Powder Coating Oven

Final Proposal

Verina Abdelmesih

Desiree Dee

Amber Malenowsky

Hussain Alismail

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Project Sponsor: Carson Pete

Faculty Advisor: Visar Farhangi and Perry Wood

Sponsor Mentor: Carson Pete

Instructor: Carson Pete

DISCLAIMER

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Executive Summary

The team was assigned to design a powder coating oven, a device that is used to cure and seal the powder coat onto metals. The powder coating process is an application of pigmented powder onto metallic parts, to provide a finalized finish before its being used. Powder coating is used to add color to a design or create a durable layer to the design. The powder coating process involves a pre-treatment process to the metal before coating and curing the design, The first step of the process is using a degreaser to clean the part. The second step is coating the part with an epoxy primer, which allows the coating to be long-lasting. The third step is to use a sandblast to blow any of the impurities off from the part. The last step comes with applying all-purpose iron phosphate, which increases adhesion and corrosion resistance to the metal part. After the curing process, the powder coating begins by grounding the part (usually with a wire attached to the powder coating gun), then spraying the part with the powder. Due to the difference in electrical charge between the powder and the part, the powder will stick to the surface of the part, which then will be ready for the last step. For the final step, the part is cured using the powder coating oven. The heat allows the powder to begin melting onto the part, creating the desire finish.

The team must design and fabricate a functional powder coating oven. The client's requirements are for the design to be mobile, to use a propane fueled torpedo heater as the source of heat, and for the oven to have a control system using a PID system. The oven will be located outside of the Renewable Laboratory for varies of projects and applications, such as the bumper project in capstone and the SAE BAJA club.

The important elements of the oven are: the overall dimensions of the design, depending on the primary use of the oven (DIY projects or for industry), a heating unit, which comes in different methods of heating sources (Electrical, Propane, Diesel, etc.), a heating fan, which allows for the circulation of the heat inside the oven, an exhaust fan, which contributes for the regulation of the oven temperature, and the PID system, which helps with the regulation of the whole system of the oven.

The final design of the oven was inspired from multiple DIY powder coating oven projects, as well as from high-quality industry ovens. The team managed to implement the final design by designing the heat source at the back of the oven, a ventilation system that is hidden at the sides and top of the oven, allowing for better heat circulation and a rack system inside the oven, to hang the parts for curing.

The final design of the project was analyzed through various technical analyses. The results of the heat transfer analysis of the composite wall observe the thickness of insulation inside the wall. The structural analysis shows that the rack system design was much more stable than the oven's frame, suggesting a further analysis into consideration. The PID system analysis provided that the system will regulate the temperature of the oven to sustain the required curing procedure and further parts to control. The ventilation analysis ensures heat circulation inside the oven is evenly distributed. The fuel consumption analysis analyzes the use of the torpedo heater with the volume of the oven and the use of the propane tank will remain optimal for long periods of time.

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1 BACKGROUND

1.1 Introduction

This project's purpose is to design a device to operate and complete tasks intended for purposes defined by the client. The stakeholders will be the NAU (Northern Arizona University)

Renewable Energy Lab, and the client will be Professor Carson Pete. Expectations for this project are to document the process from the introduction of the selected project, the engineering design methods and processes used, as well as the prototyping and demonstration of the final design selection. The team's goal is to design and fabricate a mobile gas-powered oven that is capable of housing both small and large parts. This oven should be capable of curing parts for the BAJA Car competitions and the renewable energy lab. This team will also work closely with the bumper capstone team to powder coat their finished capstone project.

1.2 Project Description

Below is the following original project description provided by the sponsor.

"Powder Coating is a dry finishing process created by utilizing an electric change that causes a dry powder to fuse to a surface (e.g., metals such as Aluminum or steel, glass, and even plastics) and is then permanently cured to the surface by baking the part in a high temperature curing oven. This creates a hard finish that is typically tougher than conventional paint. For this project, a team of engineering students will design and fabricate a "mobile" gas-powered oven that is capable of housing small to larger parts such as an off-road bumper or even the SAE Baja frame. This system should be able to be easily moved by a single person and would thus be "mobile". The product will be housed in the Renewable Energy lab compound area and will be used for numerous future NAU projects. This design will be optimized to be "mobile", heat generated by a propane heater system, develop a racking system allowing small to large parts to be cured, and have various controls to regulate the curing oven. Professor Pete has new powder coating equipment (~$1k worth of equipment) that will be utilized with this oven. In addition to building this oven, the team will collaborate with the bumper build team to power-coat 3 different bumpers. Additionally, there are other parts required to be powdered coated in the renewable energy lab. Students will need to have skills in the area of fabrication, structural strength analysis, control systems, possible welding or other metal fabrication techniques, computer & heat transfer analysis, and the ability to learn about the powder coating process. Figure 1 shows an example electric powder coating oven."

2 Requirements

To successfully design a powder coating oven, the requirements made by the customer would need to be satisfied. These requirements would ensure that the team creates an oven that fits the clients' needs. The engineering requirements will also need to be satisfied for the oven to meet all the required safety regulations. Below is provided the list of requirements that the client has given along with all the engineering requirements.

2.1 Customer Requirements (CRs)

After a discussion with the client these were found to be the most important customer needs.

List of Customer Requirements:

1.Propane fueled heater

2.Control system for the heater

3.Retractable rack system

4.Withstand 500 degrees F

5.Dimensions/Size

6.Portability

7.Weather Resistant

The powder coating oven will be housed outside of the renewable energy lab. This will require the oven to be fueled by a propane heater. Since the outlets on the outside of the lab average at about 10-15 volts it will not be enough to power the oven. There will need to be a control system for the heater control system which will allow the operator to regulate the temperature inside the oven. The client would also like there to be a retractable rack system. This will allow parts of any size to be powder coated in the oven. Dimension and size are also a customer requirement so that the SAE Baja competition team will be able to powder coat the frames of their cars. Portability is also a key component so the oven can be moved from one area to another. It also needs to reach a minimum of 500°F in order for any form of powder to be used in the oven. It also must be weather resistant since it will be stored outside the renewable energy lab.

2.2 Engineering Requirements (ERs)

To create the most optimal powder coating oven that will meet the client's standards, the team worked together to create engineer requirements. The team created the engineering requirements after analyzing the stakeholder's requirements for the oven to meet safety regulations. Below are listed all the engineering requirements necessary for the oven to meet the specified requirements.

List of Engineering Requirements:

1. PID temperature and time monitor: The PID system was found to be a consistent and safe system for regulating temperature.
2. Corrosion Protected exterior: The exterior of the oven must be weatherproof to withstand being stored outside.
3. Safe to operate: The oven must meet all safety regulations including a carbon monoxide sensor and emergency stop button.
4. Volume: 6.5' x 4' x 5.5' (L x W x H): The oven must fit a standard sized car bumper and Baja car frame.
5. Material Costs: The cost of the oven cannot exceed the $1,500 budget provided by the customer.
6. Heat Circulation and Ventilation: The circulation and ventilation are required to ensure that the oven can reach and maintain a set temperature.
7. Design Assembly/Disassembly: The design must be easily assembled and disassembled for quick movement from one location to another and for maintenance.
8. Heat Output of 500 °F: It needs to reach a minimum of 500°F so that any form of powder can be used in the oven.

2.3 Functional Decomposition

An important component in the design and development process of creating an oven for powder coating is the application of the functional decomposition method. During this process, the team developed a Black Box model and a Functional model. The Black Box, seen below in Figure 1, models the intended functionality of the oven. Arrows on either side of the box correspond to material, energy, and signal inputs and outputs during the use and operation of the oven. This is a simplistic method used to visualize the core components that will best enable the principal task of the product to be completed. Developing and completing a correct model will ensure a functional model is accurately achieved as well. As seen in Figure 1, the required material inputs are Propane, to fuel the heater; Powder, used to coat the object; Object, of various materials to be placed in the oven. The energy input for the oven is electrical- to power the oven control systems, thermal- heat being added to oven by the selected heater, chemical- reaction between powder and heat, and electrostatic- allows for the powder to cling to object before entering the oven. Signals for the oven will be delivered though on/off and to emergency shut-off switches to control the power supply to the oven.

2.3.1 Black Box Model

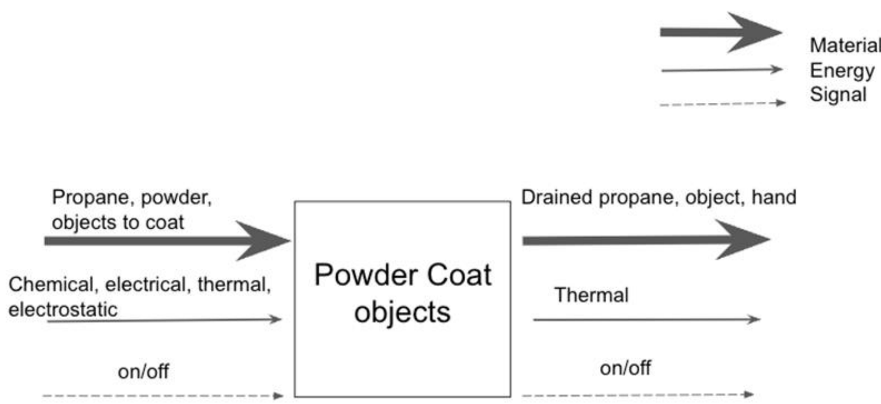

Figure 1: Black Box Model

2.3.2 Functional Model

After compiling the black box, the function model was developed. This model depicts the flow of tasks needed to be performed to meet the needs of the customer. Since providing the best possible product is critical, it is important to verify the task is completed to yield the best possible powder-coated object. The main oven will receive electrical energy to deliver power to the control system and heater. For the heater to heat the oven to the required temperatures, propane will also be added to the system. Before putting the coated object into the oven to cure completely, additional steps should be completed. First, the object being coated needs to have its surface cleaned to ensure the exterior is clear of any particulates or contaminates, followed by a chemical treatment to aid the powder adhering properly. Next, it is recommended that the object is placed in the oven during the preheating process and removed before reaching the powder's instructed curing temperature. Adding the powder coat while the item is hot will aid in attaining a thicker coat with a higher-quality finish. Understanding detailed tasks that need to be completed will enable the team to develop a product that allows each step of the process to be completed by the customer safely and effectively.

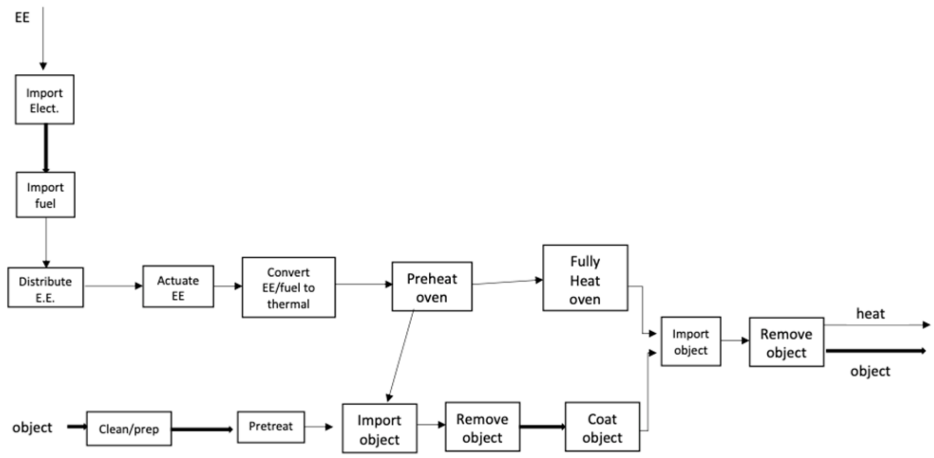

Figure 2: Functional Model

2.4 House of Quality (HoQ)

The design process of the teams' powder coating oven started with adding the initial customer requirements to the House of Quality in order to organize and develop appropriate engineering requirements. HOQ can be seen in 8.1 Appendix A: House of Quality. In addition to adding the customer and engineering requirements, similar market-available products were added to the HOQ for benchmarking. Implementation of the HOQ allowed the team to identify which needs and requirements to prioritize. To achieve the desired internal oven temperature, the team was able to start selecting materials that maintain integrity while being subjected to large temperatures. For safety purposes, not only is it important to have the correct material, but it is also critical to have a control system to monitor temperatures and fuel levels. Thus, the team was able to select a control system better equipped to monitor these systems and implement an emergency shut-off as needed. It was determined that the most challenging requirement to meet is maintaining a large enough oven size, while also preserving the ovens portability as requested by the customer.

2.5 Standards, Codes and Regulations

To meet the required safety requirements for any design or project in the industry, the standards and codes must be met with every design and project, and the powder coating oven is no exception. The requirements and standards for the powder coating oven, provided in Table 1, gives a representation on how to implement the powder coating process, and what are the safety procedures that need to be followed to minimize injuries or equipment failures. With the establishment of the safety codes in Table 1, the team has taken into consideration the type of practices and procedures that need to be followed, during the application of powder coating.

Table 1: Powder Coating Oven Standards

Standard Number or Code	**Title of Standard**	**How it applies to Project**

NFPA 33	Standard for Spray Application Using Flammable or Combustible Material	All electrically conductive objects (including personnel) in the spray area, except those objects required by the process to be a high voltage, shall be electrically connected to ground with a resistance of not more than 1 megohm.
BS EN 61241-10:2004	Electrical apparatus for use in the presence of combustible dust	The stoving oven should be situated at least 1m from the powder spraying installation and arranged so that powder cannot accumulate or be spilled near to the oven, its air intake, hot surfaces or any electrical apparatus.
NFPA 15.8	Ventilation, Dust Collection, and Explosion protection	The powder coating spray areas should be well ventilated, provided that the necessary flame prevention applications should be met, and any flammable objects, such as cigarettes, should be kept away from the powder coating area.
OSHA 1926.756	Beams & Columns	The build of the oven beams and framing should be supported with a minimum number of threads and screws to ensure safety and sturdiness in the build.

3 Testing Procedures

The team conducted two testing procedures for the powder coating oven. The first testing procedure for the project was the powder coating process and the second testing procedure was the heat transfer analysis. The two prototypes were tested and analyzed by the two testing and prototyping managers, Verina and Desiree. The overall testing description and results are discussed below.

3.1 Testing Procedure 1: Heat Transfer Analysis of Oven Wall

The first testing procedure the team analyzed was the heat transfer analysis of the oven wall. This testing procedure satisfies the engineering requirement of being able to withstand the maximum temperature 500 degrees Fahrenheit with minimal heat loss through the wall. A requirement the customer stated is that the oven needs to be able to reach the maximum temperature without having the walls overheat and turn red. The team completed this testing procedure during the weeks of April 17th, 2023 – April 30th, 2023.

3.1.1 Testing Procedure 1: Objective

The testing procedure will use a small 1ft x 1 ft sample of the oven wall. There will be four thermocouples attached into the wall to read temperature change and calculate the thermal resistive network in a two-dimensional view. The fifth thermocouple is for ambient to find the R value of the air outside of the oven. The wall sample is heated up using a heat plate and records temperature using LabVIEW and DAQ acquisition. The total heating time for the experiment is approximately 40-50 minutes and the temperature is recorded every 2-3 minutes. The testing procedure is analyzing the thickness of the insulation being 3.5” and 4” insulation.

3.1.2 Testing Procedure 1: Resources Required

The testing procedure was completed in the engineering building room 111, which is the thermos-fluids laboratory. The materials used from the laboratory are the DAQ acquisition system, 5 thermocouples, and a heat plate. Material the team had to purchase for the testing experiment is R15 insulation, 2 1ft x 1 ft 25 gauge cold rolled steel, high temperature vinyl tape, and rubber foam that withstands 375 degrees Fahrenheit. The software required for the experiment is LabVIEW, which students can access only in room 111.

3.1.3 Testing Procedure 1: Schedule

The testing procedure was during the days of April 18th, 2023 – April 25th, 2023, and the calculations were completed during the period of April 26th, 2023 – April 30th, 2023. The heat transfer is completed in advance to the second semester. With the completion of the analysis, the team now has the material needed to create the wall of the oven minus the beams, which are part of the structural analysis. This allows the team to prep and begin building over the summer.

3.2 Testing Procedure 2: Powder Coating Analysis

The second testing procedure is powder coating various types of metal and testing the durability and strength of the coating on the material with various tests. A requirement stated by the customer is the team needs to understand the process of powder coating and to create the best technique to make the coating durable and long-lasting. The team plans to complete this testing procedure during the week of April 26th, 2023 – May 3rd, 2023.

3.2.1 Testing Procedure 2: Objective

One of the requirements for the powder coating oven is the oven must be large enough to be used by the bumper capstone team and create the best process of powder coating and curing techniques for the team. The team is testing the abrasion, adhesion, impact, and strength tests on steel, aluminum, and tin metal pieces. The abrasion test consists of scraping the powder coated items and leaving them in vinegar/saltwater overnight to test powder quality. The adhesion tests whether the Epoxy primer is necessary. The impact test consists of hitting the material with a hammer. Lastly, the strength test consists of bending the material to test the durability of the powder.

3.2.2 Testing Procedure 2: Resources Required

The testing procedure was completed in the renewable energy lab located near the engineering building. The materials used and provided by the client are a 20-gallon air compressor, hammer, toaster oven, powder to coat the material, epoxy primer, aluminum, steel, tin blocks, and high temperature vinyl.

3.2.3 Testing Procedure 1: Schedule

The testing procedure is expected to be completed by May 3rd, 2023, to meet the required assignment of testing and prototyping I of capstone I in the first semester. Completing this testing procedure allows the team to create a manual for the use of the oven to prepare the material for use.

4 Risk Analysis and Mitigation (TPs)

Risk analysis and mitigation is an essential process in product development. This process can be done by completing FMEA. FMEA or failure mode and effects analysis is a systemized group of categories that recognizes and evaluates the potential failure of each part and the effect it has on the entire product. It will then document and identify the actions that could potentially eliminate or reduce the chance of the potential failure occurring. Below is a list of potential failures associated with the powder coating oven along with actions that can minimize the chance of the failure occurring.

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Corrosive Wear Effecting the Torpedo Heater

If the torpedo heater were to fail it would be due to corrosive wear from the weather impact. The potential effects of the torpedo heater failing would be inconsistent or no heat causing the powder to not evenly cure on the product. This failure can be mitigated by storing the torpedo heater indoors when it is not in use.

4.1.2 Potential Critical Failure 2: Radiation Damage Effecting 16 Gauge Steel

If the 16-gauge steel were to fail it would be due to radiation damage from the weather. The potential effects of the 16-gauge steel failing would be damage to the structural integrity of the oven causing it to collapse. This failure can be mitigated by applying rust repellent stray to help strengthen the metal against the weather.

4.1.3 Potential Critical Failure 3: Impact Deformation Effecting 20 Gauge Steel

If the 20-gauge steel were to fail it would be due to impact deformation from the heat source. The potential effects of the 20-gauge steel failing would be damage to the structural integrity causing it to collapse. This failure can be mitigated by applying high temperature paint to the metal to increase its deformation point.

4.1.4 Potential Critical Failure 4: Creep Buckling Effecting Steel Beam

If the steel beams were to fail it would be due to the creep buckling caused by a load bearing impact. The potential effect of the steel beam failing would be damage to the structural integrity causing the oven to collapse. This failure can be mitigated by ensuring that the parts loaded into the oven are not greater than 300 lbs.

4.1.5 Potential Critical Failure 5: Corrosive Wear Effecting the Wool Fiber Insulation

If the wool insulation fiber were to fail it would be due to the corrosive wear caused by structural damage. The potential effect of the wool fiber insulation failing would be excessive heat loss. This failure can be mitigated by using high temperature sealant to water does not seep into the oven.

4.1.6 Potential Critical Failure 6: Saturation Effecting the PID System

If the PID system were to fail it would be due to saturation caused by reaching the maximum or minimum temperature values. The potential effects of the PID failing would be inaccurate temperature measurements. This failure can be mitigated by tuning and/or calibrating the PID system monthly or depending on the frequency of use.

4.1.7 Potential Critical Failure 7: Metal Fatigue Effecting the Thermocouples

If the thermocouples were to fail it would be due to metal fatigue caused by expansion and/or contraction of the metal, it is attached to. The potential effects of the thermocouples failing would be no working control system. This failure can be mitigated by changing the thermocouples monthly or depending on the frequency of use.

4.1.8 Potential Critical Failure 8: Corrosive Wear Effecting the PID Box

If the PID box were to fail it would be due to corrosive wear caused by the weather impact on the box. The potential effects of the box failing would be damage to the control system. This failure can be mitigated by ensuring seepage does not occur in the box by adding high temperature sealant.

4.1.9 Potential Critical Failure 9: Electric Failure Effecting the Circulation Blower

If the circulation blower were to fail it would be due to electrical failure caused by a blown fuse from the electrical source. The potential effects of the circulation blower failing would be uneven heat distribution. This failure can be mitigated by ensuring the outlet can withstand the electrical output.

4.1.10 Potential Critical Failure 10: Buckling Effecting the Wall Duct

If the wall duct were to fail it would be due to buckling caused by improperly connected wall ducts. The potential effects of the wall duct failing would be uneven heat distribution. This failure can be mitigated by ensuring all ducts are securely connected.

4.2 Risk and Trade-offs Analysis

Upon the completion of the FMEA (located in Appendix A) it is interesting to observe the relationship between the RPN (risk priority number) and the D (detection). For example, when looking at the steel beams, which are used to create the frame of the oven, it has a detection rate of four and an RPN value of 200. However, when looking at the circulation fan that has a detection rate of two and an RPN value of 20. This is interesting given that one can argue that the circulation fan is just as important as the steel beams the only difference between the steel beams, and the circulation fan is that the circulation fan is more accessible making its failure easier to detect. Where, as the steel beam is hidden between steel and insulation, making it harder to detect the failure. However, when looking at parts, such as the thermocouples and the wire, their detection rates and RPM values are relatively similar, given its location and accessibility. Meaning that if the part has a lower detection rate it needs to have a lower occurrence rate in order to avoid potential failures.

5 Design Selected – First Semester (TPs) (Team)

The team conducted numerous technical analyses for the design of the powder coating oven that impacted the material being used and the layout of the design. The technical analyses help the team decide on the material being used and how to create the CAD models. The section talks about the engineering calculations conducted and the changes made to the final design stated in the preliminary report. A schedule is then outlined for the second semester of capstone.

5.1 Design Description

The design presented in the preliminary report was a rudimentary design created without any research. Upon completing the structural analysis, heat ventilation and circulation analysis, heat transfer analysis, fuel consumption analysis, and control system analysis many changes were made to the design of the oven. One of the key changes was removing the extruding exhaust pipes from the oven and opting for stackable wall ducts to improve the heat flow. The extruding exhaust pipes were also found to be hazards given that they could break at any time. The analysis below will show all design changes along with how the changes improved the design of the oven.

5.1.1 Structural Analysis

For this project, the team was assigned to design and fabricate a powder coating oven for the client Professor Carson Pete, which will be used primarily in the renewable energy lab. The details of the oven are the following; the oven must exceed up to 400-500F, it must be mobile and able to carry up to 300lbs (approximated weight of the bumper from the bumper capstone team). This analysis will determine the structural suitability of the oven design along with the qualifications necessary for its construction and usage. Structural analysis is a method used by engineers to evaluate the quality of a build and its structural integrity. By using statistical analysis, the forces and reactions of the structures will be determined, then it will be used to determine the safety factor of the structure, which will determine its qualification. Conducting this analysis has required the use of SolidWorks to achieve the most optimal results. After conducting the statistical analyses for both the oven's frame and the retractable racking system, it showed the results as follows. As shown in Figure 3 below, the yield strength was calculated from the applied weight of 560.24lbs, resulted to be equal to $\sigma_{overall} = 2.039 * 10^8 \frac{N}{m^2} = 29{,}573.19\ psi$. The figure below shows the analysis for the oven:

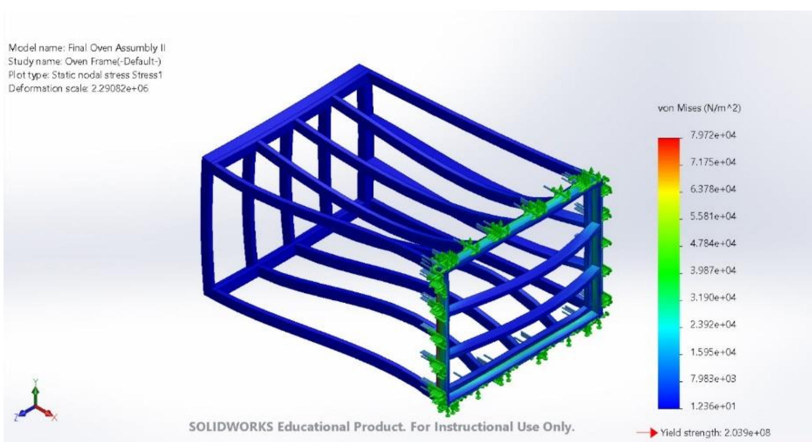

Figure 3: Statistical Load Analysis for Oven Frame

On the other hand, from the same statics analysis done on the trolly, the yield strength was calculated from the applied weight of 300lbs, resulted to be $\sigma_{overall} = 1.8 * 10^8 \frac{N}{m^2} = 26106.79\ psi$. Figure 4 shows the analysis done for the retractable oven rack system:

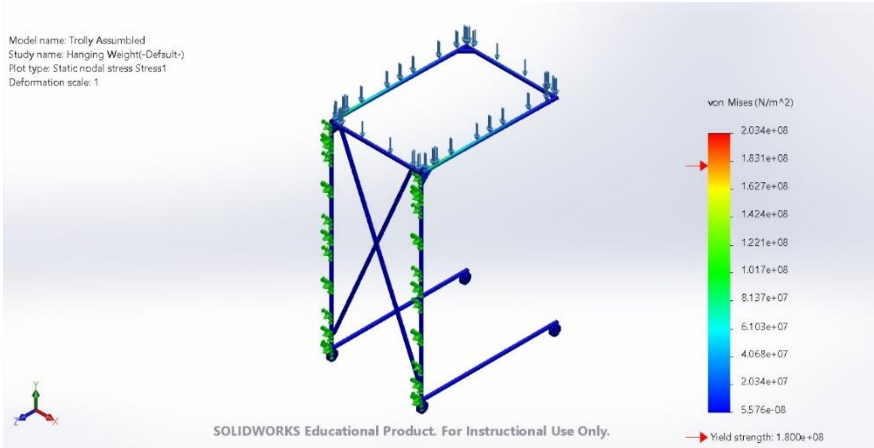

Figure 4: Statistical Load Analysis for Racking System

Using these numbers, the factor of safety for each was calculated by dividing the overall strength over the allowable strength. Recognizing that the allowable yield strength of the frame used for the oven (25 gauge steel studs) to be equal to 29,579 psi, the factor of safety was calculated to be equal to $FS = 1.0001$, while the overall strength of the trolly (Cold roll steel tubes) is estimated to be 67,000 psi, which resulted in a factor of safety to be $FS = 2.566$.

5.1.2 Control System Analysis

This analysis discussed the control system for the powder coating oven. In industry control systems are typically used to operate heating devices, fans/blowers, vents, lights, thermocouples, and emergency buttons. This control system will attempt to operate all of the listed devices using a PID (proportional integral derivative) controller. PID is generally preferred over other systems such as Arduino because it combines the average of each type of control while including quick response times. This analysis will go over the semantics of the PID controller along with the potential set up that will be used.

For the simulation the desired output was set to 350 degrees Fahrenheit. Figure 5 below shows the results of the 350 degrees Fahrenheit output.

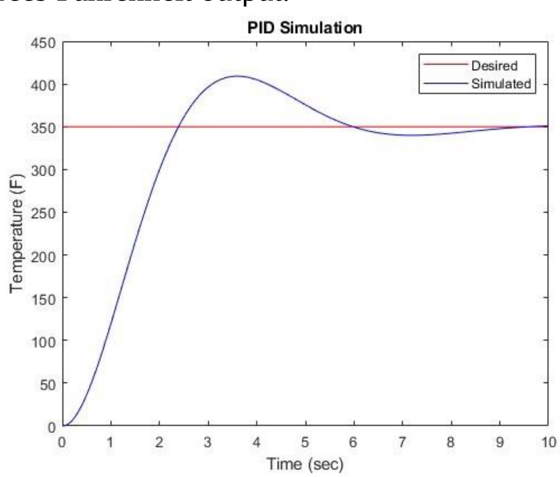

Figure 5: Set point of 350 degrees F

For the simulation shown in Figure 6 below the desired output was set to be 200 degrees Fahrenheit.

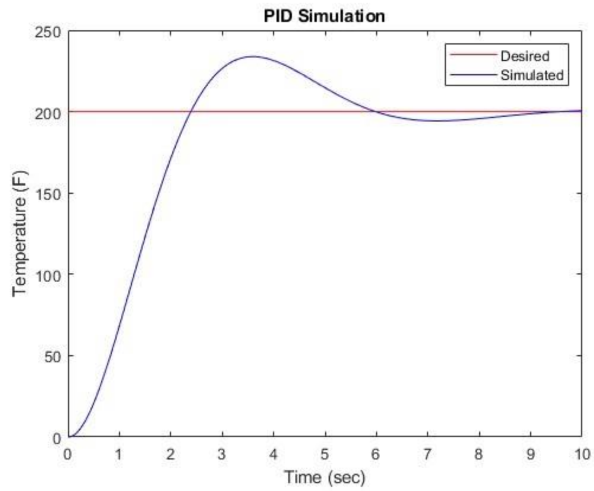

Figure 6: Set point of 200 degrees F

Figures 5 and 6 shown above demonstrate how the PID system works in an ideal environment. It shows how the system will continue to read inputs provided by feedback 1 and 2 until the feedback values match the input values. Also shown in Figures 5 and 6 the desired temperature was able to be reached in approximately 10 seconds which will vary when being used for the oven. The PID for the oven will be receiving feedback every 2 to 3 seconds, however the time in which the feedback matches the desired temperature is contingent on the heater being used along with the volume of the oven. The temperature will also be contingent on if the vent system is activated. The vent system will be active if the feedback values are found to be higher than the desired value. The vent will open to allow the oven to cool down to meet the desired value. Once the feedback value either decreases or meets the desired value the vent will close until the feedback value increases and becomes greater than the desired value again.

5.1.3 Circulation and Ventilation Analysis

The circulation and ventilation analysis observes the air flow throughout the oven. The overall goal of the analysis is to produce a ventilation system that has a circulation to be uniform for the oven, meaning air is not just flowing in the center of the oven but the sides of the oven.

To begin the circulation system heat would enter from the bottom back wall of the oven through a torpedo heater. Heat would then naturally rise and enter the inlet of the squirrel cage blower. It would then be released through the exit connected to a series of elbow and wall ducts. These ducts will run alongside the left and right side of the oven. The ducts will include holes in the oven for air to be released. These holes will vary in size from the smallest at the top and gradually increase in size to allow uniform air flow out of the ducts. The vent at the bottom will be programmed into the control system to allow the vent to open and close when the temperature becomes too great as opposed to just having the heater turn on and off to allow for fuel loss to be minimized. The vent will also open when the pressure of air inside the oven exceeds the pressure outside the oven. If the pressure inside the oven exceeds the pressure outside the oven it will not allow for proper air circulation to occur. The ventilation system's 3D model is found in appendix E.

5.1.4 Fuel Consumption Analysis (Amber)

The goal of the fuel consumption analysis is to analyze the amount of heat being used by the oven. In industry powder coating ovens have been found to have high energy consumption rates so it is an important part of the production line. This analysis will show the fuel consumption calculations along with how to make an optimal consumption plan based on the different products being used along with fuel costs.

When calculating the fuel consumption of the oven it is important to note the oven size and temperature requirements, quantity and nature of the product, oven run time, and type of price of fuel or gas. When creating the optimal consumption plan it is important to consider productivity and product quality, fuel stability, oven equipment, and environmental fuel regulations.

In order to calculate the fuel consumption of the oven the dimensions and the desired temperature are required. The oven dimensions were found to be 4 feet by 5.5 feet by 6.5 feet. When choosing the desired temperature 500 degrees Fahrenheit was chosen in order to plan for all possible temperature requirements of the powders. After analyzing for the worst-case scenario being that the oven has poor quality insulation the fuel consumption was found to be 5.8-7.9 lbs/hr. A potential method that can be used to optimize and regulate fuel consumption would be to have a programmable vent. Most of the fuel consumption comes from the fuel system turning on and off to maintain the desired temperature. By using the vent system to regulate the temperature instead of the fuel source it will allow the fuel system to have a constant input thus reducing fuel consumption.

5.1.5 Heat Transfer Analysis

The heat transfer analysis analyzed the insulation thickness to produce minimal heat loss through the oven wall. The analysis used 3.5" and 4" R15 insulation. To analyze the heat transfer of the oven wall, the team created a sample of the oven wall shown in the figure below with the thermocouple locations and the fifth being ambient temperature.

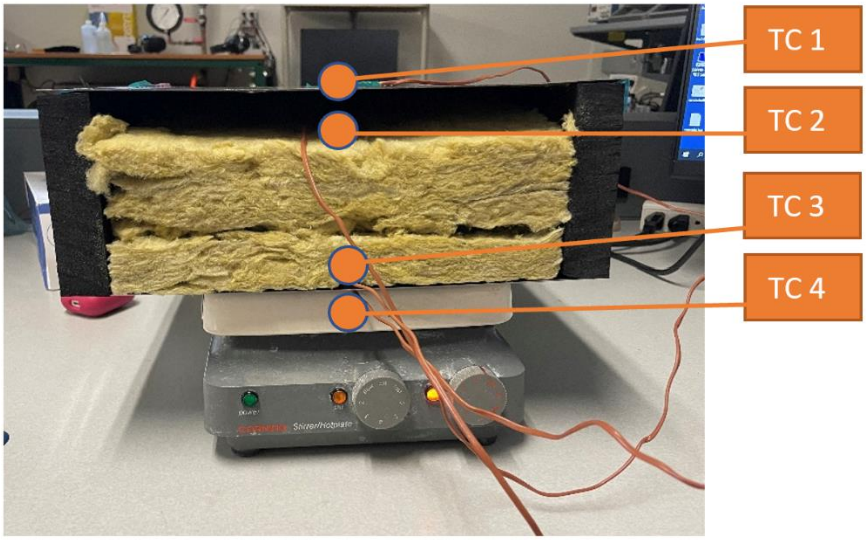

Figure 7: Oven Wall Analysis

The team analyzed the temperature change of the oven wall using 3.5” insulation and then 4” insulation. The figure below shows the temperature change through the 3.5” insulation wall. The graph shows that temperature increases in thermocouple 1 and thermocouple 2 because it is close to the heat plate, while thermocouple 3 and thermocouple 4 are not and read close to ambient temperature.

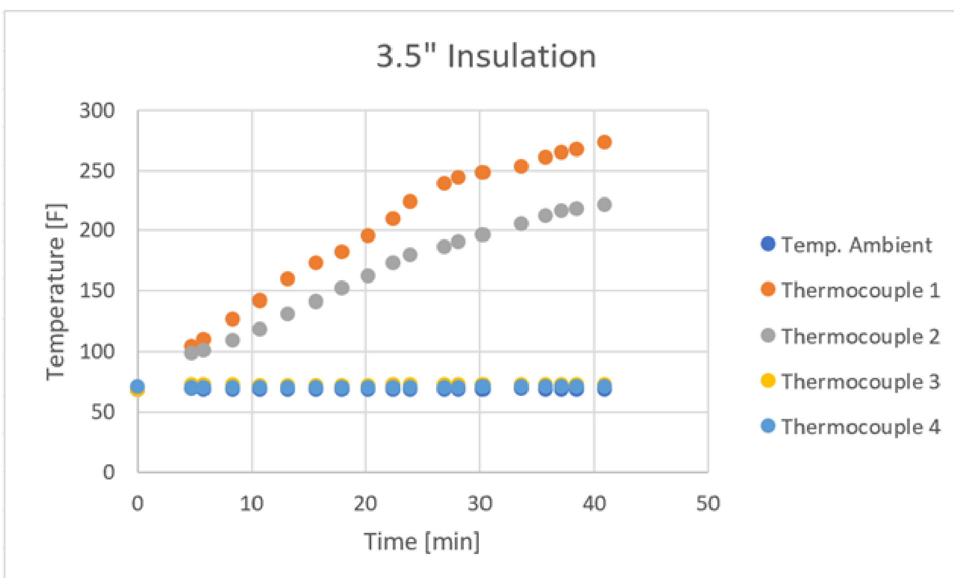

Figure 8: Temperature vs. Time in 3.5” Insulation

The remaining data and calculations are found in Appendix G. From the analysis the team concluded that since the minimal heat loss is negligible the team will use the 3.5” insulation to accommodate the use of 2x4 structural beams.

5.2 Implementation Plan (Amber)

The implementation of the design began by creating a composite wall shown in Figure 7. The composite wall helped choose which insulation would be used for the oven. The structural analysis helped verify that the 2x4 structural beam would be enough to ensure a factor of safety of 2 for the oven structure. The 2x4 beam also solidified that the insulation being used cannot be thicker than 3.5”. The structural beams also ensure that the stackable wall ducts used for the ventilation and circulation will be 3.25” thick and have 0.25” of insulation behind it to decrease the amount of heat loss and fuel consumption.

In order to build the oven, the team will first start by creating the frame of the oven along with the structural beams. The team will then attach the wall ducts, squirrel cage blower, and vent to the structural beams with rivets. The team will then attach the inside wall to the frame using rivets. Then the insulation will be added to the walls. The team will add the outside wall to the oven along with the heat duct that will attach to the torpedo heater. Lastly the oven door, and hinges along with the oven wheels and control system will be added to the oven. The rack system will be assembled separately. The rack system will be assembled by first creating the frame and then adding the wheels in order for it to move in and out of the oven freely. The oven will be constructed and tested in the renewable energy lab. Appendix H shows a detailed bill of materials that shows all the required parts that will be used to build the oven.

The schedule for the manufacturing of the oven can be found below in Appendix G. Although the schedule states oven production will begin August 28, 2023, the team will attempt to begin building the oven in June of 2023.

6 Conclusion

The main goal of this project was to design and fabricate a powder coating oven, that will primarily be used in the renewable energy lab. In the report, it was concluded that the requirements for this project have been mostly met throughout the semester. These requirements include the customer requirements provided via the client, the materials required for the project’s fabrication and the cost for such items, the type of analysis required for each part of the project and what are the conclusions provided, and the outlining for the next step in completing the project. During the semester, the team has concluded the technical analysis of individual components of the oven, which are the following; the structural analysis, which concluded that the solution of the factor of safety for the oven frame was much lower than the rack system, which suggests a revisit upon the analysis or a potential change in the design of the oven. The control system analysis, which concluded that the PID system demonstrated the regulation of the heating source of the oven and the exhaust fan, to allow for the regulation of the regulation of the desired temperature of the oven. The circulation and ventilation analysis determined that the ventilation design will allow for sufficient hot air circulation through the system, in order to maintain the desired temperature. Lastly, the heat transfer analysis, which included that the type of insulation and its required amount for the final build has met the criteria for building the oven. With the conclusion of such analysis, the next step for this project will be fabricating and building the oven, conducting physical testing and ensuring that the project has met the client’s satisfaction.

7 References

[1] "Pid Controller," *Wikipedia*, 01-Apr-2023. [Online]. Available: https://en.wikipedia.org/wiki/PID_controller. [Accessed: 30-Apr-2023].
[2] "Matlab based PID controller," *MathWorks*. [Online]. Available: https://www.mathworks.com/matlabcentral/fileexchange/35163-matlab-based-pid-controller. [Accessed: 30-Apr-2023].
[3] Libretexts, "9.2: P, I, D, PI, PD, and PID Control," *Engineering LibreTexts*, 11-Mar-2023. [Online]. Available: https://eng.libretexts.org/Bookshelves/Industrial_and_Systems_Engineering/Chemical_Process_Dynamics_and_Controls_(Woolf)/09%3A_Proportional-Integral-Derivative_(PID)_Control/9.02%3A_P%2C_I%2C_D%2C_PI%2C_PD%2C_and_PID_control#:~:text=PID%2Dcontrol%20is%20most%20commonly,additionally%20using%20the%20I%2Dcontrol. [Accessed: 30-Apr-2023].
[4] "Sys," *PID controller in parallel form - MATLAB*. [Online]. Available: https://www.mathworks.com/help/control/ref/pid.html. [Accessed: 30-Apr-2023].
[5] Northern Arizona University, "ME 495 – Intro to Data Acquisition with NI & Arduino," Flagstaff, AZ, 2022

[6] "Mineral Wool Insulation," *Engineering ToolBox*. [Online]. Available: https://www.engineeringtoolbox.com/mineral-wool-insulation-k-values-d_815.html. [Accessed: 30-Apr-2023].

[7] Dan, "Calculating the developed length of a rolled cylinder," *The Chicago Curve*, 22-May-2016. [Online]. Available: https://www.cmrp.com/blog/plate-rolling/calculating-the-developed-length-of-a-rolled-cylinder.html#:~:text=The%20AutoCAD%20default%20K%20value,your%20software%20to%20K%20%3D%200.50. [Accessed: 30-Apr-2023].

[8] "Convection heat transfer coefficient," *Convection Heat Transfer Coefficient - an overview | ScienceDirect Topics*. [Online]. Available: https://www.sciencedirect.com/topics/engineering/convection-heat-transfer-coefficient. [Accessed: 30-Apr-2023].

[9] "Custom spray booth and finishing systems | spray systems." [Online]. Available: https://www.spraysystems.com/wp-content/uploads/SpraySystems_NFPA_Doc_v2.pdf. [Accessed: 05-May-2023].

[10] "Department of Labor Logo United Statesdepartment of Labor," *1926.756 - Beams and columns. | Occupational Safety and Health Administration*. [Online]. Available: https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.756. [Accessed: 05-May-2023].

[11] "Calculation of oven fuel or gas consumption on powder coating lines ..." [Online]. Available: https://www.powdersprayline.com/calculation-of-oven-fuel-or-gas-consumption-on-powder-coating-lines.html. [Accessed: 05-May-2023].

[12] "BTU Calculator." https://www.calculator.net/btu-calculator.html?roomwidth=4&roomwidthunit=feet&roomlength=5.5&roomlengthunit=feet&ceilingheight=6.5&ceilingheightunit=feet&insulation=good&temperature=500&temperatur

8 Appendices

8.1 Appendix A: House of Quality (HoQ)

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Figure A.1: HoQ Legend

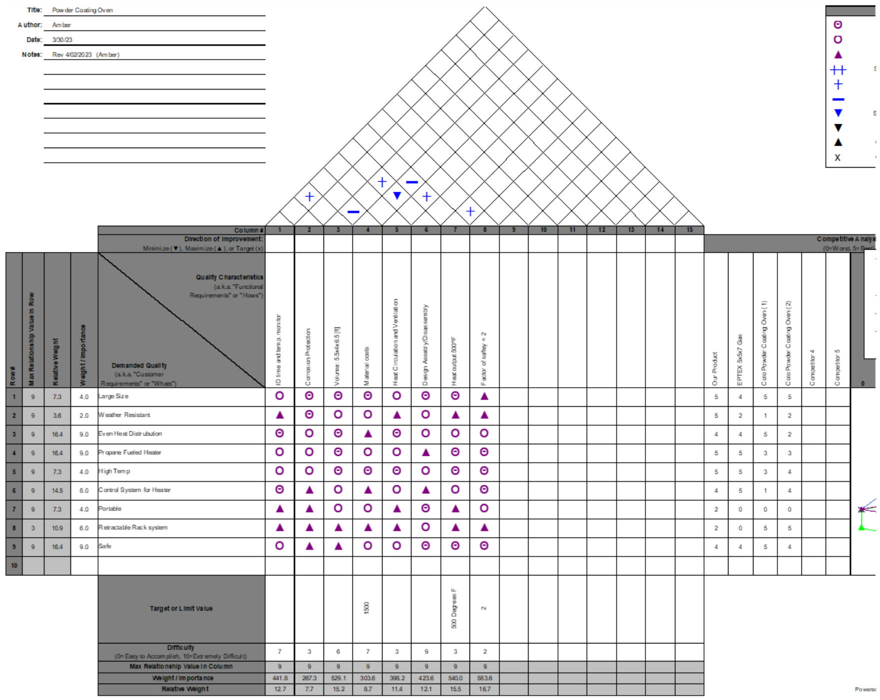

Figure A2: House of Quality

8.1 Appendix B: FMEA

Table B.1: FMEA for powder coating Oven

Product Name: Powder Coating Oven		Development Team				Page No 1 off 1			
System Name						FMEA Number			
Subsystem Name						Date: 4/18/23			
Component Name									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
BTU-125: Torpedo Heater	Corrosive wear	Inconsistent or no heat	6	Weather impact	2	Controlled heated experiment	3	36	Store indoors when not in use
GA-16-096-048: 16 gauge steel	Radiation damage	Damage structural integrity	9	Weather impact	5	Heat transfer Analysis	2	90	Coat repellant paint
GA-20-096-048: 20 gauge steel	Impact deformation	Damage structural integrity	10	Heat source impact	3	Heat transfer Analysis	2	60	use high temperature paint
GA-25-00+2-004: Steel beams	Creep buckling	Damage structural integrity	10	Load bearing impact	5	Structural Analysis	4	200	maximum load of 300 lbs
Al-DTA6-8: Duct connector	Corrosive wear	Heat loss	7	Weather impact	4	Heat transfer Analysis	2	56	cover part with tarp
R15-015-047: wool fiber insulation	Corrosive wear	Heat loss	8	Structural damage	5	Structural & heat transfer Analysis	2	80	ensure seepage does not occur
CECOMINOD004404: PID	Saturation	Inaccurate heat measurement	10	Reaching max/min heat values	2	Control System Analysis	3	60	tune/calibrate monthly
50098R: On/off switch	Electrical failure	non-working control system	10	Blown fuse from electrical source	4	Control System Analysis	3	120	ensure seepage does not occur
a12031600UX0143: Thermocouple	Metal fatigue	non-working control system	10	Expansion/Contraction of metal	5	Control System Analysis	3	150	Change thermocouples monthly
CO-HTW14-25: Wire	Corrosive wear	non-working control system	8	Structural damage	3	Control System Analysis	3	72	ensure seepage does not occur
a14030300ux0160: Buzzer light	Electrical failure	non-working control system	7	Blown fuse from electrical source	2	Control System Analysis	2	28	ensure seepage does not occur
JBH-4961-KO: Box	Corrosive wear	Damage to control system	9	Weather impact	3	Control System Analysis	2	54	cover part with tarp
a15110200ux0132: Signal Indicator	Electrical failure	non-working control system	7	Blown fuse from electrical source	2	Control System Analysis	2	28	ensure seepage does not occur
LS1225A-X: Circulation fan	Electrical failure	Uneven heat distribution	5	Blown fuse from electrical source	2	Ventilation Analysis	2	20	ensure outlet can withstand electrical output
WS-3X14DUCT: Wall duct	Buckling	Uneven heat distribution	5	improperly connected wall ducts	2	Ventilation Analysis	2	20	ensure ducts are securely connected

8.3 Appendix C: Final Design

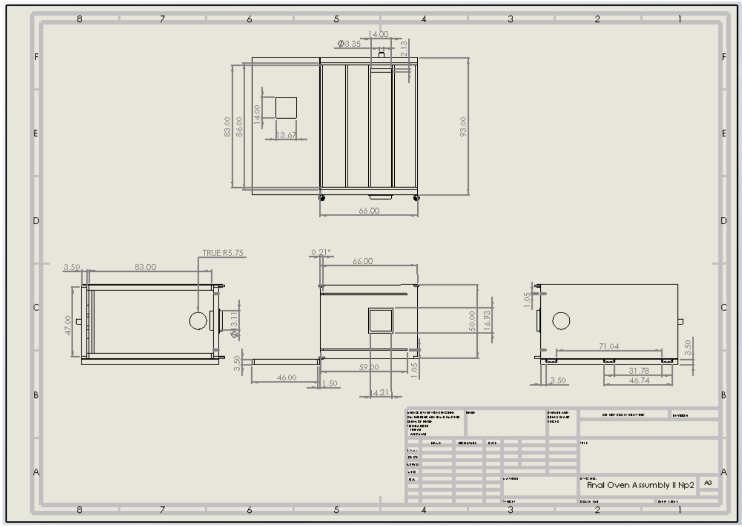

Figure C.1: Oven Assembly Schematics

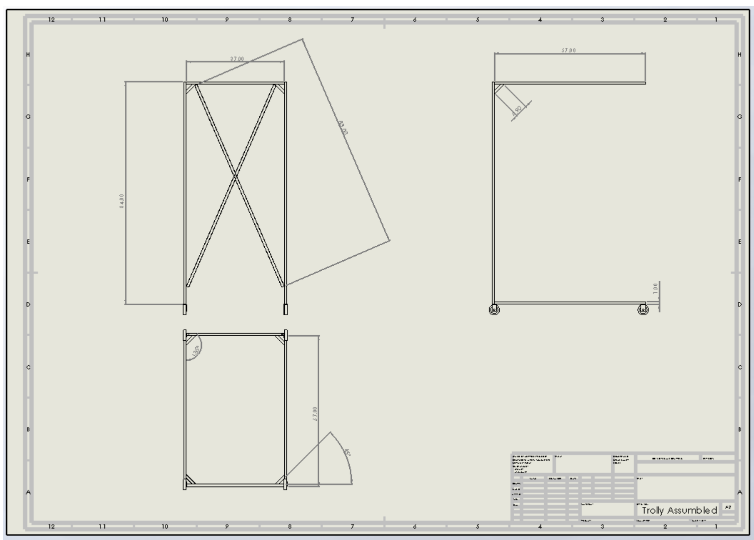

Figure C.2: Trolly Assembly Schematics

8.4 Appendix D: Control System Analysis

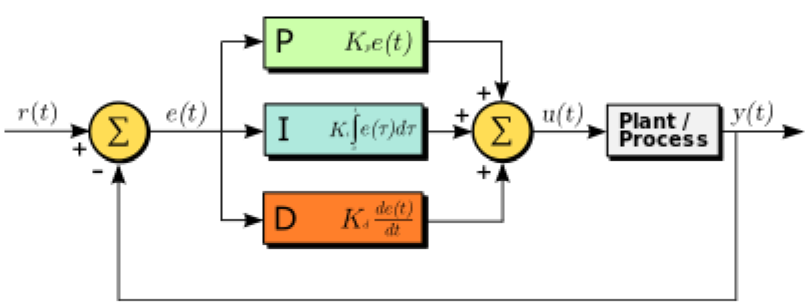

Figure D.1: PID Block Diagram [1]

```
tic                    % Timer Function:start timer to calculate CPU time

%Inputs
desired = 350;         % desired temperature (degrees Fahrenheit)
feed1 = 1;             % can be replaced with damping coefficient B or (B/Mass)
feed2 = 1;             % can be replaced with spring coefficient K or (K/Mass)
B = feed1;
K = feed2;
Kp = 1;                 % proportional term Kp
Ki = 0.01;              % Integral term Ki
Kd = 0.01;              % derivative term Kd
dt = 0.01;              % sampling time
Time = 10;              % total simulation time in seconds
n = round(Time/dt);     % number of samples
```

Figure D.2: Matlab Input Values [2]

```
% pre-assign all the arrays to optimize simulation time
Prop(1:n+1) = 0;
Der(1:n+1) = 0;
Int(1:n+1) = 0;
I(1:n+1) = 0;
PID(1:n+1) = 0;
FeedBack(1:n+1) = 0;
Output(1:n+1) = 0;
Error(1:n+1) = 0;
state1(1:n+1) = 0;
STATE1(1:n+1) = 0;
state2(1:n+1) = 0;
STATE2(1:n+1) = 0;
```

Figure D.3: Pre-assigned Arrays for Optimization [2]

```
for i = 1:n
    Error(i+1) = desired - FeedBack(i); % error entering the PID controller

    Prop(i+1) = Error(i+1);% error of proportional term
    Der(i+1)  = (Error(i+1) - Error(i))/dt; % derivative of the error
    Int(i+1)  = (Error(i+1) + Error(i))*dt/2; % integration of the error
    I(i+1)    = sum(Int); % the sum of the integration of the error

    PID(i+1)  = Kp*Prop(i) + Ki*I(i+1)+ Kd*Der(i); % the three PID terms

    STATE1(i+1) = sum(PID); % sum PID term to calculate the first integration
    state2(i+1) = (STATE1(i+1) + STATE1(i))*dt/2; % output after the first integrator
    STATE2(i+1) = sum(state2); % sum output of first integrator to calculate the second integration
    Output(i+1) = (STATE2(i+1) + STATE2(i))*dt/2; % output of the system after the second integrator
    FeedBack(i+1) = state2(i+1)*feed1 + Output(i+1)*feed2;
end

tsim = toc % simulation time

% plot results
T = 0:dt:Time;
Reference = desired*ones(1,i+1);
plot(T,Reference,'r',T,Output,'b')
xlabel('Time (sec)')
ylabel('Temperature (F)')
title('PID Simulation')
legend('Desired','Simulated')
```

Figure D.4: For Loop and Plot Code [2]

8.5 Appendix E: Circulation and Ventilation Analysis

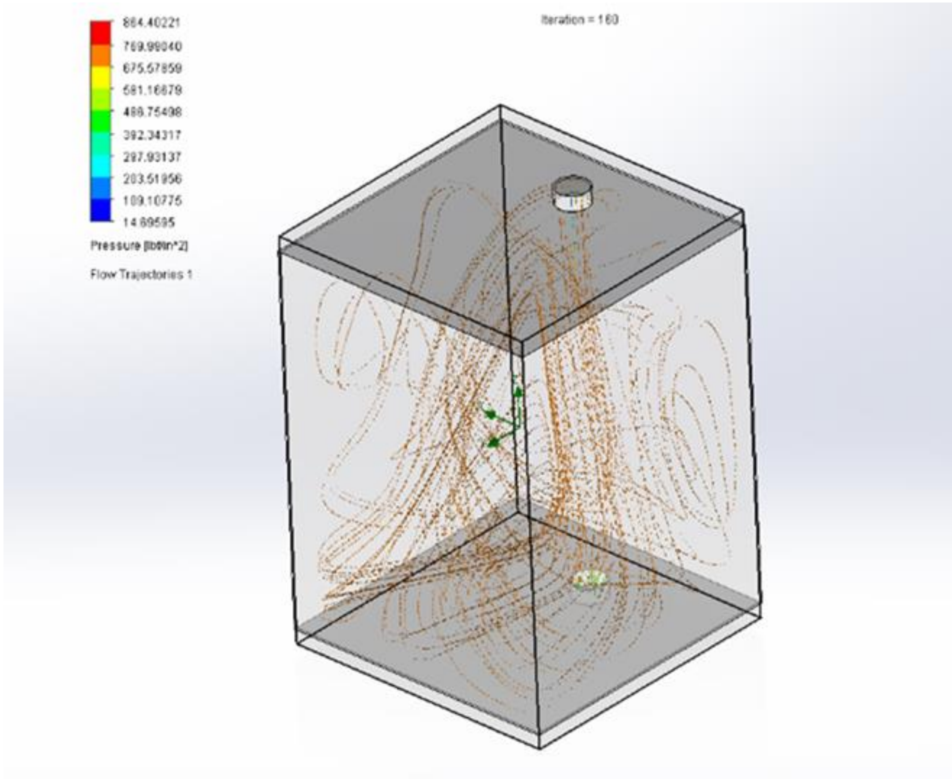

Figure E.1: Natural Air Flow Simulation

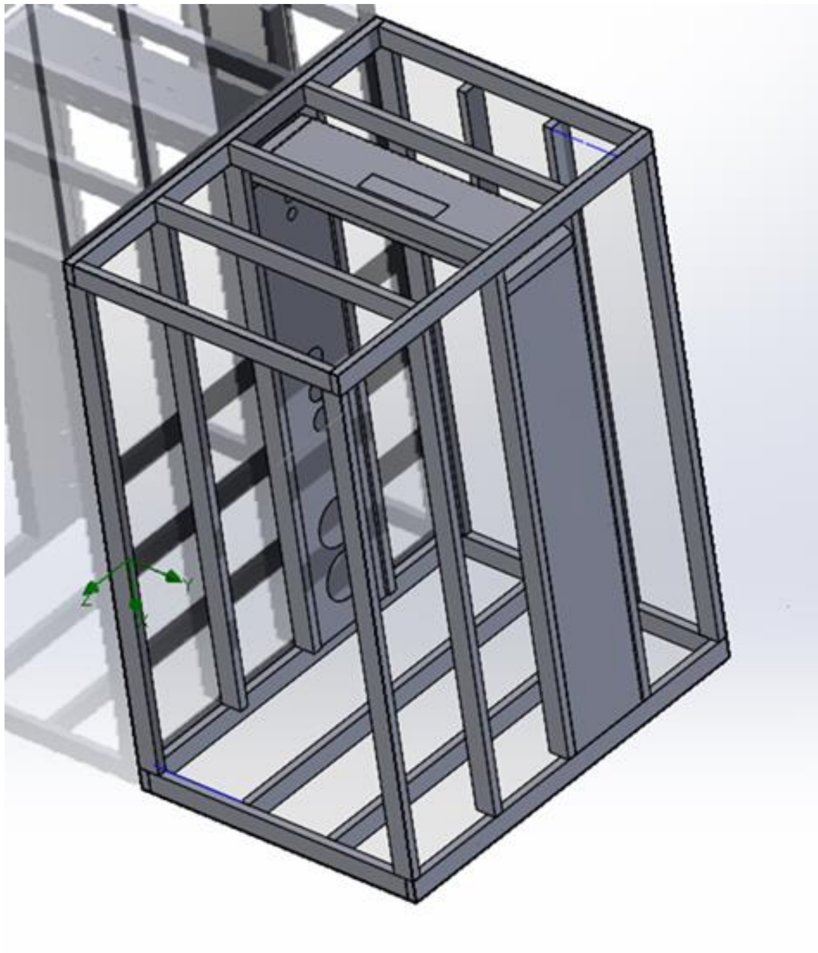

Figure E.2: Heat Circulation System

8.6 Appendix F: Fuel Composition Analysis

8.7 Appendix G: Heat Transfer Analysis

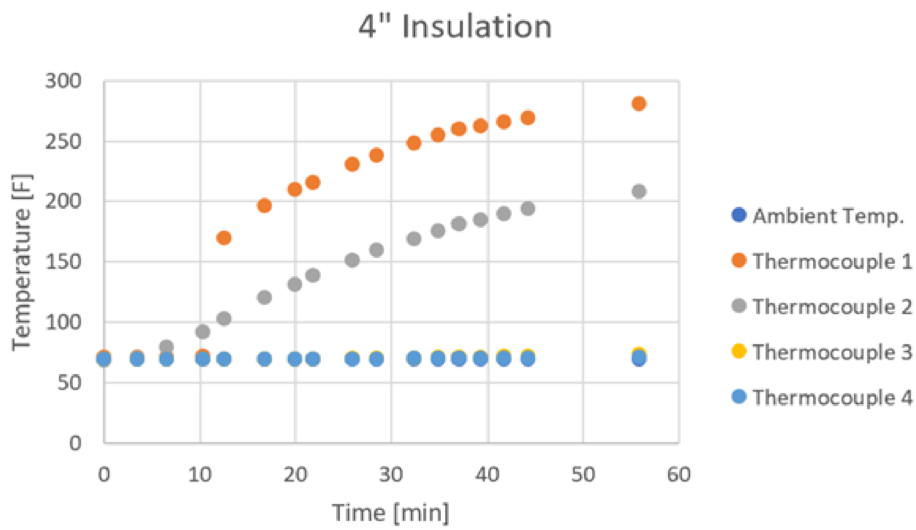

Figure G.1: Temperature vs, Time in 4” Insulation

Table G.1: Recorded Temperatures and Averages for 4” Insulation

		Average Temperature [F]				
Reading Set	Time [min]	TC (AMB)	TC 1	TC 2	TC 3	TC 4
0	0	69.01	70.6	67.95	68.98	69.12
1	3.47	68.98	70.6	69.52	68.87	68.83
2	6.54	69.11	70.76	78.76	68.8	68.73
3	10.34	69.15	71.54	91.96	69.22	69.23
4	12.59	69.18	169.12	102.75	69.08	68.96
5	16.76	69.33	195.93	119.95	69.06	68.99
6	19.93	69.42	209.79	130.59	69.13	69.06
7	21.86	69.27	215.68	138.4	69.22	69.11
8	26.01	69.26	230.85	150.9	69.51	69.29
9	28.53	69.05	237.84	159.27	69.74	69.36
10	32.46	68.83	247.96	168.92	70.13	69.5
11	34.99	68.92	254.75	175.63	70.64	69.75
12	37.09	68.74	259.79	180.88	70.88	69.91
13	39.29	68.83	262.4	184.44	71.01	69.92
14	41.71	68.85	265.89	189.75	71.3	70.03
15	44.24	68.81	269.2	193.89	71.56	70.13
16	55.89	68.76	280.89	208.24	72.9	70.42
Average:		69.03	199.03	141.87	70.00	69.43

Calculating the thermal resistive network of each component involved finding the k and h values. The team found the thermal conductivity for insulation to be 0.41 for both cases because the average temperature between thermocouple 1 and 4 was to be approximately 330 K [6]. The thermal conductivity for steel is assumed to be 0.5 from research [7]. The h value is a complex number to calculate, based on research, the team assumed h to be 13.75[8]. The data and calculations are found in Appendix B.

The team calculated the thermal resistive network through all five thermocouples and found the 3.5" insulation to be -2.08 and the 4" insulation to be -2.40. Since the values are close upon observation the difference in minimal heat loss is considered negligible. The heat flux is then analyzed between thermocouple 1, which is between the plate and steel and thermocouple two, which is between the steel at the bottom and insulation. The next heat flux was analyzed at thermocouple 4, which is between the steel at the top and open air and then thermocouple ambient (5).

The q" from thermocouple 1-2 for the 3.5" insulation is found to be 31.88 and the 4" insulation is 52.10. At the end of the thermal resistive network, between thermocouples 4-5, the heat flux for the 3.5" insulation is -14.83 and the 4" insulation is -3.07. From these heat flux values between the two different points, the team analyzed that the 4" insulation has a minimal heat loss.

8.8 Appendix H: Implementation Plan

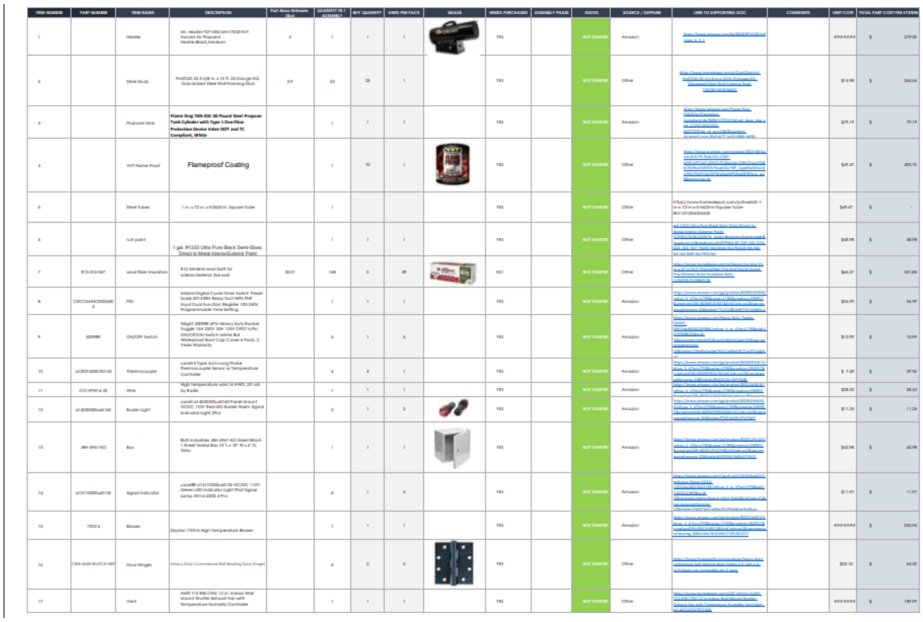

Figure H1: Bill of Materials Part 1

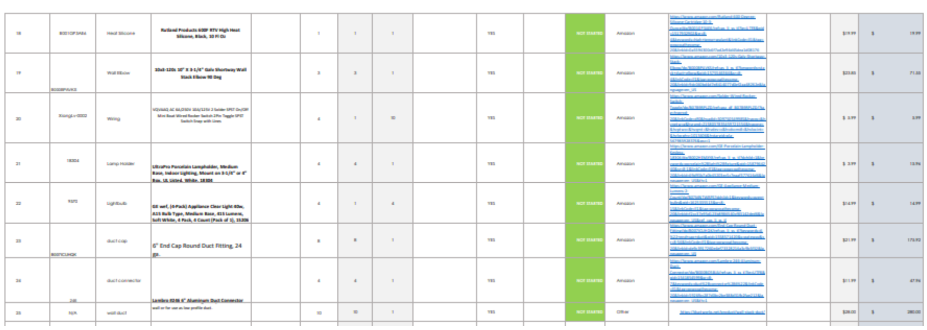

Figure H2: Bill of Materials Part 2

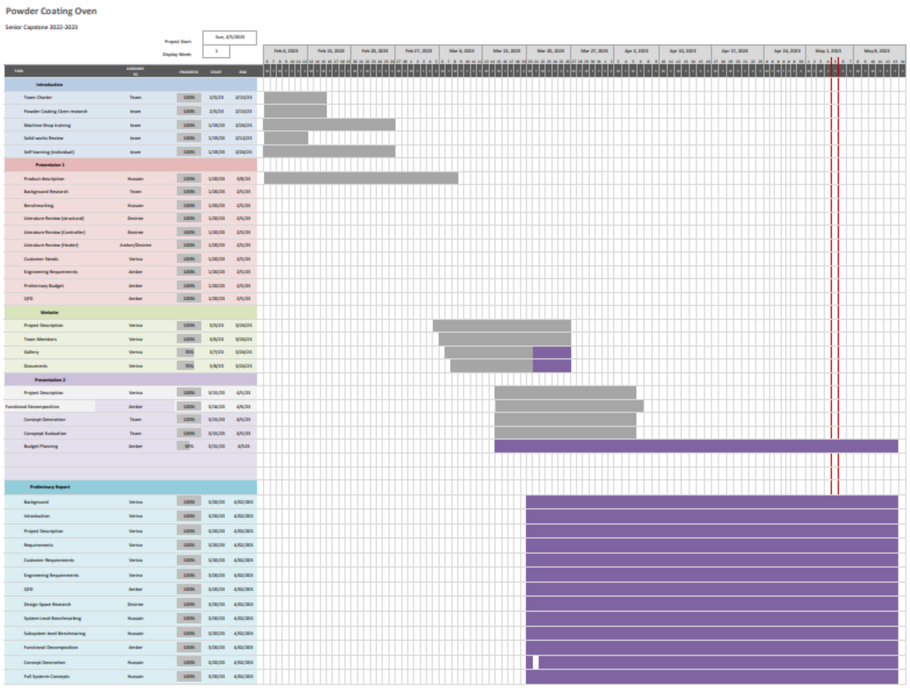

Figure H3: Gantt Chart Part 1

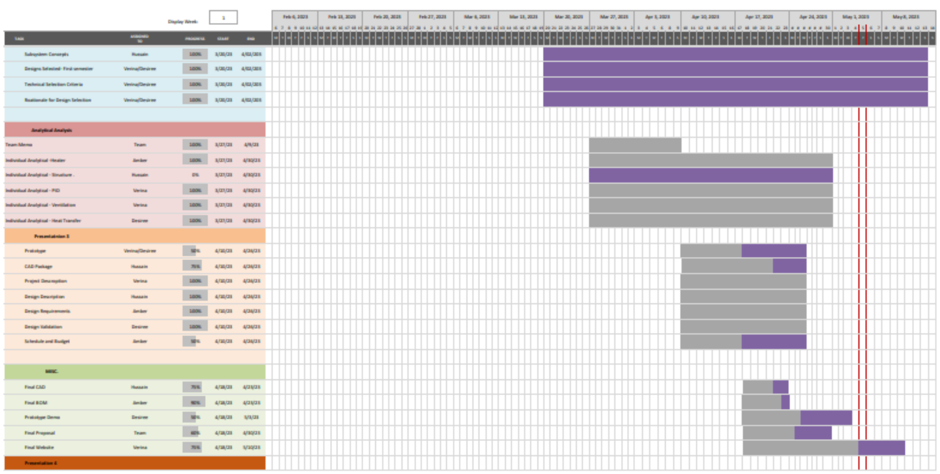

Figure H4: Gantt Chart Part 2