(k\cdot\frac{d}{dy}T\right)+\frac{d}{dz}\left(k\cdot\frac{d}{dz}T\right)+q=\rho\cdot c_p\cdot\frac{d}{dt}T$$

$$\frac{d}{dx}\left(k\cdot\frac{d}{dx}T\right)+q=\rho\cdot c_p\cdot\frac{d}{dt}T$$

$$k\cdot\frac{d}{dx}\left(\frac{d}{dx}T\right)+q=\rho\cdot c_p\cdot\frac{d}{dt}T$$

$$r=\frac{k_{ceramic}\cdot dt}{c_p\cdot\rho\cdot dx^2}$$ Diffusion Number

$$\frac{k}{\rho\cdot c_p}\cdot\frac{1}{2\cdot\Delta x^2}\cdot\left(\left(T_{x-1,t+1}-2\cdot T_{x,t+1}+T_{x+1,t+1}\right)+\left(T_{x+1,t}-2\cdot T_{x,t}+T_{x-1,t}\right)\right)=\frac{T_{x,t+1}-T_{x,t}}{\Delta t}$$

$$0.5\cdot r\cdot\left(\left(T_{x-1,t+1}-2\cdot T_{x,t+1}+T_{x+1,t+1}\right)+\left(T_{x+1,t}-2\cdot T_{x,t}+T_{x-1,t}\right)\right)+T_{x,t}=T_{x,t+1}$$

$$\left(r\cdot T_{x-1,t+1}-2\cdot r\cdot T_{x,t+1}+r\cdot T_{x+1,t+1}\right)+\left(r\cdot T_{x+1,t}-2\cdot r\cdot T_{x,t}+r\cdot T_{x-1,t}\right)+T_{x,t}=2\cdot T_{x,t+1}$$

$$r\cdot T_{x+1,t}-2\cdot r\cdot T_{x,t}+r\cdot T_{x-1,t}+T_{x,t}=2\cdot T_{x,t+1}-\left(r\cdot T_{x-1,t+1}-2\cdot r\cdot T_{x,t+1}+r\cdot T_{x+1,t+1}\right)$$

$$r\cdot T_{x+1,t}\ (2-2\cdot r)\cdot T_{x,t}+r\cdot T_{x-1,t}=-r\cdot T_{x-1,t+1}+(2+2\ r)\cdot T_{x,t+1}-r\cdot T_{x+1,t+1}$$

$$0.5\ r\cdot T_{x+1,t}+(1-r)\cdot T_{x,t}+0.5\ r\cdot T_{x-1,t}=-0.5\ r\cdot T_{x-1,t+1}+(1+r)\cdot T_{x,t+1}-0.5\ r\cdot T_{x+1,t+1}$$

$$AA\cdot\begin{bmatrix}T_{x-1,t}\\ T_{x,t}\\ T_{x+1,t}\end{bmatrix}=BB\cdot\begin{bmatrix}T_{x-1,t+1}\\ T_{x,t+1}\\ T_{x+1,t+1}\end{bmatrix}+bc(t)$$

$$AA=\begin{bmatrix}1-r & 0.5\ r & 0\\ 0.5\ r & 1-r & 0.5\ r\\ 0 & 0.5\ r & 1-r\end{bmatrix}\qquad BB=\begin{bmatrix}1+r & -0.5\ r & 0\\ -0.5\ r & 1+r & -0.5\ r\\ 0 & -0.5\ r & 1+r\end{bmatrix}\qquad bc(t)=\begin{bmatrix}r\cdot T_{x-1,t}\\ 0\\ r\cdot T_{x+1,t}\end{bmatrix}$$

Forward Euler Method (aka: Implicit Method)

$L := 1\ in = 0.025\ m$

$dx := 0.1\ in$

$disu := 1\ in$

$scale := 10$

$time := 240\ s$

$dt := 5\ s$

$timeu := 1\ s$

$tscale := 0.2$

$$diffusionNumber := \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} = 0.357$$

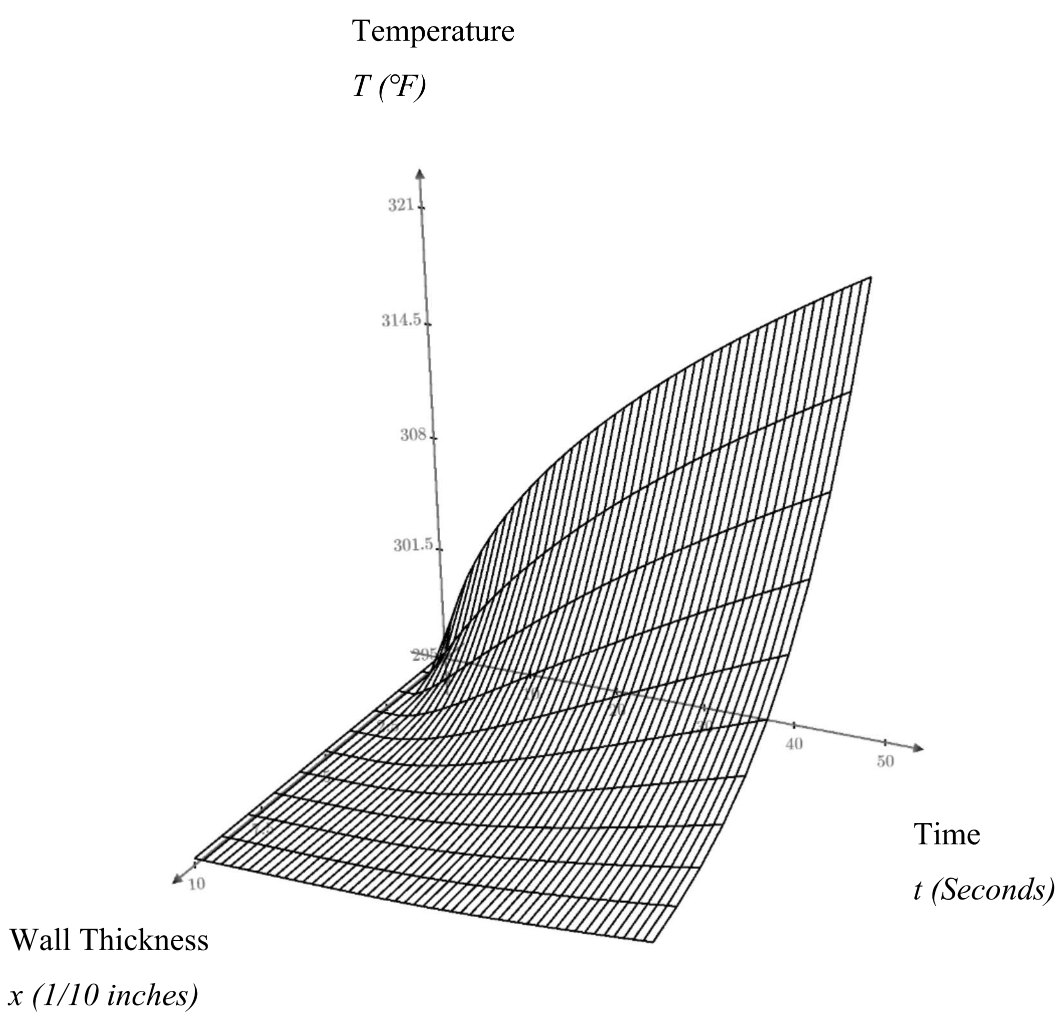
If less than 0.5, then it has met the stability criteria

Initialization

$$T := \left\| \begin{array}{l} \text{for } j \in 0, \frac{dt}{timeu} \cdot tscale \,..\, \frac{time}{timeu} \cdot tscale \\ \quad \left\| \begin{array}{l} \text{for } i \in 0, \frac{dx}{disu} \cdot scale \,..\, \left(\frac{L}{disu}\right) \cdot scale \\ \quad \left\| T_{i,j} \leftarrow T_\infty \right. \end{array} \right. \\ T \end{array} \right.$$

Equation

$$T_{lim} := \left\| \begin{array}{l} \text{for } t \in 0, \frac{dt}{timeu} \cdot tscale \,..\, \frac{time}{timeu} \cdot tscale \\ \quad \left\| \begin{array}{l} Q_{out} \leftarrow \sigma \cdot A \cdot \left( {T_{\frac{L}{disu} \cdot scale, t}}^4 - {T_\infty}^4 \right) + h_o \cdot A \cdot \left( T_{\frac{L}{disu} \cdot scale, t} - T_\infty \right) \\ T_{0,t+1} \leftarrow T_{0,t} + \left( \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} \right) \cdot \left( T_{1,t} - T_{0,t} + Q_{in} \cdot \frac{dx}{k_{ceramic} \cdot A_i} \right) \\ T_{\frac{L}{disu} \cdot scale, t+1} \leftarrow T_{\frac{L}{disu} \cdot scale, t} + \left( \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} \right) \cdot \left( T_{\frac{L}{disu} \cdot scale - 1, t} - T_{\frac{L}{disu} \cdot scale, t} - Q_{out} \cdot \frac{dx}{k_{ceramic} \cdot A_i} \right) \\ \text{for } x \in \frac{dx}{disu} \cdot scale, 2 \cdot \frac{dx}{disu} \cdot scale \,..\, \left( \frac{L}{disu} - \frac{dx}{disu} \right) \cdot scale \\ \quad \left\| T_{x,t+1} \leftarrow T_{x,t} + \left( \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} \right) \cdot \left( T_{(x-1),t} - 2 \cdot T_{x,t} + T_{(x+1),t} \right) \right. \end{array} \right. \\ T \end{array} \right.$$


Temperature
T (°F)
321
314.5
308
301.5
295
40
50
10
Time
t (Seconds)
Wall Thickness
x (1/10 inches)

$T_{lim}$ $(K)$

Crank Nicholson Method

$$diffusionNumber := \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} = 0.357$$

$$r := diffusionNumber = 0.357$$

Less than 0.5 then it has met the stability criteria

$$T := 0$$

Initialization

$$
\begin{array}{l}
T := \begin{array}{|l}
\text{for } j \in 0, \frac{dt}{timeu} \cdot tscale .. \frac{time}{timeu} \cdot tscale \\
\quad \begin{array}{|l}
\text{for } i \in 0, \frac{dx}{disu} \cdot scale .. \left(\frac{L}{disu}\right) \cdot scale \\
\quad \begin{array}{|l} T_{i,j} \leftarrow T_{\infty} \end{array}
\end{array} \\
T
\end{array}
\end{array}
$$

$$
\begin{array}{l}
AA := \begin{array}{|l}
\text{for } j \in 0, \frac{dx}{disu} \cdot scale .. \left(\frac{L}{disu}\right) \cdot scale - 2 \\
\quad \begin{array}{|l}
\text{for } i \in 0, \frac{dx}{disu} \cdot scale .. \left(\frac{L}{disu}\right) \cdot scale - 2 \\
\quad \begin{array}{|l}
\text{if } i = j \\
\quad \begin{array}{|l} T_{i,j} \leftarrow 1 + r \end{array} \\
\text{else if } i = j + 1 \\
\quad \begin{array}{|l} T_{i,j} \leftarrow -0.5\ r \end{array} \\
\text{else if } i = j - 1 \\
\quad \begin{array}{|l} T_{i,j} \leftarrow -0.5\ r \end{array} \\
\text{else} \\
\quad \begin{array}{|l} T_{i,j} \leftarrow 0 \end{array}
\end{array}
\end{array} \\
T
\end{array}
\end{array}
$$

$$BB := \left\| \begin{array}{l} \text{for } j \in 0, \frac{dx}{disu} \cdot scale .. \left(\frac{L}{disu}\right) \cdot scale - 2 \\ \quad \left\| \begin{array}{l} \text{for } i \in 0, \frac{dx}{disu} \cdot scale .. \left(\frac{L}{disu}\right) \cdot scale - 2 \\ \quad \left\| \begin{array}{l} \text{if } i = j \\ \quad \| T_{i,j} \leftarrow 1 - r \\ \text{else if } i = j + 1 \\ \quad \| T_{i,j} \leftarrow 0.5\ r \\ \text{else if } i = j - 1 \\ \quad \| T_{i,j} \leftarrow 0.5\ r \\ \text{else} \\ \quad \| T_{i,j} \leftarrow 0 \end{array} \right. \end{array} \right. \\ T \end{array} \right.$$

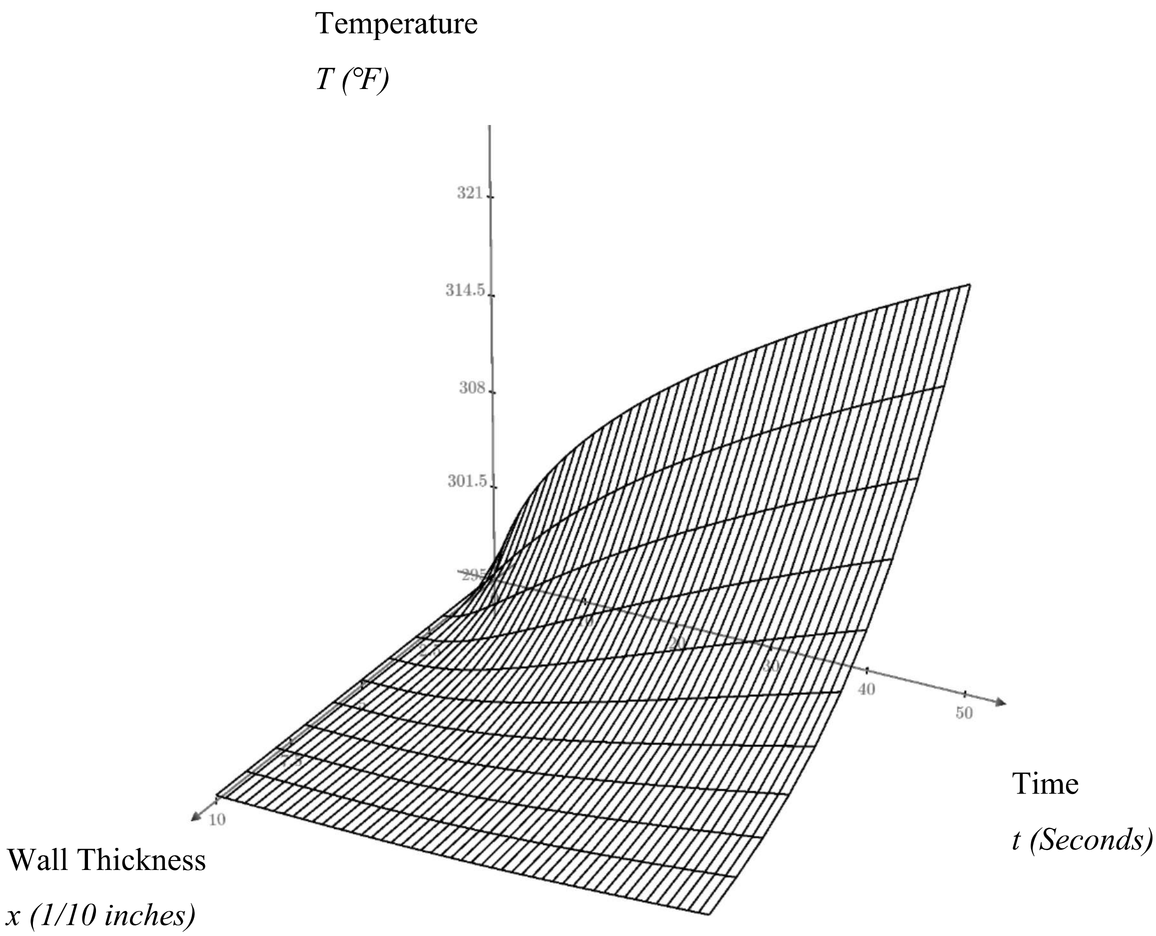
$$bc := \left\| \begin{array}{l} \text{for } j \in 0, \frac{dx}{disu} \cdot scale .. \left(\frac{L}{disu}\right) \cdot scale - 2 \\ \quad \| bc_j \leftarrow 0\ \boldsymbol{K} \\ bc \end{array} \right.$$

$$
T_{CN} := \left\| \begin{array}{l} \text{for } t \in 0, \frac{dt}{timeu} \cdot tscale .. \frac{time}{timeu} \cdot tscale \\ \left\| \begin{array}{l} Q_{out} \leftarrow \sigma \cdot A \cdot \left( T_{\frac{L}{disu} \cdot scale, t}{}^{4} - T_{\infty}{}^{4} \right) + h_o \cdot A \cdot \left( T_{\frac{L}{disu} \cdot scale, t} - T_{\infty} \right) \\ T_{0, t+1} \leftarrow T_{0, t} + \left( \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} \right) \cdot \left( T_{1, t} - T_{0, t} + Q_{in} \cdot \frac{dx}{k_{ceramic} \cdot A_i} \right) \\ T_{\frac{L}{disu} \cdot scale, t+1} \leftarrow T_{\frac{L}{disu} \cdot scale, t} + \left( \frac{k_{ceramic} \cdot dt}{c_p \cdot \rho \cdot dx^2} \right) \cdot \left( T_{\frac{L}{disu} \cdot scale - 1, t} - T_{\frac{L}{disu} \cdot scale, t} - Q_{out} \cdot \frac{dx}{k_{ceramic} \cdot A_i} \right) \\ bc_{0} \leftarrow T_{0, t+1} \\ bc_{\frac{L}{disu} \cdot scale - 2} \leftarrow T_{\frac{L}{disu} \cdot scale, t+1} \\ T_{sub}{}^{\langle t+1 \rangle} \leftarrow \text{lsolve}\left( AA, BB \cdot \text{submatrix}\left( T^{\langle t \rangle}, 1, \frac{L}{disu} \cdot scale - 1, 0, 0 \right) + r \cdot bc \right) \\ T^{\langle t+1 \rangle} \leftarrow \text{stack}\left( T_{0, t+1}, T_{sub}{}^{\langle t+1 \rangle}, T_{\frac{L}{disu} \cdot scale, t+1} \right) \end{array} \right. \\ T \end{array} \right.
$$

$$
error := \left| \frac{T_{lim_{\frac{L}{disu} \cdot scale, \frac{time}{timeu} \cdot tscale}} - T_{CN_{\frac{L}{disu} \cdot scale, \frac{time}{timeu} \cdot tscale}}}{T_{lim_{\frac{L}{disu} \cdot scale, \frac{time}{timeu} \cdot tscale}}} \right| \cdot 100 = 0.034
$$

$$
T_{lim_{\frac{L}{disu} \cdot scale, \frac{time}{timeu} \cdot tscale}} = 296.2\ K
$$

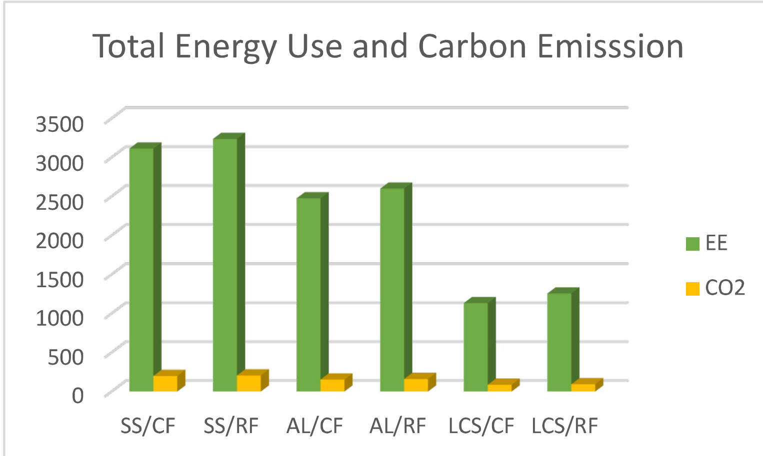
$$
T_{CN_{\frac{L}{disu} \cdot scale, \frac{time}{timeu} \cdot tscale}} = 296.301\ K
$$

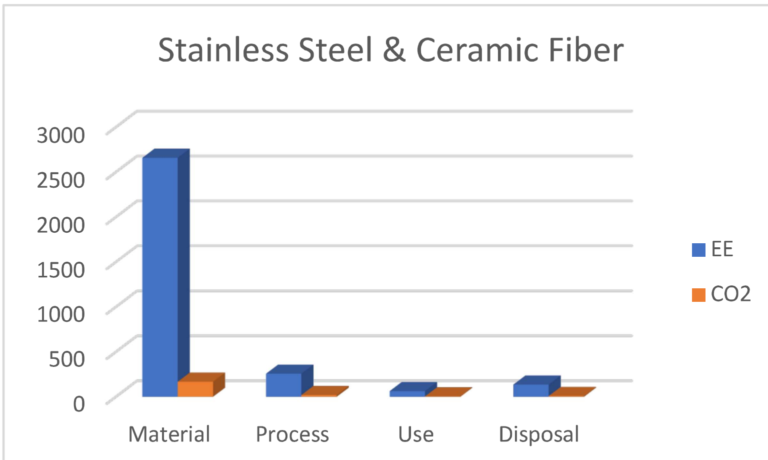

Temperature
T (°F)
321
314.5
308
301.5
40
50
10
Time
t (Seconds)
Wall Thickness
x (1/10 inches)

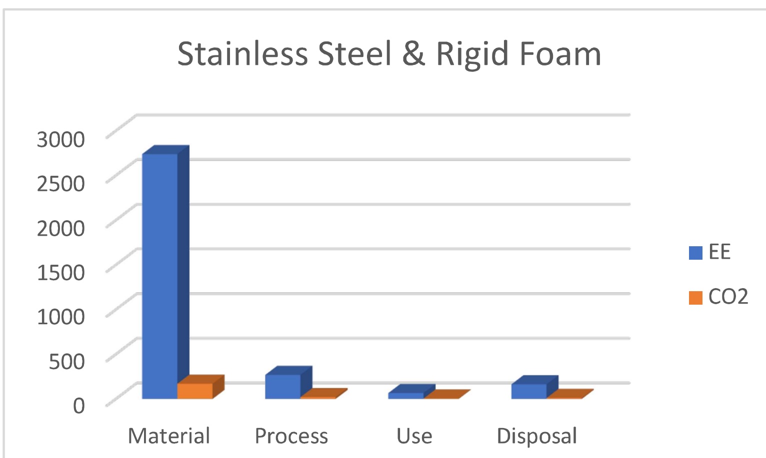
$T_{CN}$ $(K)$

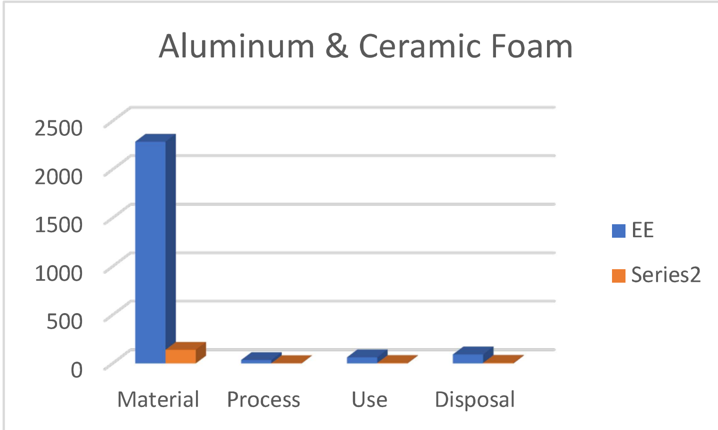
| | | Object | Material | Process | Density | Volume | Mass | Material EE | Material CO2 | Process EE | Process CO2 | Use EE | Use CO2 | Disposal % | Disposal EE | Disposal CO2 | Total EE | Total CO2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | kg/m3 | m3 | kg | MJ/kg | kg/kg | MJ/kg | kg/kg | MJ/kg | kg/kg | | | | MJ | kg |
| Base | | Circuits | | | | | 0.02 | 3000 | 300 | 0 | 0 | | | | | | | |
| | | Wire | Copper | Deformation | 9000 | 1.11111E-05 | 0.1 | 59 | 3.7 | 0.95 | 0.16 | | | 50 | 18 | 1.3 | | |
| | | Wire Shield | Glass Fiber | Fabric | 2575 | 3.1068E-05 | 0.08 | 65.5 | 94 | 2.6 | 0.2 | | | | | | | |
| | | Ceramic Heater | Ceramic Pipe | Powder Forming | 3890 | 1.28535E-06 | 0.005 | 52 | 2.8 | 26.5 | 2.12 | 59.1643 | 4.1665 | | | | | |
| | | | Ni./Cr. Wire | Forging | 8400 | 1.19048E-07 | 0.001 | 182 | 11.5 | 4.7 | 0.39 | | | | | | | |
| | | SubTotal | Circuits | | | | | 60 | 6 | 0 | 0 | | | | | | 60 | 6 |
| | | | Wire | | | | | 5.9 | 0.37 | 0.095 | 0.016 | | | | | | 5.995 | 0.386 |
| | | | Wire Shield | | | | | 5.24 | 7.52 | 0.208 | 0.016 | | | | | | 5.448 | 7.536 |
| | | | Ceramic Heater | | | | | 0.442 | 0.0255 | 0.1372 | 0.01099 | | | | | | 0.5792 | 0.03649 |
| | | SubTotal Total | | | | 4.35835E-05 | 0.206 | 71.582 | 13.9155 | 0.4402 | 0.04299 | | | | | | | |
| Variants | Variant 1 | Case | Stainless Steel | Deformation | 7850 | 0.003883025 | 30.48174625 | 84.5 | 5 | 8.2 | 0.6 | 3.523234 | 0.248115 | 0.37 | 12 | 0.73 | | |
| | | Insulation | Ceramic Fiber | Extrusion | 12 | 0.0180848 | 0.2170176 | 52 | 2.76 | 26 | 2.13 | | | 0.7 | 0 | 0 | | |
| | Variant 2 | Case | Stainless Steel | Deformation | 7850 | 0.003883025 | 30.48174625 | 84.5 | 5 | 8.2 | 0.6 | 6.41696 | 0.451899 | 0.37 | 12 | 0.73 | | |
| | | Insulation | Rigid Foam | Molding | 50 | 0.0180848 | 0.90424 | 101.5 | 3.9 | 20 | 1.7 | | | 0.75 | 41 | 3.4 | | |
| | Variant 3 | Case | Aluminum | Deformation | 2702 | 0.003883025 | 10.49193355 | 210 | 12 | 2.7 | 0.21 | 3.525601 | 0.248282 | 0.44 | 20 | 1.2 | | |
| | | Insulation | Ceramic Fiber | Extrusion | 12 | 0.0180848 | 0.2170176 | 52 | 2.76 | 26 | 2.13 | | | 0.7 | 0 | 0 | | |
| | Varinat 4 | Case | Aluminum | Deformation | 2702 | 0.003883025 | 10.49193355 | 210 | 12 | 2.7 | 0.21 | 6.423468 | 0.452357 | 0.44 | 20 | 1.2 | | |
| | | Insulation | Rigid Foam | Molding | 50 | 0.0180848 | 0.90424 | 101.5 | 3.9 | 20 | 1.7 | | | 0.75 | 41 | 3.4 | | |
| | Variant 5 | Case | Low Carbon Steel | Deformation | 7850 | 0.003883025 | 30.48174625 | 26.5 | 1.8 | 4.5 | 0.34 | 3.525127 | 0.248248 | 0.42 | 7.4 | 0.44 | | |
| | | Insulation | Ceramic Fiber | Extrusion | 12 | 0.0180848 | 0.2170176 | 52 | 2.76 | 26 | 2.13 | | | 0.7 | 0 | 0 | | |
| | Varinat 6 | Case | Low Carbon Steel | Deformation | 7850 | 0.003883025 | 30.48174625 | 26.5 | 1.8 | 4.5 | 0.34 | 6.421693 | 0.452232 | 0.42 | 7.4 | 0.44 | | |
| | | Insulation | Rigid Foam | Molding | 50 | 0.0180848 | 0.90424 | 101.5 | 3.9 | 20 | 1.7 | | | 0.75 | 41 | 3.4 | | |
| | Variant 1 | SubTotal | Case | Stainless Steel | | | | 2575.708 | 152.4087 | 249.9503 | 18.28905 | 107.3943 | 7.562981 | 11.27825 | 365.781 | 22.25167 | 3298.833 | 200.5124 |
| | | | Insulation | Ceramic Fiber | | | | 11.28492 | 0.598969 | 5.642458 | 0.462247 | 0 | 0 | 0.151912 | 0 | 0 | 16.92737 | 1.061216 |
| | Variant 2 | | Case | Stainless Steel | | | | 2575.708 | 152.4087 | 249.9503 | 18.28905 | 195.6001 | 13.77466 | 11.27825 | 365.781 | 22.25167 | | |
| | | | Insulation | Rigid Foam | | | | 91.78036 | 3.526536 | 18.0848 | 1.537208 | 0 | 0 | 0.67818 | 37.07384 | 3.074416 | | |
| | Variant 3 | | Case | Aluminum | | | | 2203.306 | 125.9032 | 28.32822 | 2.203306 | 36.99037 | 2.604955 | 4.616451 | 209.8387 | 12.59032 | | |
| | | | Insulation | Ceramic Fiber | | | | 11.28492 | 0.598969 | 5.642458 | 0.462247 | 0 | 0 | 0.151912 | 0 | 0 | | |
| | Variant 4 | | Case | Aluminum | | | | 2203.306 | 125.9032 | 28.32822 | 2.203306 | 67.3946 | 4.746099 | 4.616451 | 209.8387 | 12.59032 | | |
| | | | Insulation | Rigid Foam | | | | 91.78036 | 3.526536 | 18.0848 | 1.537208 | 0 | 0 | 0.67818 | 37.07384 | 3.074416 | | |
| | Variant 3 | | Case | Low Carbon Steel | | | | 807.7663 | 54.86714 | 137.1679 | 10.36379 | 107.452 | 7.567045 | 12.80233 | 225.5649 | 13.41197 | | |
| | | | Insulation | Ceramic Fiber | | | | 11.28492 | 0.598969 | 5.642458 | 0.462247 | 0 | 0 | 0.151912 | 0 | 0 | | |
| | Variant 4 | | Case | Low Carbon Steel | | | | 807.7663 | 54.86714 | 137.1679 | 10.36379 | 195.7444 | 13.78482 | 12.80233 | 225.5649 | 13.41197 | | |
| | | | Insulation | Rigid Foam | | | | 91.78036 | 3.526536 | 18.0848 | 1.537208 | 0 | 0 | 0.67818 | 37.07384 | 3.074416 | | |

| | | | Material EE | Material CO2 | Process EE | Process CO2 | Use EE | Use CO2 | | Disposal EE | Disposal CO2 | Total EE | Total CO2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | MJ | kg | MJ | kg | MJ | kg | | MJ | kg | | |
| Totals | Variant 1 | SS/CF | 2658.574 | 166.9232 | 256.033 | 18.79429 | 62.68753 | 4.414615 | | 135.339 | 8.23312 | 3112.634 | 198.3652 |
| | Variant 2 | SS/RF | 2739.07 | 169.8508 | 268.4753 | 19.86925 | 65.58126 | 4.618399 | | 163.1443 | 10.53893 | 3236.271 | 204.8773 |
| | Variant 3 | AL/CF | 2286.173 | 140.4177 | 34.41088 | 2.708544 | 62.6899 | 4.414782 | | 92.32902 | 5.539741 | 2475.603 | 153.0807 |
| | Variant 4 | AL/RF | 2366.668 | 143.3452 | 46.85322 | 3.783504 | 65.58777 | 4.618857 | | 120.1344 | 7.845553 | 2599.244 | 159.5932 |
| | Variant 3 | LCS/CF | 890.6332 | 69.38161 | 143.2505 | 10.86903 | 3.525127 | 0.248248 | | 94.73727 | 5.633027 | 1132.146 | 86.13192 |
| | Variant 4 | LCS/RF | 971.1286 | 72.30918 | 155.6929 | 11.94399 | 6.421693 | 0.452232 | | 122.5426 | 7.938839 | 1255.786 | 92.64424 |

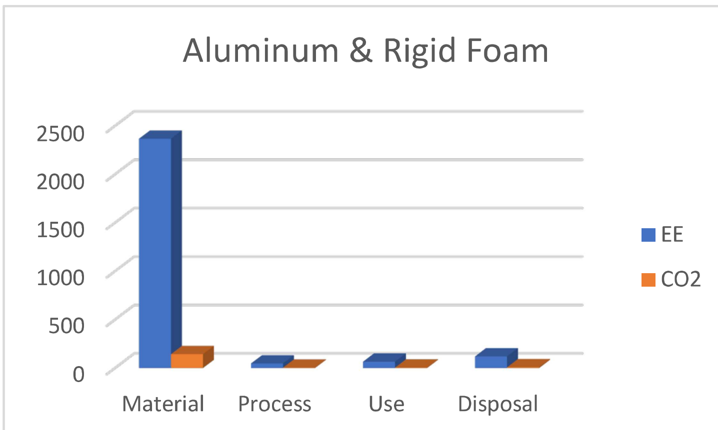

Total Energy Use and Carbon Emisssion
3500
3000
2500
2000
1500
1000
500
0
SS/CF
SS/RF
AL/CF
AL/RF
LCS/CF
LCS/RF
EE
CO2


Stainless Steel & Ceramic Fiber
3000
2500
2000
1500
1000
500
0
Material
Process
Use
Disposal
EE
CO2

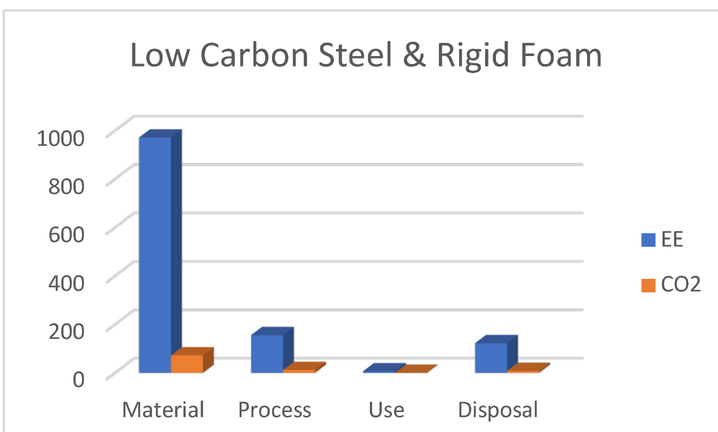

Stainless Steel & Rigid Foam
3000
2500
2000
1500
1000
500
0
Material
Process
Use
Disposal
EE
CO2



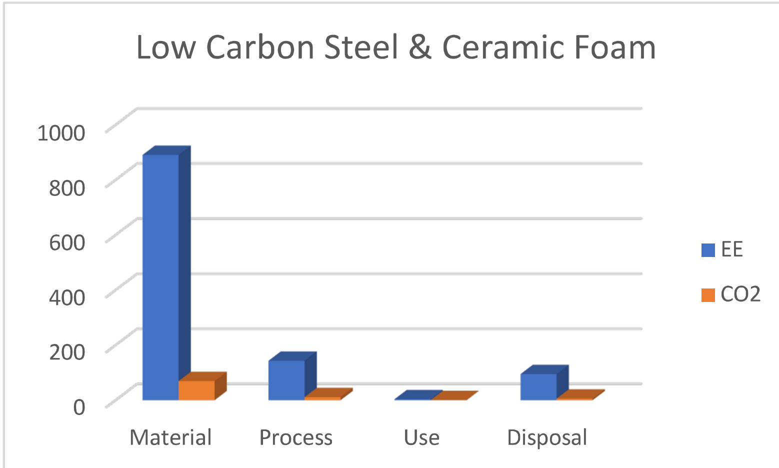
Aluminum & Ceramic Foam
2500
2000
1500
1000
500
0
Material
Process
Use
Disposal
EE
Series2

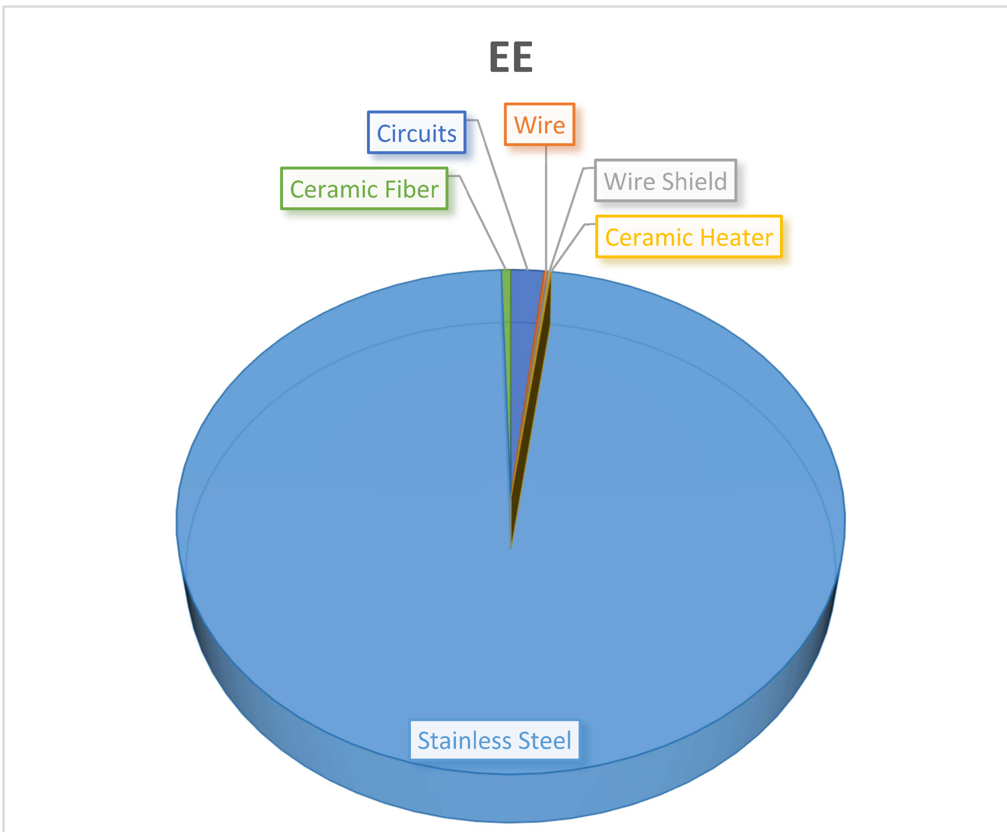



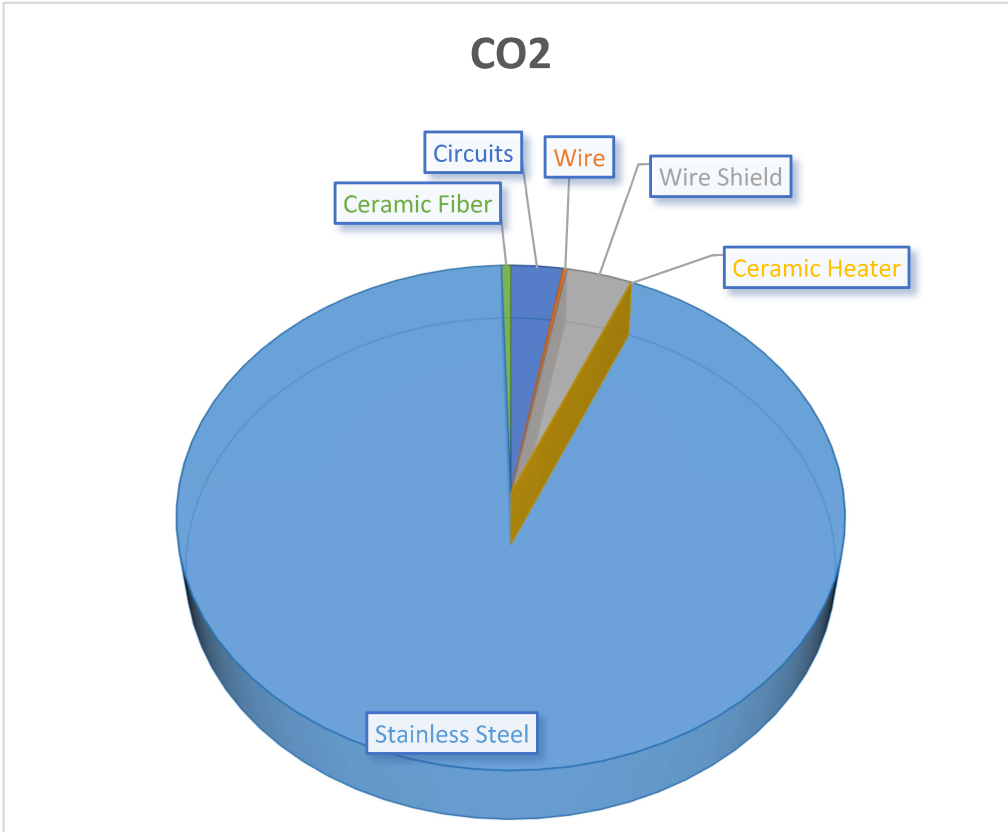
Aluminum & Rigid Foam
2500
2000
1500
1000
500
0
Material
Process
Use
Disposal
EE
CO2

Low Carbon Steel & Rigid Foam
1000
800
600
400
200
0
Material
Process
Use
Disposal
EE
CO2


Low Carbon Steel & Ceramic Foam
1000
800
600
400
200
0
Material
Process
Use
Disposal
EE
CO2


EE
Circuits
Wire
Wire Shield
Ceramic Fiber
Ceramic Heater
Stainless Steel


CO2
Circuits
Wire
Wire Shield
Ceramic Fiber
Ceramic Heater
Stainless Steel