Powder Coating Oven

Final Report

Verina Abdelmesih

Hussain Alismail

Desiree Dee

Spring 2023 – Fall 2023

Project Sponsor: Dr. Carson Pete

Faculty Advisor: Professors David Willy, Perry Wood, and Ben Dymond

DISCLAIMER

EXECUTIVE SUMMARY

The team was tasked to design a powder coating oven, a device that is used to cure and seal the powder coat onto materials such as metals or glass. The powder coating process is an application of pigmented powder onto metallic parts, to provide a finalized finish. Powder coating is used to add color to a design or create a durable layer to the design. The process involves a pre-treatment process to the material 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 that 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 desired finish.

The team must design and fabricate a functional powder coating oven. The client's requirements are for the design to use a propane fueled torpedo heater as the source of heat, and for the oven to have a handmade control system using a PID system. The oven will be located outside of the renewable laboratory at Northern Arizona University (NAU) 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 side 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. With the conclusion of such analysis, the next step for the project was to fabricate and build the oven, conduct physical testing, and ensure that the project has met the client's satisfaction. The team was then able to manufacture the oven and conduct all seven required tests in order to ensure the oven met all the customer requirements.

ACKNOWLEDGEMENTS

The team would like to thank professors David Willy, Ben Dymond, and Perry Wood for guiding the team throughout the project. The team would also like to thank Daniel Ekstrum, mechanical engineer student, and Declan Getmatcher, civil engineer student, for helping the team with the manufacturing process when needed. Lastly, the team would like to thank our anonymous sponsors, who allowed the team to exceed the budget necessary to build the finalized design.

TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

The 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 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.

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 the most important customer needs are shown below:

List of Customer Requirements:

1. Weather Resistant
2. Even Heat Distribution
3. Material Cost < $1,500
4. Volume (4 x 4 x 8 ft)
5. Retractable Rack System
6. Propane Fueled Heater
7. Control System for Heater

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's control system which will allow the operator to regulate the temperature inside the oven. The client would also like 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. It also needs to reach a minimum of 400°F for any form of powder to be used in the oven. The design 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 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. Rack Holding Weight: The rack system must be able to hold up to 200 pounds.
2. Volume: 4' x 4' x 8' (L x W x H): The oven must fit a standard sized car bumper and Baja car frame.
3. Material Costs: The cost of the oven cannot exceed the $1,500 budget provided by the customer.
4. Heat loss: The oven must maintain a heat loss rate of less than 6 $\frac{W}{m^2}$
5. Heat Output of 400 °F: It needs to reach a minimum of 400°F so that any form of powder can be cured 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 next two sections go into detail about the two figures the team created and the meaning of each component.

2.3.1 Black Box 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.

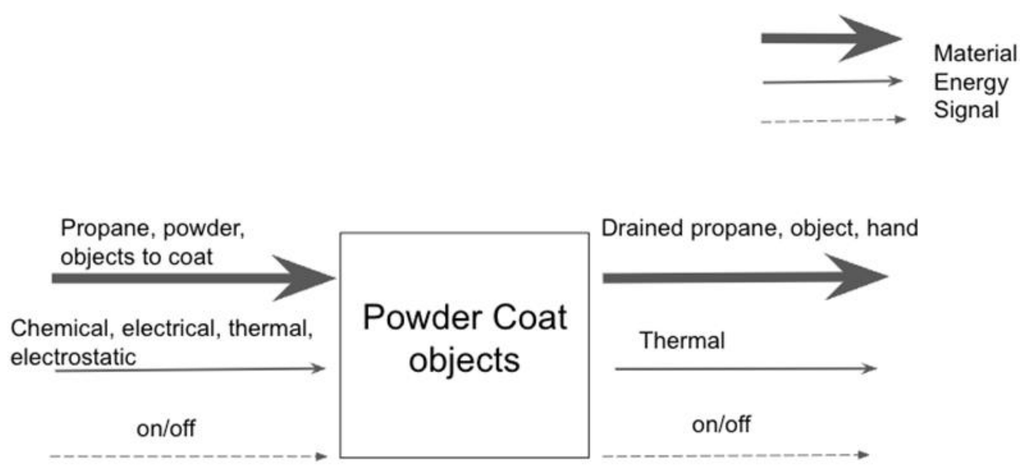


Figure 1: Black Box Model

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

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.

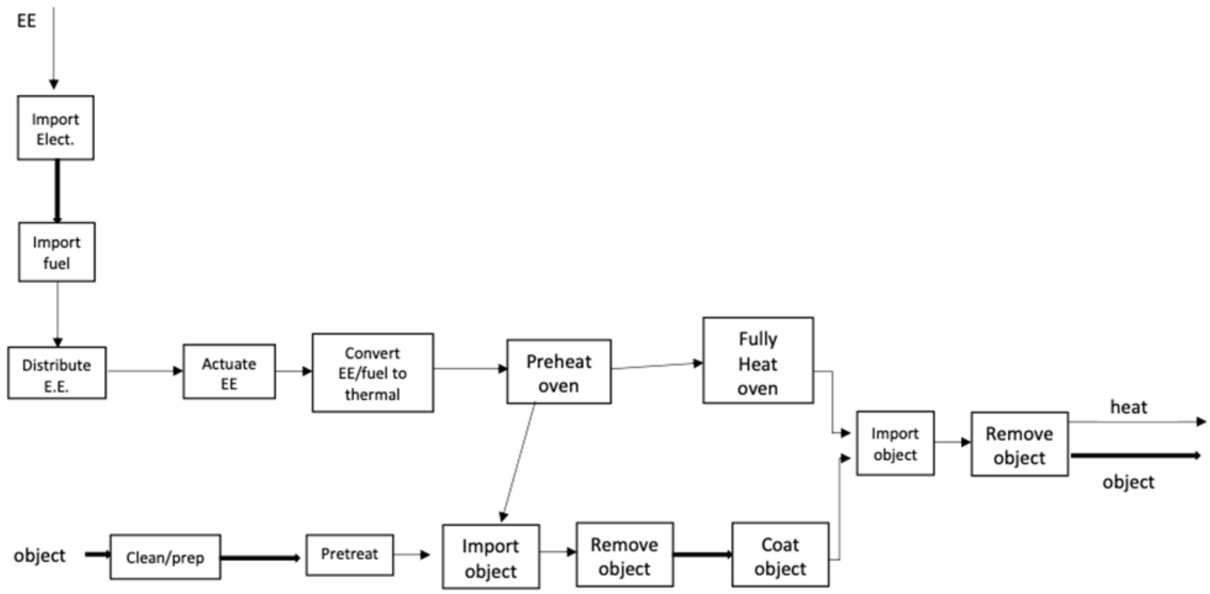


Figure 2: Functional Decomposition Model

2.4 House of Quality (HoQ)

The engineering requirements listed in the QFD is that the rack system of the oven must withstand the weight of 200 pounds (ER 1), the volume of the oven must be 4 feet x 4 feet x 8 feet (ER 2), the maximum cost of $1,500 (ER 3), a minimum heat loss of 6 W/m^2 (ER 4), and the heater must reach the maximum temperature of 400 degrees Fahrenheit (ER 5). The customer requirements listed in the QFD is the oven must be weather resistant (CR 1), have even heat distribution (CR 2), have a maximum cost of $1,500 (CR 3), have the volume of 4 feet x 4 feet x 8 feet (CR 4), have a retractable rack system (CR 5), contain a propane fueled heater (CR 6), and a self-made control system for the heater (CR 7).

The engineering requirements and the client requirements from the QFD correspond to one another. The client requirement number three aligns with engineering requirement three as well for both requirements want to spend a maximum of $1,500 on the design project. Engineering requirement one corresponds with the client requirement five as both requirements link with the rack system of the oven. Engineering requirement two corresponds with client requirement four that both require a certain volume of the oven stated by the client. Engineering requirement four corresponds with client requirements two, six, and seven as the requirements concern the heat distribution of the oven and how it operates. Engineering requirement corresponds with client requirement two as the temperature reaches the maximum temperature of 400 degrees Fahrenheit, the oven must contain an even distribution from the thermal couples for the control system to operate properly. The client requirement number one also corresponds with engineering requirement five because as the oven is consistently being used this causes the sheet metal to heat and cool, but the Rust oleum paint that can withstand the high temperature will protect the material. The complete HoQ can be found in Appendix A.

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: Standards of Practice as Applied to the Project

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 DESIGN SPACE RESEARCH

The team conducted thorough research on powder coating ovens, being able to assign each member an important factor of the oven. The important factors of the oven stated by the client are the control system, structure, heating, and insulation. The team gathered a literature review of each factor of the requirements stated in the next section.

3.1 Literature Review

The team conducted sources for the project to benchmark the design and further research on ovens and powder coating techniques. The literature review conducts an important part each member researched about the project.

3.1.1 Powder Coating Oven and Structure

[1] Lab oven – Blue M
Type-website
This source gives an example of a powder coating oven that is available on the market. The source is beneficial for the team in terms of understanding the different designs that exist for powder coating ovens, and the difference between them.

[2] Innovative powder coating oven airflow from Reliant
Type – Article
This source gives the team a sense of the air circulation of the oven. The source is important for not just understanding the circulation of hot air of the system, but how does this process allow for the regulation of temperature inside the system, so the curing process will be more accurate.

[3] A uniform cure
Type – Article
This source shows a direct illustration of what could be an optimal design for an airflow system for powder coating ovens. This source is most beneficial because it gives the team better ideas for the air circulation for the final design.

[4] Colo-1864 small batch powder coating gas oven
Type – Website
This source gives another example of a powder coating oven. This source will help the team in understanding another powder coating oven design and provide new design ideas.

[5] Colo-0813 LPG gas powder coating oven
Type – Website
The source given above gives a third example of a powder-coating oven that is available on the market. The team will benefit from this source because it gives more opportunity for design ideas and resolves some problems that the ovens industry may have encountered.

3.1.2 Control System and Curing Instructions

[6] Columbia Coating Basic Instructions
Type – Article
This source summarizes and gives the steps of powder coating. This source is useful as the team needs to create a manual on the steps of powder coating and prepping the oven to cure coating. The source is beneficial, and it talks about prepping and pretreatment for the metal before powder coating.

[7] Feedback Controllers - UC Santa Barbara
Type – lecture
The source is a PowerPoint lecture from a university in California that talks about different feedback controllers. This source is useful as it incorporates equations used for the controllers.

The team plans to use a Proportional, Integral, Derivative Control (PID) system based on meetings with Professor David Willy.

[8] Model Predictive Control vs. Proportional, Integral, Derivative Control
Type – Article
The source summarizes the differences between a model predictive control and a proportional, integral, derivative control. The source talks about the benefits of an MPC and states that an MPC is more efficient based on cost and energy efficiency. This source helps the team have a variety of control systems to choose from.

[9] The negative consequences of poor PID controller tuning: Process Dynamics and PID controller tuning: Textbook
Type – article
The source summarizes the importance of calibrating the control system, the PID controller. The source states that when the system is not calibrated/tuned errors could occur and lists possible errors. Calibrating data is crucial to being an engineer when designing projects and doing experimental labs.

[10] PID & Process Temperature Controllers
Type – article
The source talks about the overall PID controller system and temperature control. Further research on the PID control system to create an on/off switch for the oven and to be able to control the temperature setting. These are two important factors for the control system.

[11] What is a PID temperature controller?
The source focuses on the type of PID temperature controllers and the history of PID controllers. This source will allow the team to further analyze the control system and choose the final design. The requirement for the control system is to be made from scratch over a kit already made.

3.1.3 Ventilation and Safety

[12] Air flow and ventilation of paint booths: Production systems
Type – Article
The source talks about the different types of ventilation locations and how it affects the airflow of the oven. The source is useful as the team chooses where to place the ventilation system for the powder coating oven. The team plans to place the ventilation system at the bottom of the oven to allow the air to circulate up.

[13] The importance of ventilation for built-in ovens
Type – article
The source summarizes the safety and health of ventilation systems for ovens. The ventilation system ensures no fumes or gas are released into the surrounding environment the person is in. Allowing these fumes to exit into clean air can harm a person’s eyes and lungs.

[14] Do ovens need to be vented?
Type – Article

The source talks about the importance of ventilation for a general oven. The source also talks about how to keep a ventilation system clean and what could cause the system to clog. This source is important as the team learns how to stay up to date with maintenance for the oven.

[15] Safety and regulatory overview for powder coating
Type – article
The source states the safety and regulations of the powder coating. The source mentions that the metal needs to be grounded or combustion can occur. The team plans on adding a rack for the metals that are mobile for inside and outside of the oven. A safety requirement for the oven is the air flow movement to reduce the risk of combustion. The team is incorporating these factors into the design to ensure combustion does not occur.

[16] Powder coating oven design, Operation & Maintenance
Type – Article
The source summarizes the important factors to analyze for a powder-coating oven. The source also states the importance of maintenance for the oven with weekly and monthly inspections. These inspections are to ensure that the oven operates correctly, and that no damage occurs. For example, a monthly inspection is Piping, wiring, and connections of all interlocks and shutoff valves. The team plans to gather inspections needed and hand off the information to the client

3.1.4 Insulation and Heating

[17] Heating BTU Calculator: How Many BTUs Per Square Foot?
Type – Article
The source talks about converting the area of the system converted to BTU to heat the area. The source talks about being able to heat a house with a heater. This source gives the team an area of deciding the type of heater to used based on the structural analysis

[18] Thermal properties
Type – Article
The source summarizes the stone wool insulation, the team is deciding to use to encase the heat into the oven. The source states several strengths of using the stone wools, being aesthetics, circularity, robustness, fire resilience, acoustic capabilities, and water properties. The team will do further research into the alternative insulation used for ovens.

[19] BTU Calculator
Type – Article
The source talks about how to calculate the BTU needed for room dimensions. This source is beneficial for when a team member must analyze the size of the heater needed for the oven. The steps of calculating BTU are finding the room dimension, insulation level, and desired rise in temperature.

[20] 125,000 BTU Forced Air Propane Heater
Type – Article
This source shows one of the possible heaters the team will use for the oven based on the dimensions. The heater heats up to 4,000 square feet and uses a 20-pound propane tank. This heater has a range of 75,000-125,000 BTU.

[21] 170,000 BTU Forced Air Propane Heater
Type – Article
This source shows one of the possible heaters the team will use for the oven based on the dimensions. The heater heats up to 4,000 square feet and uses a 20-pound propane tank. This heater has a range of 125,000-170,000 BTU.

3.2 Benchmarking

In the past few years, powder coating has become known as an effective process for finishing parts. Many of the industry and hobbyists were able to design and fabricate their powder coating ovens to achieve the best curing for their parts. To achieve similar if not better results, the team will be using a direct comparison with similar products on the market to see what has worked from their design aspects and what flaws stemmed from these products. The team will be comparing two categories of the overall designs, system level and sub-system level benchmarking. The system benchmarking will be used to compare the overall system designs, while the sub-system benchmarking will compare the parts of the overall design.

3.2.1 System Level Benchmarking

The implementation of this section is to give a few examples of powder coating ovens that are presented on the market and to discuss their relevant designs to the team's project. The selection for this system was based on the customer requirement provided at the beginning of the semester, for the dimensions are like the customer requirements, the heat output and the controlling system, and the oven must be completely mobile.

3.2.1.1 Existing Design #1: Eptex Powder Coating Oven

The first benchmark system is a powder coating oven from EPTEX company. The design of their oven was able to meet the criteria of the final design in terms of the overall dimensions (4.7' wide x 6.7' height x 4.7' depth). Their overall design was also able to meet the requirement in terms of the output heat, for it achieves up to 500 degrees Fahrenheit for maximum output. However, the price of this product varies heavily with the requirement of the final design, which exceeds $21,060.00, while the budget for our design is no more than $1000 – 1500.

Figure 3: EPTEX Gas Oven Front View *Figure 4: EPTEX Gas Oven PID and Heater*

3.2.1.2 Existing Design #2: Colo Powder Coating Oven (1)

The second benchmark system is a powder coating oven made by Colo Company. Just like the previous company, this design was able to meet the requirements of the project by providing similar dimensions for the overall design (5.25’ length x 4.59’ width x 5.91’ height). The design was also able to achieve a close maximum temperature of 482 degrees Fahrenheit. However, this example lacks in mobility, which is required for the current design.

Figure 5: Colo Gas Oven Front View *Figure 6: Colo Gas Oven Rear View*

3.2.1.3 Existing Design #3: Colo Powder Coating Oven (2)

The third benchmark system is another Colo Company powder coating oven. The exception to this design is that it contains a separate room for the heater air circulation. This design meets the requirement in terms of exceeding the required maximum temperature (482 degrees Fahrenheit). The design, however, shows a lack of mobility, and a major difference in terms of the required measurements.

Figure 7: Colo Gas Oven Interior

Figure 8: Colo Gas Oven Exterior

3.2.2 Subsystem Level Benchmarking

The relevance of this section is to provide exceptional examples for the subsystems that the powder coating oven is relying on. These three are: heat generation, airflow system (circulation) and airflow system (exit). Each of these subsystems will be described below.

3.2.2.1 Subsystem #1: Heat Generation

The heat generation is the main function of the oven, specifically when it comes to the location of the heat generation source on the oven. In this section, examples will be given to show the relevant locations of heat sources on some ovens that exist on the market, and how these designs meet the criteria for our project.

3.2.2.1.1 Existing Design #1: EPTEX Powder Coating Oven

As shown in the figure above, this design shows the housing of the heat source of the oven. The housing unit that the EPTEX powder coating oven provides a solution for storing the heat source of the oven (the torpedo heater), which will help with most weather conditions. This design is relevant for the team because it shows a way to secure the heat source from weather exposure, as well as provide more design options for concept generation.

Figure 9: Heating System Housing for EPTEX

3.2.2.1.2 Existing Design #2: Colo Powder Coating Oven (1)

The second design by Colo Company shows that the heat source is located separately from the oven, which allows for easier access. Also, to achieve better performance, the design includes a back room that allows for less heat generation, thus lowering the power usage for the oven. The benefit of this design stems from its simplicity, and its ability to be compact while producing the same heat rate that is required for the team's design.

Figure 10: Heating System Housing for Colo

3.2.2.1.3 Existing Design #3: Colo Powder Coating Oven (2)

The third design, also by Colo Company, provides a similar case to their previous oven, apart from a fixed heat source instead of a detachable option. This design will be helpful for the team in generating ideas about the housing of the heat source, and what benefits could arise from such a decision.

Figure 11: Heating System Housing for Colo

3.2.2.2 Subsystem #2: Air Flow System (Circulation)

This section will provide benchmarking examples of products that show different air circulation designs. This section, like the previous, is most important because it allows the team to see different ways of keeping the heat in the system to accomplish an optimal powder coating finish, without the usage of extra electrical or gas power in the process.

3.2.2.2.1 Existing Design #1: EPTEX Powder Coating Oven

The first design by EPTEX Company shows that their air circulation is installed at the top of the oven. For the design, since hot air rises, the fan at the top will circulate the hot air back into the system from the top as well. The design shows the team another idea for installing the heat fan, without the cost of space. The design also shows the team how much accessibility could be implemented into the final design, to provide better maintenance for the airflow system.

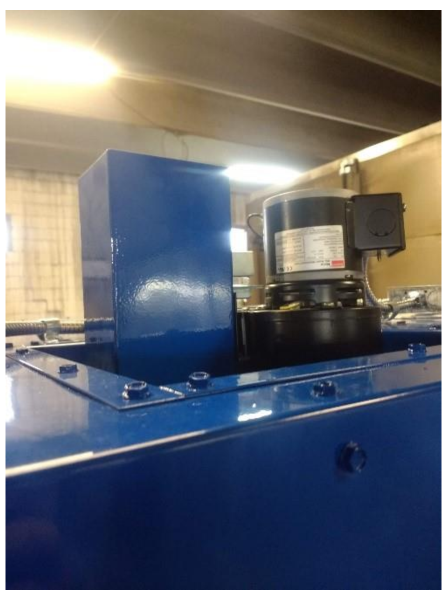


Figure 12: Circulation System for EPTEX

3.2.2.2.2 Existing Design #2: Colo Powder Coating Oven (2)

The second design by Colo company shows that the air circulation is housed in a separate compartment. The design shows a different and more efficient way for air circulation, for as the cold air sinks to the bottom of the oven, the heat fan behind the second housing is recycling it back into the system as hot air from the top. This design relates to the requirements because it shows an efficient way of regulating the temperature of the oven, with the cost of extra space.

Figure 13: Circulation System for Colo

3.2.2.3 Subsystem #3: Air Flow System (Exit)

The last step when it comes to regulating the heat inside the oven is through the heat exhaust system. This subsystem is meant to demonstrate the benchmarking of different air flow exit designs from different companies.

3.2.2.3.1 Existing Design #1: Colo Powder Coating Oven (1)

The first oven from Colo Company shows a simple design for their heat exhaust. Their design consists of a heat exhaust pipe placed in the same housing unit as the airflow system at the back of the oven. The design is helpful for its compatibility, whilst producing an equivalent temperature stabilization for better outcomes.

Figure 14: Exhaust System for Colo

3.2.2.3.2 Existing Design #2: EPTEX Powder Coating Oven

The second oven from Eptex shows a different design for heat exhaust, where the cold air leaves the system through an opening at the bottom of the oven. As the cold air accumulates at the bottom of the oven, the opening allows for the cold air to escape from the system, while the rest of the hot air is picked up by the heat fan, so it can be circulated back into the system. The design meets the requirement in terms of achieving similar dimensions to the team's design, with easily accessible systems that allow for instant repairs if needed.

Figure 15: Exhaust System for EPTEX

4 CONCEPT GENERATION

For this section, the team have constructed some concepts for the final design of the powder coating oven. These designs were generated based on the evaluation of the systems and the subsystems of powder coating ovens that are available on the market. From this, the team will evaluate each design based on a few criteria that are provided via the customer requirements, as well as safety requirements overall.

4.1 Full System Concepts

The full concept designs that are provided below will demonstrate the intent of such designs by explaining the pros and cons of each design and whether they meet the design requirements.

4.1.1 Full System Design #1: Prototype 1 (Full System)

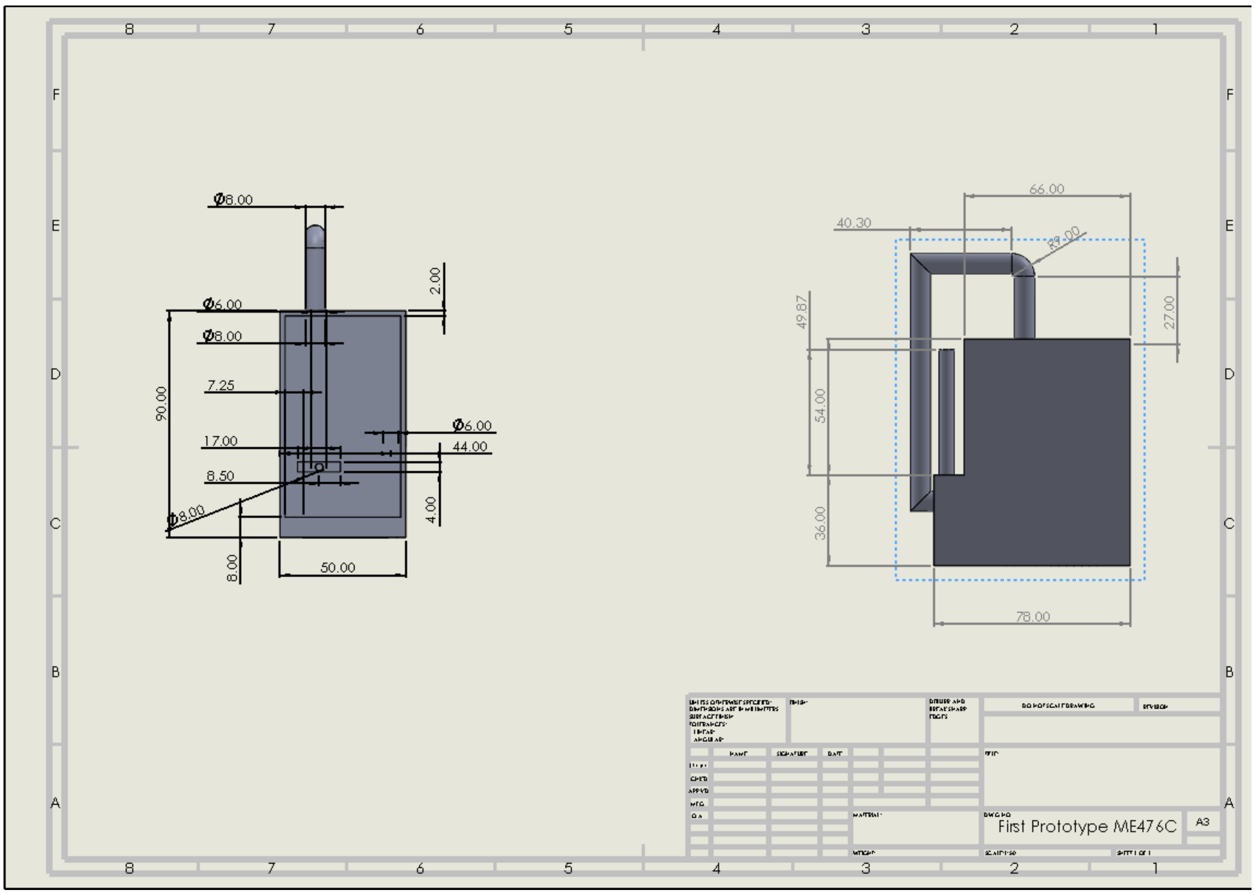


Figure 16: First Prototype – Full System Design

The first system design was designed to meet the requirements in terms of measurements, heat system, and compatibility. As seen on the right, the design offers back housing for the heat generation element (Torpedo heater), the heat fan (air circulation system) and the heat exhaust. One of the pros of this design is that it allows for the most critical parts to be secured from the harsh weather conditions. Another benefit of this design is the efficient air circulation, for the temperature will remain level for the duration of the curing process. The con of this design is the extra material used at the bottom of the oven, which will extend the project's overall budget.

4.1.2 Full System Design #2: Prototype 2 (Full System)

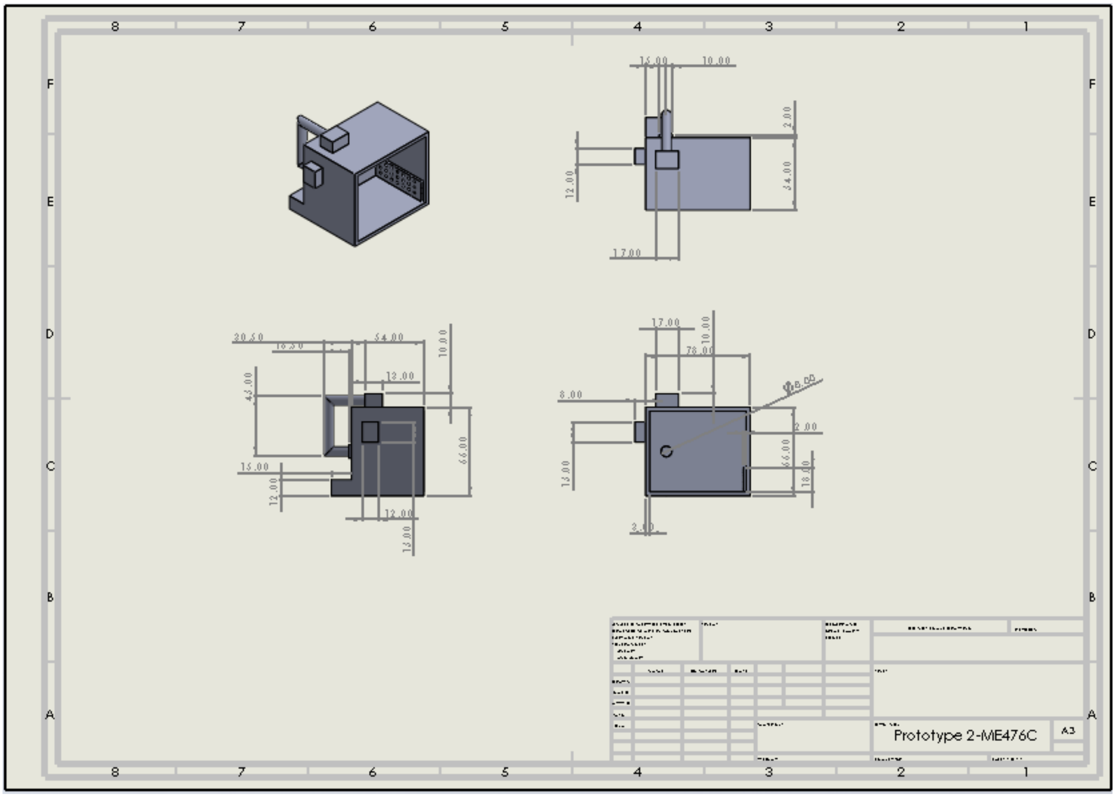


Figure 17: Second Prototype – Full System Design

The second system design was intended to increase the width of the oven, which will allow for easier heat circulation. The decision behind this design was to allow for more space inside the oven, so more parts can be cured at once. Few pros stem from this design. The first was increasing the width of the overall oven. The second was the housing of the heat fan (shown in the top right corner) and the heat generation element (shown in the bottom left corner). These additional adding were considered for the harsh weather conditions and other environmental conditions that might occur, like dust accumulation. The con of this design is mobility, for the design does not allow for the oven to be easily transported.

4.1.3 Full System Design #3: Prototype 3 (Full System)

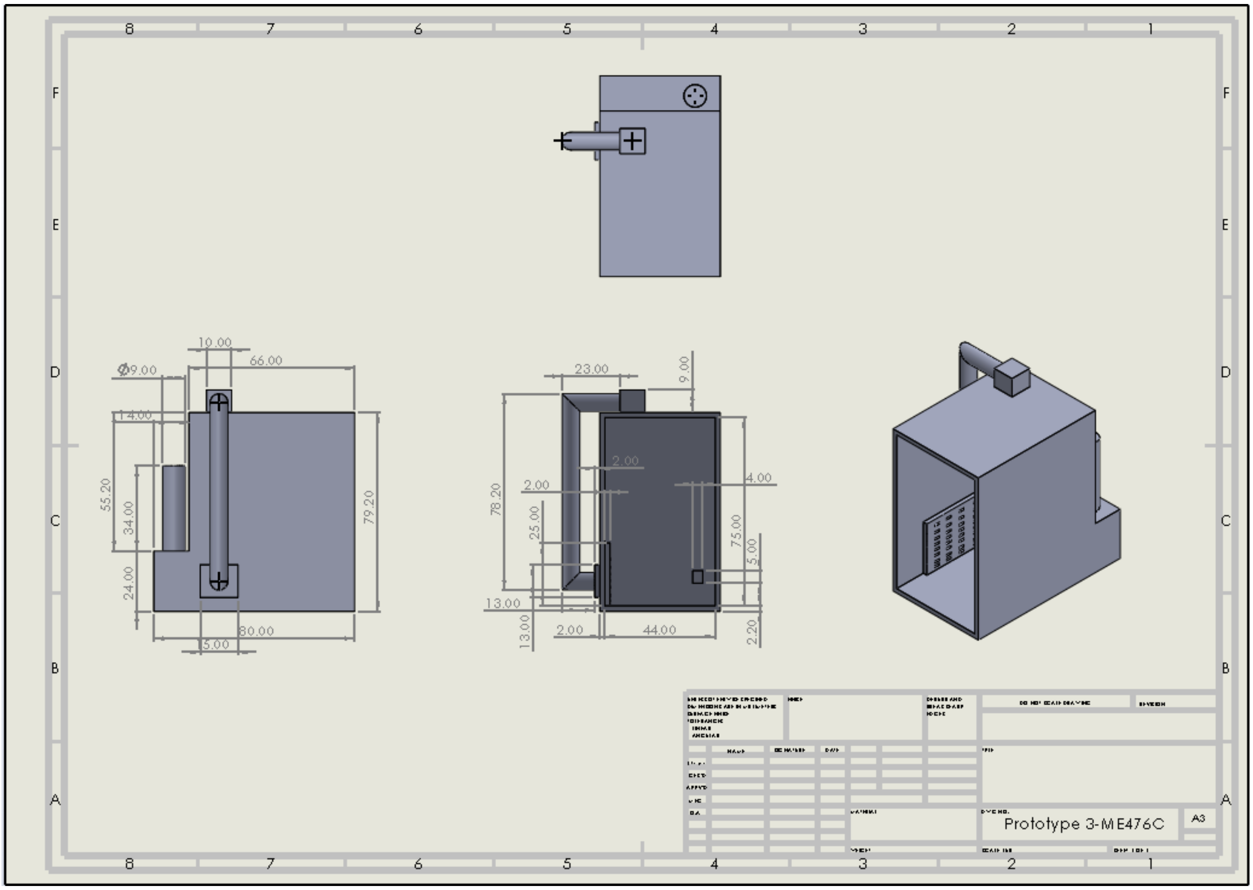


Figure 18: Third Prototype – Full System design

The third design, like the first, was designed to compact the critical elements of the powder coating oven while meeting the requirements of the final design. The difference in this design was the heat circulation system. This system was designed so the hot air would circulate from the side of the oven, through vent opening on the side of the oven (shown in the bottom right corner). One of the pros of this design is the simplicity of the heat circulation system, which allows for much easier repair management if needed. Another benefit of the design is mobility, for the system was designed for more distributed weight, which will allow for a single person to transport the oven. The con of this design is the extra material that will be used to create the vent opening for heat circulation, which will add to the cost of the oven.

4.2 Subsystem Concepts

The subsystems provided below will demonstrate the different designs for the subsystems of the powder coating oven, highlighting the pros and cons of each design.

4.2.1 Subsystem #1: Heat Generation

4.2.1.1 Design #1: Torpedo Heater Housing #1

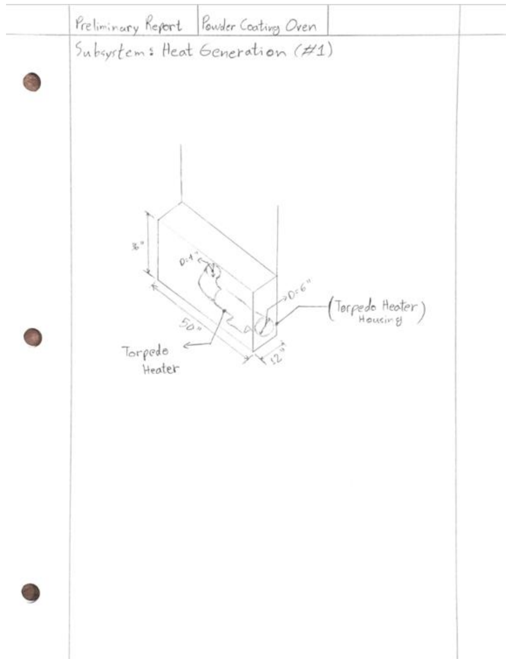


Figure 19: First Prototype – Heat Generation Sub-System Design

The first design was meant to create a housing unit for the heat generation element. The design intended to secure the Torpedo heater for Flagstaff's weather conditions that may cause damage to the heater. As seen in the figure, the heater will be placed inside the housing unit via an opening from the back. The heater will be then connected to the oven via a tube. The pro of this design is that it will allow for the safety of the torpedo heater, which will ensure longer service for the heater, and additional space for the fuel compartment. The con of this design is the extra material that needs to be fabricated for the housing unit.

4.2.1.2 Design #2: Torpedo Heater Housing #2

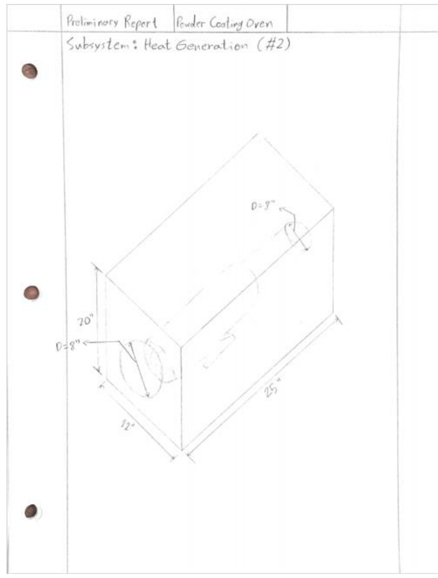


Figure 20: Second Prototype – Heat Generation Sub-System Design

Just like the first, this design was meant to safely secure the Torpedo heater during the usage of the oven. The difference in this design is that the housing unit is connected to the oven from its front end. The benefit of this design is the use of less material to construct the unit. The con of the design is the unbalanced distribution of the overall weight of the oven, with the addition of the housing unit.

4.2.2 Subsystem #2: Air Flow System (Circulation)

4.2.2.1 Design #1: Heating System #1

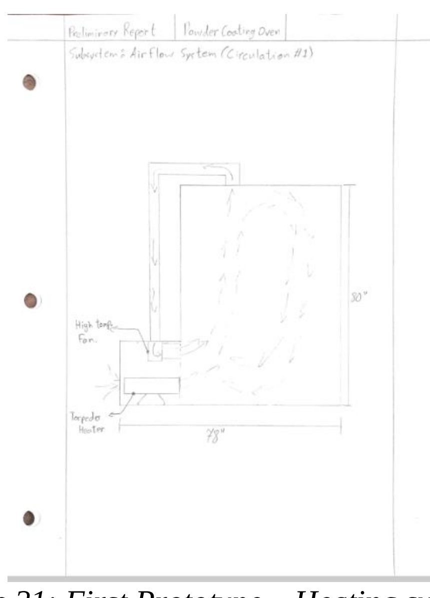


Figure 21: First Prototype – Heating system #1

The idea of this subsystem was to create a more beneficial heat circulation system for the powder coating oven. The first design shown above shows the heat generated from the Torpedo heater into the system, which rises to the top of the oven. At some point, some of the hot air will be collected from the opening at the ceiling of the oven by a heat fan, which will be transported into the tubes and back into the oven. The pro of this design is the lack of complexity and overall efficiency. The con of this is the non-expected increase in heat circulation, which will cause overheating inside the oven, thus resulting in a desired cure of the parts.

4.2.2.2 Design #2: Heating System #2

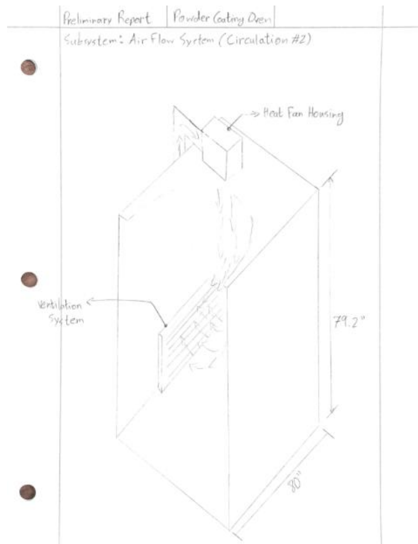


Figure 22: Second prototype – Heating system #2

The second design for the heating system was built on the third concept generation of the overall system. As shown from the illustration, as the heat comes into the system, the opening on the side of the oven will begin to extract the hot air, transporting it to the top of the oven, which will be released back into the system. The benefit of this design is its simplicity, with easy access for maintenance. The con of the design is the extra material that will be used to make the side vent inside the oven.

4.2.3 Subsystem #3: Air Flow System (Exit)

4.2.3.1 Design #1: Heat Exhaust #1

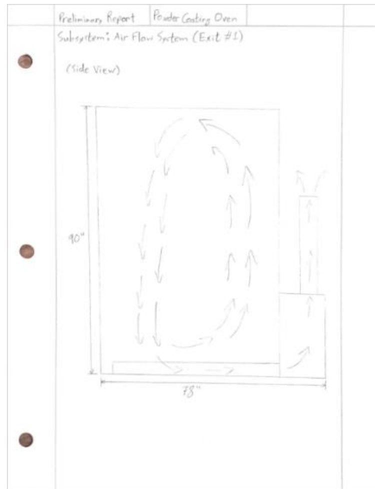


Figure 23: First Prototype – Heat Exhaust #1

For the heat exhaust system, the designs were created to extract as much cold air as possible. The first design shown above demonstrates how the cold air is extracted from the system. When the cold air is lowered to the bottom of the oven, an opening at the bottom of the oven will allow for the air to ventilate. This opening is then connected to the back of the oven (housing unit) which includes the exhaust pipe. The benefit of this design is that it allows for natural circulation of the air without the use of extra power to do so. The con of this design is the use of extra space on the inside of the oven.

4.2.3.2 Design #2: Heat Exhaust #2

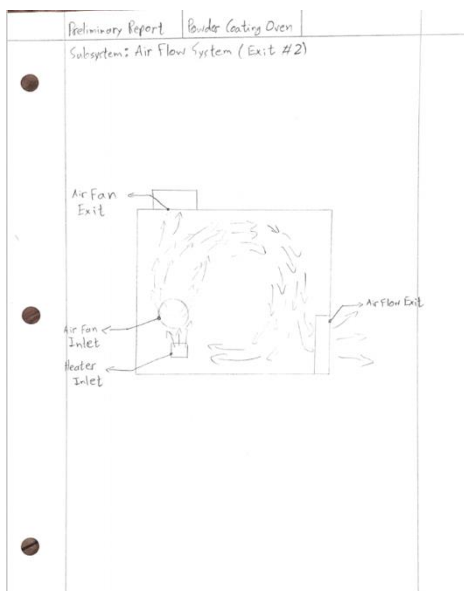


Figure 24:Second Prototype – Heat Exhaust #2

The second design was meant for a simpler solution to the air ventilation. As seen above, as the hot air circulates inside the oven, some of it will enter the opening on the right side of the oven, which will allow for an easy exit for the cold air. The benefit of this design is the use of less material to build, and its simplicity during fabrication. The con of this design is the lack of control of the temperature inside this system, which may cause issues during the curing stages of the power coated parts.

5 DESIGNS SELECTED – First Semester

The team created designs for a powder coating oven from concept generation and benchmarking. The team created a Pugh chart and decision matrix to be able to choose the top two designs the team will analyze and decide for their final design based on further work of technical analysis and prototyping.

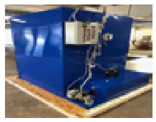
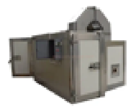
5.1 Technical Selection Criteria

For the team to be able to choose the top two designs for the powder coating oven, the design needs to meet the engineering requirements and the customer needs, which are used and scored in the Pugh chart and the decision matrix. The requirements the team input into these two tables is to have a propane-fueled heater, heat output of 400°F, to have a control system, meet safety requirements, be weatherproof, cost-efficient, heat circulation and ventilation, oven volume, retractable rack system, and portability. The team decided to propane-fueled heater because propane is cost-efficient, fuel-efficient, and long lasting compared to other energy sources, and it is not considered a hazardous leak if fuel is lost. The maximum temperature required to cure powder coating on metal is approximately 400°F. One of the requirements the client had for the team is to create a control system that has on/off switch, can control the temperature of the oven, and has a safety feature. The most important requirement for any engineering design is the safety of the oven, the client, Carson Pete, stated that the oven should not overheat and have the metal turn red. The powder oven is being placed outside the renewable energy lab, so the oven needs to handle weather all year round in Flagstaff, Arizona. The team has a budget of $1500 and the team needs to ensure the cost of the oven remains in the cost provided by the client. To ensure that the heater does not explode and to allow the heated air to circulate inside the oven, the team is examining where to place the ventilation system. A customer needs is the oven volume; the team needs to be able to fit the bumper's made by a capstone team and to fit the parts of the SAE Baja team. The oven needs a retractable rack system to be able to hold the material being powder coated and cured and needs to be portable to be able to move around outside the renewable energy lab.

5.2 The Rationale for Design Selection

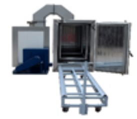
The team created a Pugh chart and a decision matrix to be able to select the top two designs the team may choose for their final design. The team first created a Pugh chart and selected design number one as the datum because the design meets most of the criteria listed on the left side of the table shown below. The Pugh chart is used to show if the other designs are better (+), worse (-), or similar (S) to the datum. From the Pugh chart, the team decided that one of the propane ovens, an electric oven, and a gas oven and the last few designs in the decision matrix.

Table 2: Part of Pugh Chart

Concept / Criteria	Design 1	Design 2	Design 3	Design 4
				
	Epoxy Oven [25]	Cole Oven [26]	Propane Oven [22]	Eptex Oven [27]
1.Propane fueled heater	Datum	+	+	-
2.Control system	Datum	S	+	+
3.Safe to Operate	Datum	S	S	S
4.Weatherproof	Datum	-	S	S
5.Material Cost	Datum	-	S	-
6.Heat Output of 500 F	Datum	+	+	+
7.Heat Circulation and Ventilation	Datum	+	+	+
8.Oven Volume	Datum	-	+	S
9.Retractable Rack System	Datum	-	-	-
10.Portability	Datum	-	+	-
Σ +		3	6	3
Σ -		5	1	4
Σ S		2	3	3

The team created a decision matrix in order to score the top three designs. These three designs were ranked based on the importance of having a propane fueled heater, a control system, and being safe to operate. The least important criteria were having a retractable rack system and being portable. Although concept two and three were electric and gas fueled, they still met many of the other customer requirements. If a propane fueled heater was not a top criteria concept 3 would have been the selected concept. Concept 1 meets all of the requirements from propane fuel to heat circulation and ventilation. It is also the only concept that met the portability requirement.

Table 3: Decision Matrix

Criterion	Weight	Propane Oven [1] 		Electric Oven [2] 		Gas Oven [3] 	
1.Propane fueled heater	0.2	100	20	0	0	70	14
2.Control system	0.2	80	16	50	10	50	10
3.Safe to Operate	0.2	74	14.8	70	14	80	16
4.Weatherproof	0.01	81	0.81	75	0.75	90	0.9
5.Material Cost	0.08	70	5.6	40	3.2	30	2.4
6.Heat Output of 500 F	0.07	80	5.6	73	5.11	60	4.2
7.Heat Circulation and Ventilation	0.12	70	8.4	62	7.44	20	2.4
8.Oven Volume	0.06	90	5.4	80	4.8	80	4.8
9.Retractable Rack System	0.03	65	1.95	87	2.61	80	2.4
10.Portability	0.03	100	3	0	0	0	0
Total	1		81.56		47.91		57.1
Relative Rank			1		3		2

5.3 Technical Analysis

For this section, the team considered providing two analysis on both subsystems of the oven, the rack system, and the oven, to ensure that both subsystems have met the engineering and customer requirements. The first analysis provided in the current oven design consists of the static analysis, which was conducted on the racking system. One of the requirements for the powder coating oven is the ability to powder coat the newly designed bumper from the bumper capstone team. With that in mind, the analysis that was conducted on the racking system demonstrates the ability of the sub-system to withstand large weights during the curing process.

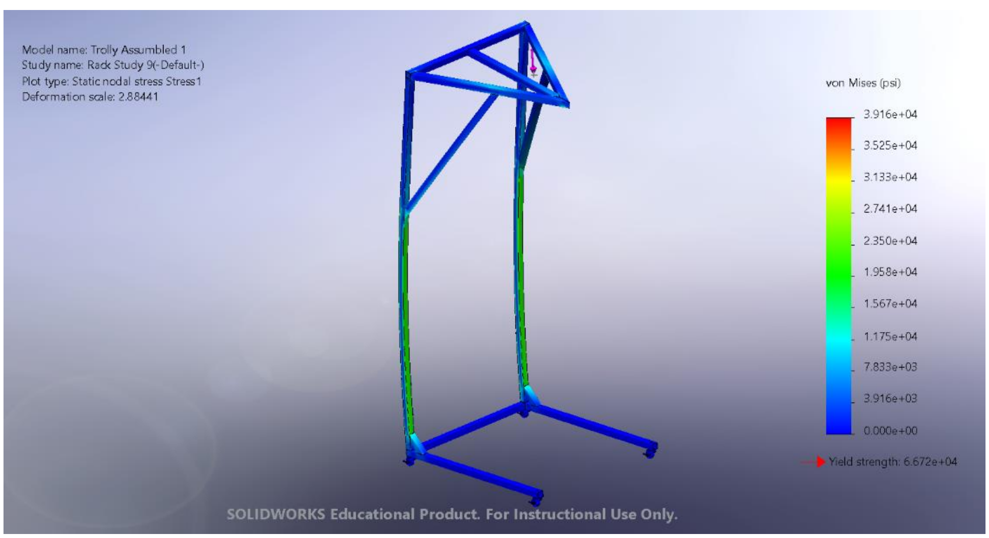


Figure 25: Final Rack System Analysis

Using SolidWorks, the team was able to simulate the maximum load that the rack system will be able to withstand without failing, which was measured to be 225lbf, located at the front of the rack system. The success of the analysis was dependent on the factor of safety, which was given to be 1.5, will be compared to the factor of safety calculated from the resultant yield strength of the analysis and the maximum yield strength of the material used, calculated via the FOS equation:

$$FOS = \frac{Material's\ Yeild\ Strength}{Maximum\ resulted\ Yeild\ Strength} \qquad \text{Equation (1)}$$

From the analysis shown in Figure 23, the FOS was calculated to be 1.7, indicating the success of the rack system design.

The second analysis provided consists of static load of the oven. The aim of this analysis is to simulate some of the weather conditions that the oven will endure, so a snow load calculation was conducted using the equation below:

$$P_f = 0.7C_eC_tI_sP_g \qquad \text{Equation (2)}$$

Provided by the ASCE 7-10, the equation was used to calculate the snow load dependent on the surface area of the structure. Presented in the equation are the following: P_f, the snow load, which was calculated to be 183lbs. C_e, the exposure factor, given between 0.8 to 0.9. C_t, the thermal factor, given as 1.1. I_s, the importance factor, also given as 1.1. P_g, the minimum snow load, depended on the region, given to be 15lbs/ft^2. With the snow load number being calculated, it was used to conduct the analysis via SolidWorks:

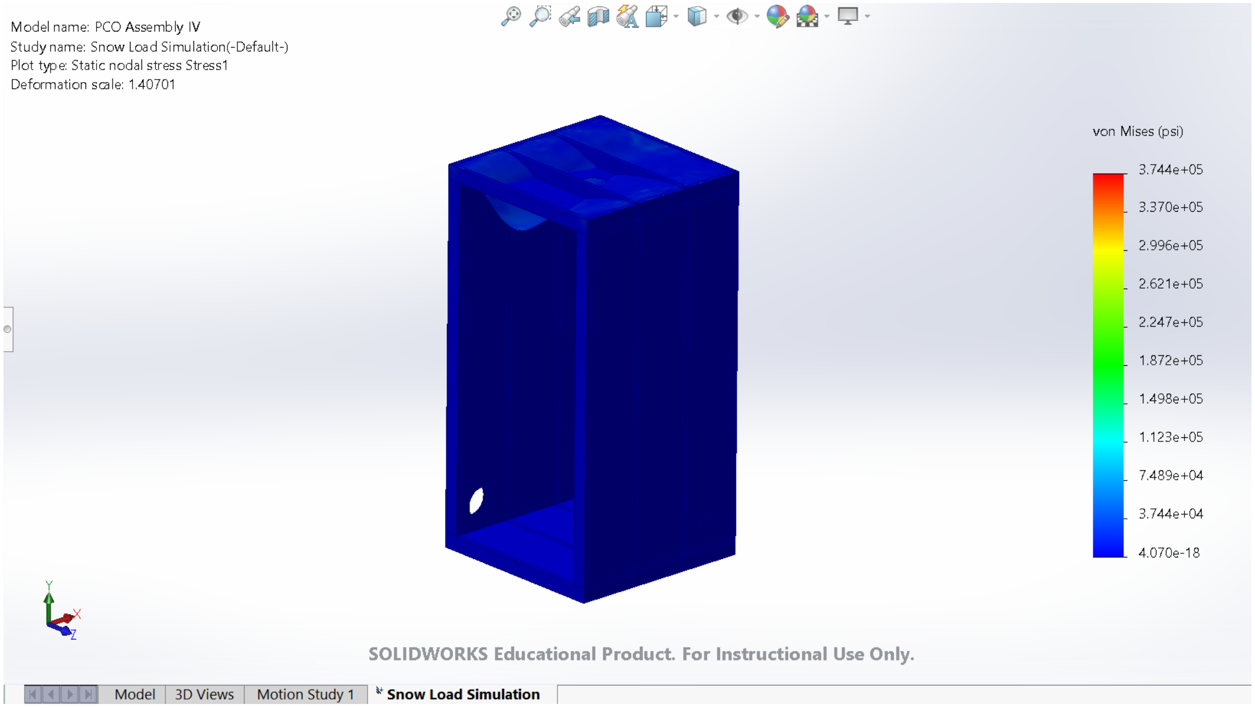


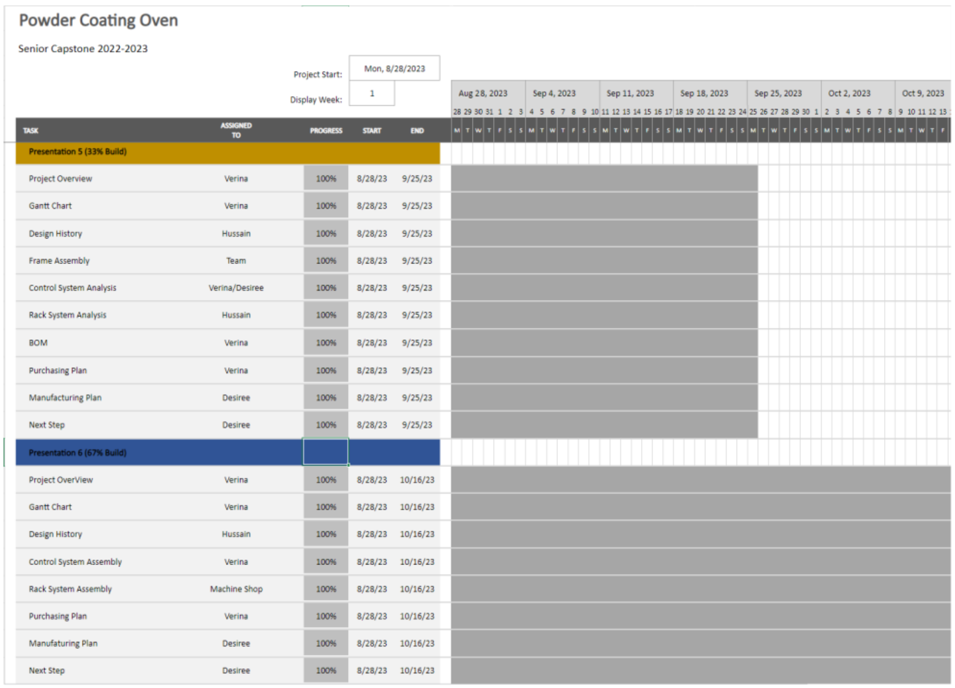
Figure 26: Snow load analysis

As shown in Figure 26, the oven was able to withstand the snow load applied, with the implication that it will hold to real life conditions throughout its usage. Using the tensile strength of the material used for the oven walls, cold rolled steel, which was given to be 60,915psi, the factor of safety resulted as 1.63, further proving the sturdiness of the design.

6 Project Management – Second Semester

6.1 Gantt Chart

The team created a Gantt chart for the second semester to ensure the team met the require due dates of the percentage build completion. The figure below shows an outline of the Gantt chart. The team outlined the Gantt chart based on 33% build, 67% build, 100% build, final testing results, and miscellaneous. The remaining parts of the Gantt chart can be in Appendix B.



TASK	ASSIGNED TO	PROGRESS	START	END
Presentation 5 (33% Build)				
Project Overview	Verina	100%	8/28/23	9/25/23
Gantt Chart	Verina	100%	8/28/23	9/25/23
Design History	Hussain	100%	8/28/23	9/25/23
Frame Assembly	Team	100%	8/28/23	9/25/23
Control System Analysis	Verina/Desiree	100%	8/28/23	9/25/23
Rack System Analysis	Hussain	100%	8/28/23	9/25/23
BOM	Verina	100%	8/28/23	9/25/23
Purchasing Plan	Verina	100%	8/28/23	9/25/23
Manufacturing Plan	Desiree	100%	8/28/23	9/25/23
Next Step	Desiree	100%	8/28/23	9/25/23
Presentation 6 (67% Build)				
Project OverView	Verina	100%	8/28/23	10/16/23
Gantt Chart	Verina	100%	8/28/23	10/16/23
Design History	Hussain	100%	8/28/23	10/16/23
Control System Assembly	Verina	100%	8/28/23	10/16/23
Rack System Assembly	Machine Shop	100%	8/28/23	10/16/23
Purchasing Plan	Verina	100%	8/28/23	10/16/23
Manufaturing Plan	Desiree	100%	8/28/23	10/16/23
Next Step	Desiree	100%	8/28/23	10/16/23

Figure 27: Part of the Gantt Chart

The changes that the team made from the original Gantt chart in the beginning of the semester is adding on the type of tests conducted to ensure that the design meets all engineering requirements and client requirements. In the beginning of the semester, the team was undecided on the tests that needed to be completed to fulfill this requirement, but along the number of tests needed to be completed by the end of the semester. The team would make no changes to the Gantt chart for the second semester as it helped the team complete required manufacturing, tests, and documents on time.

6.2 Purchasing Plan

The team outlined the purchasing plan for the second semester using a bill of materials (BOM) which is outlined in the figure below. The entire BOM can be found in Appendix C. The BOM is organized by the component part of the oven, material, product and project dimensions, quantity per pack and quantity needed, who purchased the materials, where the material was purchased, and cost per pack with total cost.

	No.	Material:	Product Dimensions:	Project Dimensions	Quantity Per Pack	Quantity Needed	Cost per unit	Total Cost:	Purchased By:	Source:	Link:	Purchase?	Arrived
For the Oven	1	20 gauge sheet metal	4 ft x 8 ft	4 ft x 8 ft	1	11	$80	$880	Carson/Verina	Artisan Metal Works	N/A	Yes	Yes
	2	25 gauge steel stud	25 3-5/8 in x 10 ft	4 ft x 8 ft	1	24	$14.98	$359.52	Carson	Home Depot	https://www.homedepot.c	Yes	Yes
	3	piano hinge	12 in x 1.18 in	8 ft	2	7	$11.99	$47.96	Carson	Amazon	https://www.amazon.com/	Yes	Yes
	4	rivets	3/16 in x 1/8 in	3/16 in x 1/8 in	50	300	$7.27	$43.62	Verina	Home Depot	https://www.homedepot.c	Yes	Yes
	5	rustoleum paint	300 sq ft	144 sq ft	1	1	$26.98	$26.98	Verina	Home Depot	https://www.homedepot.c	Yes	Yes
	6	wheels	6 inches	6 inches	4	4	$58.99	$58.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes
	7	R15 wool insulation	15in x 47 in	15in x 47 in	1	3	$69.68	$209.04	Verina/Carson	Home Depot	https://www.homedepot.c	Yes	Yes
	8	Oven Gasket	30ft	24ft	2	1	$13.99	$13.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes
	9	Door Latch and Screws	N/A	N/A	4	4	$20.98	$20.98	Carson	Amazon	https://www.amazon.com/	Yes	Yes
	10	Oven Window Glass	10 in x 10 in	10 in x 10 in	1	1	$65.19	$65.19	Verina	One Day Glass	https://proxy.onedayglass.c	Yes	Yes
	11	High Temperature Sealant	N/A	N/A	1	2	$7.68	$15.36	Verina	Amazon	https://www.amazon.com/	Yes	Yes
For the Rack	12	Steel rods	10ft	50ft	1	5	$1.79	$105.22	Carson	Mayorga's Welding	N/A	Yes	Yes
	13	Eye Hooks	N/A	N/A	1	1	$4.65	$4.65	Verina	Home Depot	N/A	Yes	Yes
	14	wheels	2 inches	2 inches	4	4	$16.99	$16.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes
For the Control System	15	k thermo	3M	N/A	1	3	13.99	41.97	Verina	Amazon	https://www.amazon.com/	Yes	Yes
	16	PID	N/A	N/A	1	1	62.98	62.98	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes
	17	Box	N/A	N/A	1	1	99.98	81.98	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes
	18	E stop	N/A	N/A	1	1	6.99	6.99	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes
	19	Toggle switch	N/A	N/A	1	1	3.4	3.4	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes
	20	alarm light	N/A	N/A	1	1	6.95	6.95	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes
	21	ON/OFF switch	N/A	N/A	1	3	9.98	29.94	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes
	22	Wiring	20 ft	20 ft	1	1	$7.21	$7.21	Verina	Home Depot	N/A	Yes	Yes
	23	Lamp Holder	3-1/4 in	N/A	1	1	$3.99	$3.99	Verina	Amazon	https://www.amazon.com	Yes	Yes
	24	Lightbulb	N/A	N/A	1	1	$1.39	$1.39	Verina	Walmart	N/A	Yes	Yes
	25	duct cap	6in	N/A	1	2	$21.99	$43.98	Verina	Amazon	https://www.amazon.com	Yes	Yes
	26	duct connector	6 in	N/A	1	1	$11.99	$11.99	Verina	Amazon	https://www.amazon.com	Yes	Yes
	27	Switch Wire		N/A	6	6	11.99	11.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes
	28	120 V Cable Plug	6 ft	N/A	1	1	20.99	20.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes

Figure 28: Partial Bill of Materials

The BOM is extremely different from the original document created in the beginning of the semester. The team changed where the materials were being purchased to cut down prices of the oven. Another change to the BOM is the control system of the oven. The team had a lack of knowledge about designing the control system, previously there was no wires in the BOM because the team was unsure about the type of wire required for a control system and to withstand high temperatures. The BOM also had no solid state relay (SSR) for the control system in the beginning of the semester. The team also added materials to ensure the oven would be completely sealed like sealant glue and an oven gasket for the door.

6.3 Manufacturing Plan

The team implemented the manufacturing plan into the bill of materials along with the components of the oven. The team aligned the part being manufactured with the material and the total time to manufacture the part. The figure below shows the manufacturing plan of the bill of materials.

Manufacturing Time	Notes
Frame Assembly: 37.5 Hours	$500 Donated
Over All Oven Assembly: 20 hrs	
	Donated
Rack Assembly: 6 hours	Donated
	Donated
Control System Assembly: 8 hours	
	+ 40A heat sink
	light bulb to PID
	PID to Switch
	PID TO OUTLET
	Carson Ordered should be here soon
	Aprroved
	Donated

Figure 29: Manufacturing Plan of Bill of Materials

In the beginning of the semester the team created the manufacturing plan in a word document to organize the process of assembling the powder coating oven. The outline of the manufacturing plan is displayed below:

Building Procedure

1. Calculate and measure the distance of the rivet on the oven frame.
2. Measure and cut out the holes in the cold-roll steel panels for the heater, vent, and blower.
3. Cut the top inside panel of the oven wall for the light placement.
4. Cut out holes in the door panels for the tempered glass.
5. Rivet the framing of the oven together.
6. Create the frame of the door. Include a frame for the tempered glass so that it doesn't make contact with insulation.
7. Attach the inner panels of the oven to the frame. Attach the burner to the inner panels to powder coat the interior wall to create a coat to withstand heat and rust. The team will then powder coat the exterior bottom panel of the oven and the interior panel of the door. Allow the panels to cool overnight.
8. Analyze and check the powder coat layer on the interior of oven and if layer is set attach the wheels to the exterior panel, then attach the exterior bottom panel to the frame of the oven. Add insulation between the interior and exterior panels.
9. Attach the interior panel to the door. Then add the tempered glass and use silicone sealant adhesive. Then add insulation and outside panel.
10. Attach the hinges and latches to the door. Then attach the u-shaped door sealant adhesive to the edges of the door. Then attach the door to the oven.
11. Powder coat the exterior of the oven. Leave to cure overnight.
12. Attach the blower, vent, and heater to the oven.

Figure 30: Semester 1 Manufacturing Plan

In the beginning of the semester, the team had planned to assemble the oven frame then insert the metal sheets to fit inside and outside the oven. The team ran into complications with the original manufacturing plan because the metal sheets could not be riveted to the frame properly. The team then changed the plan to riveting the inside metal sheets to the frame of the oven. The team then assembled the oven frame and riveted the outside metal sheets onto the frame. The assemble of the oven box was what the team would have done better this semester. This error caused the team to damage a piece of sheet metal and had to repurchase this material.

7 Final Hardware

This section highlights the final design of the powder coating oven with each component discussed in detail. Through the second semester the team made changes in the design to fit the client needs that were made in the beginning of the semester. Each change is mentioned with how and why the change in the design were made.

7.1 Final Hardware Images and Descriptions

The team accomplished the goal of designing and manufacturing a powder coating oven that meets all engineering requirements and client requirements previously stated in section 2.1 and section 2.2. In the figure below displayed the overall build of the powder coating of that is the volume of 4’ x 4’ x 8’. The oven is coated with black high temperature rust oleum to be compatible for weather resistant. In the figure, to the left is the propane fueled heater that is operated by the control system, the tan box.

Figure 31: Final Hardware Design of Powder Coating Oven

The figure below displays the retractable rack system that is a component for the oven. The rack has self-locking wheels to be able to stay in one place when powder coating or placed in the oven. The rack system can withstand 200 lbs. as tested during the manufacturing process and the testing plan.

Figure 32: Rack System of Powder Coating Oven

The most important component of the oven is the control system, as shown below in the figure. The control system operates the functionality of the oven with an on/off switch, timer, temperature control, and an emergency off switch. The functionality of the oven cannot operate without the solid state relay (SSR), which regulates the inputs from the heater to the PID allowing the heater to turn on and off. The wires of the control system run in the control box and through the framing of the oven. The layout of the control system is shown in the next figure.

Figure 33: Control System Attached to Powder Coating Oven

The figure below displays the control system circuit diagram in detail. The black labeled wiring is a neutral wire, the red wiring is live meaning a current is going through the wire, the green is the ground wire, and yellow is terminal to terminal wire.

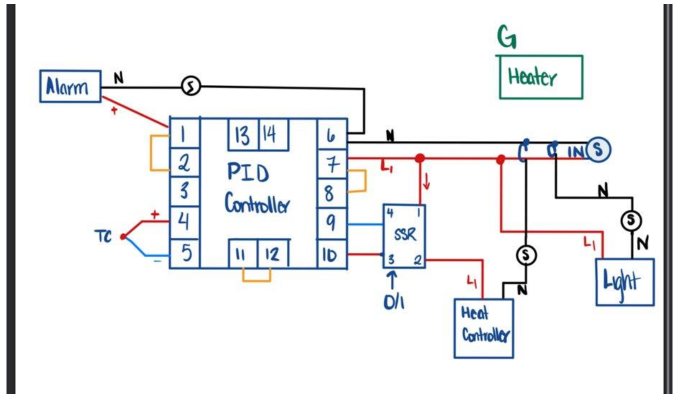


Figure 34: Control System Circuit Diagram

7.2 Design Changes in Second Semester

From the first semester of the design project, the team made changes in the second semester. The design changes and iterations are discussed below in detail.

7.2.1 Design Change 1: Oven Size

In the beginning of the semester, the team originally had the dimensions to be 4’x5.5’x6.5’, which met the requirement for the SAE BAJA club’s components to fit properly in the oven. The team changed the dimensions to the oven to be 4’x4’x8’ to meet the client’s new requirement stated in the beginning of second semester. The team also agreed to make these changes to fit the industry standards to cut costs of materials rather than exceeds the allotted budget to customized materials.

7.2.2 Design Change 2: Mobility of Oven

In the beginning of the semester, a requirement made by the client was for the oven to be portable in the renewable energy lab. The team had planned and added wheels onto the oven, but the team then ran into complications. The client and a team member were trying to rotate the oven at a 90 degree angle to attach the outside sheet metal and the floor of oven had buckled, damaging the base of the wheels. The damage of the oven is displayed in the figure below. With the client being there and experiencing the challenge, the oven no longer required to be mobile, and the wheels were removed. The oven is now placed on bricks for the use of the retractable rack system.

Figure 35: Results of Buckling Powder Coating Oven

7.2.3 Design Change 3: Oven Door Design

A change made during the second semester is adding a window onto the oven door. This allows the client to see inside the oven when a product is curing. The figure below shows the hole made in the door for the window.

Figure 36: Oven Door with Hole Placement for Window

7.2.4 Design Change 3: Rack System

The rack system overall was added to the design in the second semester. In order to complete manufacture the rack system, the team began by creating structural analysis using SolidWorks to compute the factor of safety stated by the client. The team struggled due to the lack of knowledge in this particular structural analysis. The design iterations of the rack system are displayed below:

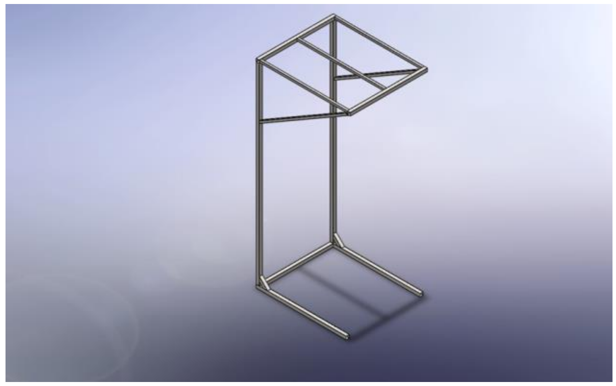


Figure 37: Rack System Iteration 1

Figure 38: Rack System Iteration 2

7.3 Challenges Bested

The team experienced many challenges this semester to meet 30%, 67%, and 100% build hardware on time. The oven is placed outside the renewable energy lab at NAU, which made it difficult to manufacture during the fall semester of 2023 with the weather. It would rain and snow on days the team needed to get work done and would be set back. The team overcame this challenge by working over nine hours in one day to complete the task on time. The next challenge that the team faced was figuring out what tools to use to manufacture and where to acquire them. The project involved manufacturing the design alone with limited tools in the renewable energy lab. The team overcame this challenge with the help and guidance of the machine shop at NAU. Talking to the students that worked there about the goals the team tried to accomplish in cutting material, they gave us the right tools to use to get the job done. Manufacturing the oven assembly with three team members alone was very challenging. Note that all members are under the height of 5’5, while the height of the oven is 8 ft. The team received help from engineering friends to help assemble the oven. The last challenge that the team faced was acquiring the material. The steel studs for the frame of the oven were 10 ft. long and the sheet metal for the oven were 4 ft. x 8 ft. and it made it difficult for the team to transfer the material as no member had a truck to haul the material. The team bested this challenge with the source of other people’s vehicles.

8 Testing

8.1 Testing Plan

The team created a testing plan to ensure that all test meeting the engineering requirements and the client requirements of the QFD found in Appendix A. A top-level summary of the testing plan is displayed below:

Table 4: Test Summary Table

Test	Design Requirement
Test 1: Budget	ER3, CR3
Test 2: Heat Transfer of Composite Wall	ER2, ER4, CR1, CR4
Test 3: Control System Test	ER5, CR2, CR6, CR7
Test 4: Heat Ventilation and Circulation	ER5, CR2, CR6, CR7
Test 5: Curing Technique on Rack	CR2, CR5
Test 6: Rack System Weight Test	ER1, CR5

8.1.1 Test 2: Heat Transfer of Composite Wall

One of the engineering requirements is for the oven to withstand the maximum temperature of 400 ° Fahrenheit without having the material burn red and to not have minimum heat loss from the insulation. The team plans to analyze this requirement by observing the heat transfer analysis through a sample of the oven wall. This will determine if the team selected the right materials for the oven to hold the hot air in.

8.1.1.1 Test/Experiment Summary

For this test the team will create a two-dimensional model of the oven wall to analyze the thermal resistive network using two different types of insulations. The design requirements being tested are ER2, ER4 and CR1. ER2 and CR4 ensures that the dimensions of the oven are 4ft x 4ft x 8ft. ER4 ensures that the composite wall has a heat loss value of less than 6 W/m^2. CR1 ensures that the material of the oven is weather resistant. The materials required to complete this test are:

1. Two 1 ft. x 1 ft. 25 gauge cold rolled steel plates.
2. 10in. x 11in. R15 mineral wool insulation (3.5” thick)
3. Synthetic rubber Maxx foam that withstands 300-375 degrees Fahrenheit
4. High temperature vinyl tape that withstands 400 degrees Fahrenheit
5. 4 K thermocouples

The team will use these materials to calculate the heat loss by also calculating the R value, material resistance to heat flow, for the steel, insulation, and air in order to find the total R value. The team will also need the specific heat constant of air, the heat flux in the oven wall, the ambient temperature, the surface temperature, and the temperature at each thermocouple.

8.1.1.2 Procedure

The steps taken to conduct this test are as follows:

1. The team cut the Maxx foam to three pieces of 12 in. x 4 in.
2. The foam pieces are attached to the three sides of the steel plates using high temperature vinyl.
3. The insulation is then placed inside the box shape of the wall.
4. The team then set up LabVIEW and the DAQ acquisition system for the thermocouples to read the temperature. The team followed the lab 04 manual set-up of experimental thermos-fluids class (ME 495).
5. The team set the DAQ system by placing the 4 k thermocouples into the oven wall and the fifth thermocouple temperature to be ambient.
6. The team analyzed the temperature change through the wall for approximately 40 minutes and recorded the readings every 2-3 minutes.

8.1.1.3 Results

The team calculated the thermal resistive network of each component involved by finding the k and h values. The team found the thermal conductivity for insulation to be 0.41 W*m/k for both cases because the average temperature between thermocouple 1 and 4 was to be approximately 330 K [2]. The thermal conductivity for steel is assumed to be 0.5 W*m/k from research [3]. The h value is a complex number to calculate, based on research, the team assumed h to be 13.75 W*m2/K [4]. The data and calculations are found in Appendix A.

The team calculated the thermal resistive network through all five thermocouples and found the 3.5" insulation to be -5.22 W/m2 and the 4" insulation to be -5.28 W/m2. 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 9.72 W/m2 and the 4" insulation is 15.88 W/m2. The equation used to solve for the heat flux us shown below:

$$q'' = T_\infty - T_s * R_{tot}$$

where q" is the heat flux in the oven wall [W/m2], T_∞ is the temperature of the air surrounding the oven wall (T ambient) and Ts is the temperature of the surface, the inside of the wall at thermocouple 1. Rtot is the summation of the R values. The equations used to determine the R values can be found below:

Rtot=2Rsteel+RInsulation+RairRtot=2Rsteel+RInsulation+Rair

The R value is material resistance to heat flow. The R value is calculated for the steel, insulation, and the air outside of the oven. The steel has a value of 2 in front because of the steel on the top and on the bottom.

Rsteel=Lsteelksteel∗ARsteel=Lsteelksteel∗A

L is the length of the steel [m], k is the thermal conductivity of the steel [W*m/k], and A is the area of the steel [m2]. The steel is thin, that area will be neglected.

Rinsulation=Linsulationkinsulation∗ARinsulation=Linsulationkinsulation∗A

L is the length of the insulation [m], k is the thermal conductivity of the insulation [W*m/k], and A is the area of the insulation [m2].

Rair=Lair*kair∗A*Rair=Lair*kair∗A

The variable h is the specific heat constant of air [W*m2/K] and A is the area [m2] of the air but will be neglected. At the end of the thermal resistive network, between thermocouples 4-5, the heat flux for the 3.5” insulation is -14.83 W/m2 and the 4” insulation is -3.07 W/m2. From these heat flux values between the two different points, the team analyzed that the 4” insulation has a minimal heat loss.

8.1.1.4 Conclusion

The team observed two different insulations to analyze which thickness would withstand a high temperature of approximately 300 degrees Fahrenheit and produce minimal heat loss through the wall. The team wants to ensure that the heat that the propane fueled torpedo heater releases stay inside of the oven. The team then analyzed a 2D thermal resistive network of the oven wall to calculate heat flux. Since the minimal heat loss is negligible the team will use the 3.5” insulation to accommodate the use of 2x4 structural beams.

8.1.2 Test 4: Heat Ventilation and Circulation Test

The purpose of the ventilation and circulation test is to ensure that the oven has uniform air flow throughout the oven without overheating. Ventilation and circulation are essential to every oven because it is responsible for uniform heat distribution and temperature control. Without uniform heat distribution and circulation, it could cause the items being powder coated to cure unevenly causing damage to occur to the coat. It will also cause issues such as the oven overheating or excessive fuel consumption.

8.1.2.1 Test/Experiments Summary

For this test the team will be powder coating the inside of the oven to ensure that uniform air flow also reaches the corners of the oven without overheating the oven. The design requirements being tested are ER5, CR2, CR6, and CR7. ER5 ensures that the oven meets a heat output value of 400 ° Fahrenheit. CR2 ensures that there is even heat distribution throughout the oven. CR6 ensures that the oven's heat supply is a propane fueled heat source. CR7 ensures that there is a control system that will sync the propane fueled heater to the oven. The materials required to complete this test are:

1. Powder coating oven
2. Functional control system
3. Blue powder coating powder
4. All prep (iron phosphate)
5. Sander
6. Grounding wire
7. Air compressor
8. Power and flow control unit

No measurements or calculations will be required for this test.

8.1.2.2 Procedure

The steps taken to conduct this test are as follows:

1. The team starts by sanding down the inside walls of the oven to remove all impurities from the surface of the oven.
2. The team then wiped down the oven with all prep (iron phosphate) to remove all the debris and oil caused by fingerprints and sanding.
3. The team then follows the manual and assembles the power and flow control unit along with connecting the ground wire and air compressor to it.
4. The team then fills the bottle connected to the power and flow control unit with the blue powder coating power.
5. Upon filling the bottle with the powder, the team connects the other side of the ground wire to the powder coating oven.
6. The team then sprays the inside of the oven with the powder.
7. The team then closes the oven and runs the oven at 375 ° Fahrenheit for 15 minutes.
8. The oven is then left for 24 hours to cool upon inspection of the interior.

8.1.2.3 Results

Upon letting the oven cool down for at least 24 hours the team will then inspect the interior of the oven. The team will inspect all the corners of the oven to ensure that the powder has cured without any chips or inconsistencies. This will show that the oven not only reached the desired temperature but was also able to maintain the temperature for a preset period of time. It will also show that the oven was able to maintain uniform air flow throughout the oven including the corners of the oven. If the oven is not fully cured on the interior corners, then the team will implement a stackable wall duct system designed to ensure uniform air flow throughout the entire oven.

8.1.2.4 Conclusion

The team will use powder coating the interior of the oven as a method in which to assess the heat ventilation and circulation of the oven. If the oven does not overheat and also cures the corners of the oven the current system in place will meet all the design requirements, ensuring a fully functional oven.

8.2 Testing Results

The table below displays a list of the customer requirements along with whether or not the requirements were met.

Table 5: CR Summary Table

Customer Requirement	CR met (yes or no)	Client Acceptable (yes or no)
CR1 – Weather Resistant	Yes	Yes
CR2 – Even Heat Distribution	Yes	Yes
CR3 – Material < $1,500	Yes	Yes
CR4 – Volume (4 x 4 x 8 ft)	Yes	Yes
CR5 – Retractable Rack System	Yes	Yes
CR6 – Propane Fueled Heater	Yes	Yes
CR7 – Control System for Heater	Yes	Yes

The customer requirements provided in the table were listed as weather resistance, even heat, distribution material cost, volume, retractable rock system, propane fuel heater, and control system for the heater. The weather resistance requirement was meant by using rust oleum to paint the outside of the oven. The even heat distribution material volume and retractable rock system requirements were met during the construction of the oven, allowing it to be airtight and meet a certain volume. The propane, fuel heater requirement was met by using a torpedo heater, which requires a propane input in order to operate the control system for the heater requirement was met by creating a homemade control system using a PID controller. The table below displays a list of the engineering requirements along with whether or not the requirements were met.

Table 6: ER Summary Table

Engineering Requirement	Target	Tolerance	Measured/ Calculated Value	ER met? (yes or no)	Client Acceptable (yes or no)
ER1 – Rack Holding Weight < 200 lbs	200 lbs	$\pm 5\ lbs$	200 lbs	Yes	Yes
ER2 – Volume (4 x 4 x 8 ft)	4 x 4 x 8 ft	$\pm 0.5\ inches$	4 x 4 x 8 ft	Yes	Yes
ER3 – Material Cost < $1,500	$1,500	$\pm \$ 1,118$	$2,618	Yes	Yes
ER4 – Heat Loss < 6 W/^2	2.5 W/m^2	± 2 W/m^2	5.28 W/m^2	Yes	Yes
ER5 – Heat Output of 400° Fahrenheit	400 ° Fahrenheit	± 25 ° Fahrenheit	400° Fahrenheit	Yes	Yes

The engineering requirements listed in the table for a rack system, capable of holding a maximum of 200 pounds, an oven with a volume of 4 x 4 x 8‘, the material cost of the oven being less than $1500, the heat loss being less than 6 W per meter squared, and the oven capable of having a heat output of at least 400°F. The first requirement was tested by hanging a 200 pound bumper onto the rock system to powder coat. The second requirement was met during the manufacturing of the oven, requiring all the outer panels of sheet-metal to be 4 x 4 x 8‘. The third criteria was met during the construction of the overall oven although the oven material cost was higher than $1500 the team fund raised to gain more funds for the oven manufacturing process. The oven heat loss was measured using the composite wall test and was found to have a heat loss value of approximately 5 $\frac{W}{m^2}$ which is less than the requirement of 6 $\frac{W}{m^2}$. The heat output of 400° was tested during the curing of the interior of the oven using the heat ventilation and circulation test in which the oven had to be at 400° Fahrenheit for the powder to cure.

9 RISK ANALYSIS AND MITIGATION

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.

9.1 Potential Failures Identified First Semester

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.

9.1.1 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.

9.1.2 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.

9.1.3 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.

9.1.4 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.

9.1.5 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.

9.1.6 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.

9.1.7 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.

9.1.8 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.

9.1.9 Potential Critical ailure 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.

9.1.10 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.

9.2 Potential Failures Identified This Semester

The only failure experienced this semester was due to one of the requirement made by the client which required the oven to be portable in the renewable energy lab. However, during the manufacturing process of the oven, the floor of the oven buckled under the weight of the overall oven due to the placement of the wheels. Upon receiving input from the client, the team decided to make stationary by placing it on bricks in order to add structural support to the floor of the oven.

9.3 Risk Mitigation

Upon the completion of the FMEA (located in Appendix D) 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.

10 LOOKING FORWARD

The team was able to successfully execute the manufacturing of the powder coating oven. However, the team did run into issues that require design iterations. Moving forward the team would like to advise for future designs that the teams consider, the overall weight of the oven to ensure buckling does not occur on the bottom of the oven. The team would also like to advise that the future group should purchase two PID controllers, one for temperature, and one for a timer and wire them together, as opposed to just one dual PID so that the team can have multiple thermocouples, as opposed to being limited to one thermocouple. If the team has more thermocouples, it will allow the oven control system to read a more accurate temperature inside the oven. Below will include a list of future testing procedures, and future iterations that can be done to improve upon the powder coating oven.

10.1 Future Testing Procedures

The team was able to successfully test every sub system of the oven. That will ensure that there is no future testing required by future teams.

10.2 Future Iterations

An important iteration the teams can make in the future for this project is obtaining a programmable vent to make the powder coating oven more sustainable. If the teams can program the vent to allow it to open and close once it reaches a certain temperature, as opposed to the heater, turning on and off to try and obtain the set temperature of value this will allow the oven to consume a lesser amount of fuel due to the heater, being consistently on as opposed to turning on and off consuming excess fuel. This iteration would allow the oven to be more fuel efficient and decrease the cost of propane refills required to powder the oven.

11 CONCLUSIONS

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 met throughout the year. 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 analyses required for each part of the project and what are the conclusions provided, the manufacturing process of the oven, and the testing of the oven. During the year, 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. Also, 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 the project was to fabricate and build the oven, conduct physical testing, and ensure that the project has met the client's satisfaction. The team was then able to manufacture the oven and conduct all seven required tests in order to ensure the oven met all the customer requirements. Below the team has provided a reflection that will discuss the engineering principles applied to the project along with a resource wish list and project applicability to industry.

11.1 Reflection

During the process of manufacturing the powder coating oven, the team had to apply many engineering design principles with regards to public safety, along with environmental and economic factors. The design factor of a public safety was addressed during the design of the overall oven. The overall oven had to have a high factor of safety in order to ensure that it was a stable structure using a SolidWorks analysis, the team was able to ensure that the oven had an extremely high factor of safety along with the rack system, allowing it to me all of the required ASTM regulations another issue with regards to public safety was the location of the oven the oven needed to be placed in an area where the propane tank was capable of off gassing without risk of the tank combusting. The environmental factor was addressed using the control system to power the propane heater, allowing the oven to be more fuel efficient. The economic factor was addressed using the bill of materials. In order to over or come the economic strain of being given a low budget the team had to fund raise. The remaining funds require to manufacture the oven. These were just some of the engineering design principles that the team had to apply in order to successfully manufacture the powder coating oven.

11.2 Resource Wishlist

Upon completing the manufacturing of the powder coating oven, the team has reflected, and found that there was a specific sort of skills that the team should have obtained before manufacturing the oven. The skill was the skill of welding. This would allow the team to have welded both the rock system and the oven together, allowing the oven to be more structurally sound as opposed to using rivets to maintain the structure of the oven. The team had to rely on the welding of the machine shop to help in manufacturing the rack system. If the team is capable of welding, the team would have welded not only the oven assembly, but the latches and hinges on the oven to ensure that the screws do not loosen overtime and compromise the integrity of the oven. The team has found that for capstones that rely heavily on manufacturing it is essential for at least one member to be proficient in welding.

11.3 Project Applicability

This Capstone has allowed the team to gain valuable knowledge that will be useful for the team in industry. Through the completion of those caps on the team has been able to learn how to use all forms of tools located in the machine shop, but most importantly, the team gained the knowledge to create a control system from scratch using just a PID and a solid state relay. The team also game the knowledge to program and auto tune, a thermocouple using the PID system. These skills will be useful in industry and a one viewing companies, such as Raytheon or Boeing, who requires systems, similar to powder coating ovens when manufacturing their products. Overall, this capstone project enforces the rules of manufacturing taught by multiple engineering classes and allows the team to gain industry experience and improve upon and refine their skills.

12 REFERENCES

[1] "Lab oven 'Blue M,'" *English translation*. [Online]. Available: https://www.bluem.com/products/benchtop-ovens/lab-oven. [Accessed: 01-Apr-2023].

[2] R. News, "Innovative powder coating oven airflow from Reliant," *Reliant Finishing Systems*, 26-Mar-2021. [Online]. Available: https://reliantfinishingsystems.com/innovative-powder-coating-oven-airflow-leads-to-improved-performance/. [Accessed: 01-Apr-2023].

[3] "A uniform cure - wisoven.com." [Online]. Available: https://www.wisoven.com/sites/default/files/2016-10/Finishing%20Today-A%20Uniform%20Cure.pdf. [Accessed: 02-Apr-2023].

[4] "Colo-1864 small batch powder coating gas oven," *Hangzhou Color Powder Coating Equipment Co.,Ltd*. [Online]. Available: https://www.colo-group.com/small-batch-powder-coating-gas-oven-16196055760267873.html. [Accessed: 02-Apr-2023].

[5] "Colo-0813 LPG gas powder coating oven," *Hangzhou Color Powder Coating Equipment Co.,Ltd*. [Online]. Available: https://www.colo-group.com/gas-powder-coating-oven-15241959192006723.html. [Accessed: 02-Apr-2023].

[6] "Columbia Coating Basic Instructions," *Basic instructions*. [Online]. Available: https://www.columbiacoatings.com/resources/basic-instructions. [Accessed: 02-Apr-2023].

[7] "Feedback Controllers - UC Santa Barbara." [Online]. Available: https://sites.chemengr.ucsb.edu/~ceweb/faculty/seborg/teaching/SEM_2_slides/Chapter_8.pdf. [Accessed: 02-Apr-2023].

[8] "Model Predictive Control vs. Proportional, Integral, Derivative Control," *Carnot Innovations*. [Online]. Available: https://www.carnot-innovations.com/post/model-predictive-control-vs-proportional-integral-derivative-control#:~:text=Regarding%20MPC%20vs. [Accessed: 02-Apr-2023].

[9] "The negative consequences of poor PID controller tuning: Process Dynamics and PID controller tuning: Textbook," *Control*. [Online]. Available: https://control.com/textbook/process-dynamics-and-pid-controller-tuning/negative-consequences-poor-pid-controller-tuning/#:~:text=If%20robust%20PID%20control%20can,failure%20frequency%20and%20safety%20incidents. [Accessed: 02-Apr-2023].

[10] "PID & Process Temperature Controllers," *PID Controllers - Temperature Controllers*. [Online]. Available: https://sea.omega.com/ph/prodinfo/temperaturecontrollers.html. [Accessed: 02-Apr-2023].

[11] "What is a PID temperature controller?," *West Control Solutions*. [Online]. Available: https://www.west-cs.com/products/l2/pid-temperature-controller/#:~:text=The%20PID%20controller%20measures%20both,primary%20element%20to%20the%20setpoint. [Accessed: 02-Apr-2023].

[12] Denby, D. (2021, September 7). *Air flow and ventilation of paint booths: Production systems: High point NC*. Production Systems | High Point NC. Retrieved April 2, 2023, from https://productionsystems-usa.com/air-flow-and-ventilation-of-paint-booths/

[13] Ruan, C. (2022, September 28). *The importance of ventilation for built-in ovens*. ROBAM Living. Retrieved April 2, 2023, from https://robamliving.com/blogs/news/the-importance-of-ventilation-for-built-in-ovens#:~:text=Gas%20ovens%20use%20dangerous%20fumes,irritate%20your%20eyes%20and%20lungs.

[14] Sasha. (2022, June 1). *Do ovens need to be vented?* Cookery Space. Retrieved April 2, 2023, from https://cookeryspace.com/do-ovens-need-to-be-vented/

[15] Streepey, M. (2015, January 8). *Safety and regulatory overview for powder coating*. The Fabricators. Retrieved April 2, 2023, from https://www.thefabricator.com/thefabricator/article/finishing/safety-and-regulatory-overview-for-powder-coating

[16] *Powder coating oven design, Operation & Maintenance*. PowderCoatingOnline.com. (2021, November 19). Retrieved April 2, 2023, from https://www.powdercoatingonline.com/powder-coating-ovens-and-oven-maintenance/

[17] LearnMetrics, “Heating BTU Calculator: How Many BTUs Per Square Foot?,” *LearnMetrics*, Oct. 29, 2022. https://learnmetrics.com/heating-btu-calculator/
[18] “Thermal properties,” *ROCKWOOL*. https://www.rockwool.com/group/advice-and-inspiration/why-stone-wool/thermal-properties/
[19] “BTU Calculator,” *MFBurners Heat Tech*, Jan. 19, 2019. http://www1.mfburners.com/btu-calculator/
[20] “125,000 BTU Forced Air Propane Heater,” *MrHeater*. https://www.mrheater.com/catalog/product/view/id/1249/s/125-000-btu-forced-air-propane-heater/category/99/
[21] “170,000 BTU Forced Air Propane Heater,” *MrHeater*. https://www.mrheater.com/catalog/product/view/id/1250/s/170-000-btu-forced-air-propane-heater/category/99/
[22] “Natural gas/propane powder coating oven,” *EPTEX Coatings*, 16-Jul-2020. [Online]. Available: https://www.eptexcoatings.com/product/gas-powder-coating-oven/. [Accessed: 05-Apr-2023].
[23] *Google image result for https://reliantfinishingsystems.com/wp-content/uploads/2021/09/industrial-oven-1024x1024.jpg*. [Online]. Available: https://www.google.com/imgres?imgurl=https%3A%2F%2Freliantfinishingsystems.com%2Fwp-content%2Fuploads%2F2021%2F09%2FIndustrial-Oven-1024x1024.jpg&tbnid=5WWRef0sxptOqM&vet=12ahUKEwiRlqrTipL-AhV-OEQIHfI_Du4QMygDegUIARDBAg..i&imgrefurl=https%3A%2F%2Freliantfinishingsystems.com%2Felectric-powder-coating-ovens%2F&docid=3zbYiGoZRUgp7M&w=1024&h=1024&q=electric+fueled+powder+coating+oven&ved=2ahUKEwiRlqrTipL-AhV-OEQIHfI_Du4QMygDegUIARDBAg. [Accessed: 05-Apr-2023].
[24] “[hot item] electrostatic gas powered powder coat curing oven,” *Made*. [Online]. Available: https://coatingsystem.en.made-in-china.com/product/UNwxSgeMZnku/China-Electrostatic-Gas-Powered-Powder-Coat-Curing-Oven.html. [Accessed: 05-Apr-2023].
[25] *Google image result for https://www.industrialoven.com/images/product/epoxy-curing-oven-3.jpg*. [Online]. Available: https://www.google.com/imgres?imgurl=https%3A%2F%2Fwww.industrialoven.com%2Fimages%2Fproduct%2Fepoxy-curing-oven-3.jpg&tbnid=OH8udpBi6CFvSM&vet=12ahUKEwid6Z-Rx5P-AhUcMUQIHWVSCB4QMygZegUIARDcAw..i&imgrefurl=https%3A%2F%2Fwww.industrialoven.com%2Fepoxy-curing-oven.html&docid=rkVoP2ycLYWGYM&w=501&h=398&q=epoxy+oven&ved=2ahUKEwid6Z-Rx5P-AhUcMUQIHWVSCB4QMygZegUIARDcAw. [Accessed: 05-Apr-2023].
[26] *Google image result for https://resourcewebsite.singoo.cc/14772778143583715/en/image/computer_5f100d9d2485c.jpg?x-oss-process=image/resize,w_2500/watermark,type_d3f5lxplbmhlaq,text_d3d3lmnvbg8tz3jvdxauy29t,t_50,color_cc8d7b,size_20,shadow_0,rotate_0,fill_0,g_center,x_10,y_10,voffset_0*. [Online]. Available: https://www.google.com/imgres?imgurl=https%3A%2F%2Fresourcewebsite.singoo.cc%2F14772778143583715%2Fen%2Fimage%2Fcomputer_5f100d9d2485c.jpg%3Fx-oss-process%3Dimage%2Fresize%2Cw_2500%2Fwatermark%2Ctype_d3F5LXplbmhlaQ%2Ctext_d3d3LmNvbG8tZ3JvdXAuY29t%2Ct_50%2Ccolor_cc8d7b%2Csize_20%2Cshadow_0%2Crotate_0%2Cfill_0%2Cg_center%2Cx_10%2Cy_10%2Cvoffset_0&tbnid=y4nuddo6fKCCZM&vet=

12ahUKEwjRu5C-x5P-AhVcN0QIHSUCA7EQMygjegUIARChAw..i&imgrefurl=https%3A%2F%2Fwww.colo-group.com%2Fpowder-coating-ovens.html&docid=GE0UAxKvPiwhzM&w=501&h=334&q=cole+powder+coating+oven&ved=2ahUKEwjRu5C-x5P-AhVcN0QIHSUCA7EQMygjegUIARChAw. [Accessed: 05-Apr-2023].

[27] *Google image result for https://www.cyriousmetalworks.com/wp-content/uploads/2023/01/eptexoven.jpg*. [Online]. Available: https://www.google.com/imgres?imgurl=https%3A%2F%2Fwww.cyriousmetalworks.com%2Fwp-content%2Fuploads%2F2023%2F01%2Feptexoven.jpg&tbnid=G23Q3tSGCQQXMM&vet=12ahUKEwjAjfn0jpf-AhVJh-4BHbHnBgQQMyg-egUIARCfAQ..i&imgrefurl=https%3A%2F%2Fwww.cyriousmetalworks.com%2Fpowder-coat%2F&docid=OQqKoMdiS9A-GM&w=768&h=960&q=eptex+powder+coating+oven&ved=2ahUKEwjAjfn0jpf-AhVJh-4BHbHnBgQQMyg-egUIARCfAQ. [Accessed: 06-Apr-2023].

[28] *Google image result for https://i.pinimg.com/236x/25/1a/67/251a67e2c25293658e38ab1d44cc5158.jpg*. [Online]. Available: https://www.google.com/imgres?imgurl=https%3A%2F%2Fi.pinimg.com%2F236x%2F25%2F1a%2F67%2F251a67e2c25293658e38ab1d44cc5158.jpg&tbnid=vM8C-qGHv7uhCM&vet=12ahUKEwjAjfn0jpf-AhVJh-4BHbHnBgQQMyhUegUIARDSAQ..i&imgrefurl=https%3A%2F%2Fwww.pinterest.com%2Feptexcoatings%2F&docid=ZXSe0h2QfYSasM&w=236&h=314&q=eptex+powder+coating+oven&ved=2ahUKEwjAjfn0jpf-AhVJh-4BHbHnBgQQMyhUegUIARDSAQ. [Accessed: 06-Apr-2023].

[29] "Deluxe shop powder coating oven - EPTEX coatings." [Online]. Available: https://www.eptexcoatings.com/product/deluxe-shop-powder-coating-oven/. [Accessed: 07-Apr-2023].

[30] "Colo-1864 electric powder coating oven (1.6*1.4*1.8m)," *Hangzhou Color Powder Coating Equipment Co.,Ltd*. [Online]. Available: https://www.colo-group.com/top-selling-powder-coating-oven-15242013832809942.html. [Accessed: 06-Apr-2023].

[31] "[hot item] colo powder coating oven equipment (Colo-1688)," *Made*. [Online]. Available: https://coatingsystem.en.made-in-china.com/product/uNaJPqVCXTcX/China-Colo-Powder-Coating-Oven-Equipment-Colo-1688-.html. [Accessed: 06-Apr-2023].

13 APPENDICES

[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report. These can contain engineering calculations, engineering drawings, bills of materials, current system analyses, and surveys or questionnaires. Letter the Appendices and provide descriptive titles. For example: Appendix A-House of Quality, Appendix B- Budget Analysis, etc. All Appendices should start on a new page.]

13.1 Appendix A: HoQ (House of Qualities)

Customer Needs	Customer Weights	Percentage of Customer Importance Rating	Rack System Holds < 200 lbs	Volume (4 x 4 x 8 ft)	Material Cost > $1,500	Heat Loss 6 < W/m^2	Heat Output of 400 degrees Fahrenheit	1 Poor	2	3 Acceptable	4	5 Excellent
Control System for Heater	5	21.74	2	3	10	10	10					
Even Heat Distribution	5	21.74	4	4	3	10	7					
Retractable Rack System	3	13.04	10	9	9	3	3					
Propane Fueled Heater	4	17.39	3	3	9	8	10					
Material Cost > $1,500	3	13.04	8	10	7	4	7					
Weather Resistant	1	4.35	6	2	5	1	2					
Volume (4 x 4 x 8 ft)	2	8.70	9	10	8	4	6					
Technical Requirements Units			lbs	ft	$	W/m^2	degree					
Technical Requirements Targets			42	41	51	40	45					
Absolute Technnical Importance			19.18	18.72	23.29	18.26	20.55					
Relative Technical Importance			3	4	1	5	2					

Figure A.1: House of Qualities

13.2 Appendix B: Gantt Chart

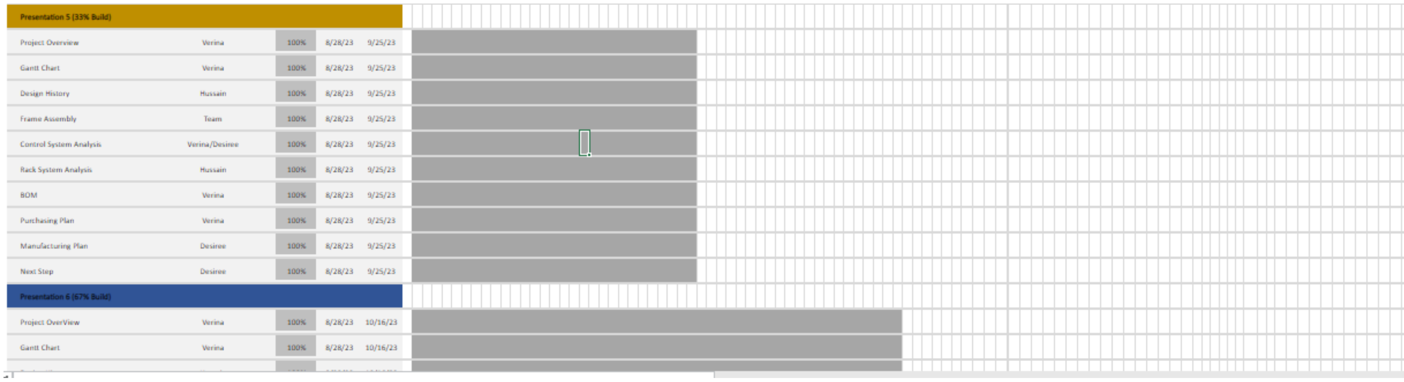


Figure B.1 : Gantt Chart Part 1

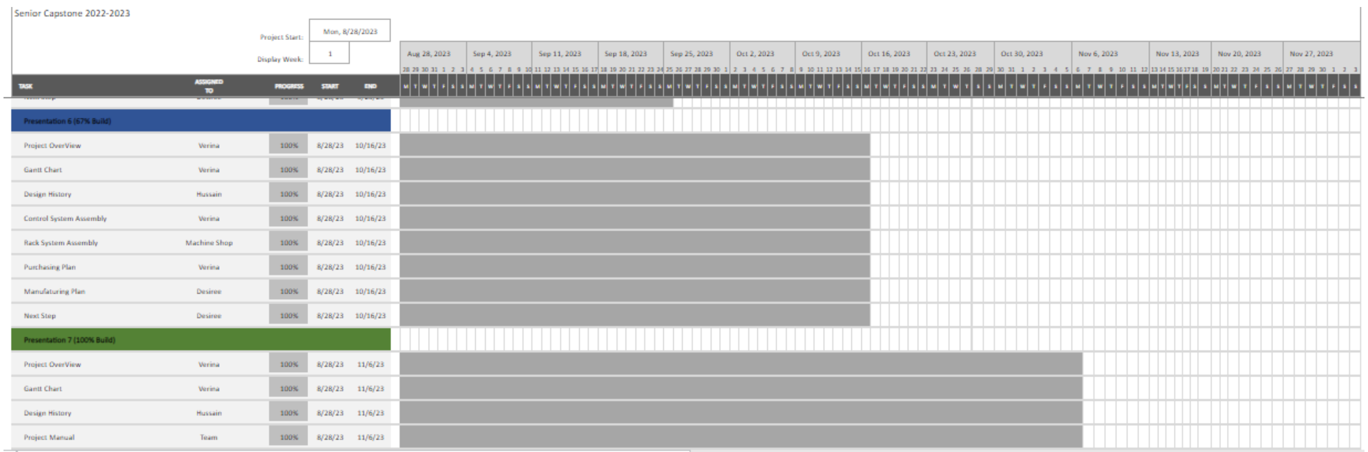


Figure B.2 : Gantt Chart Part 2

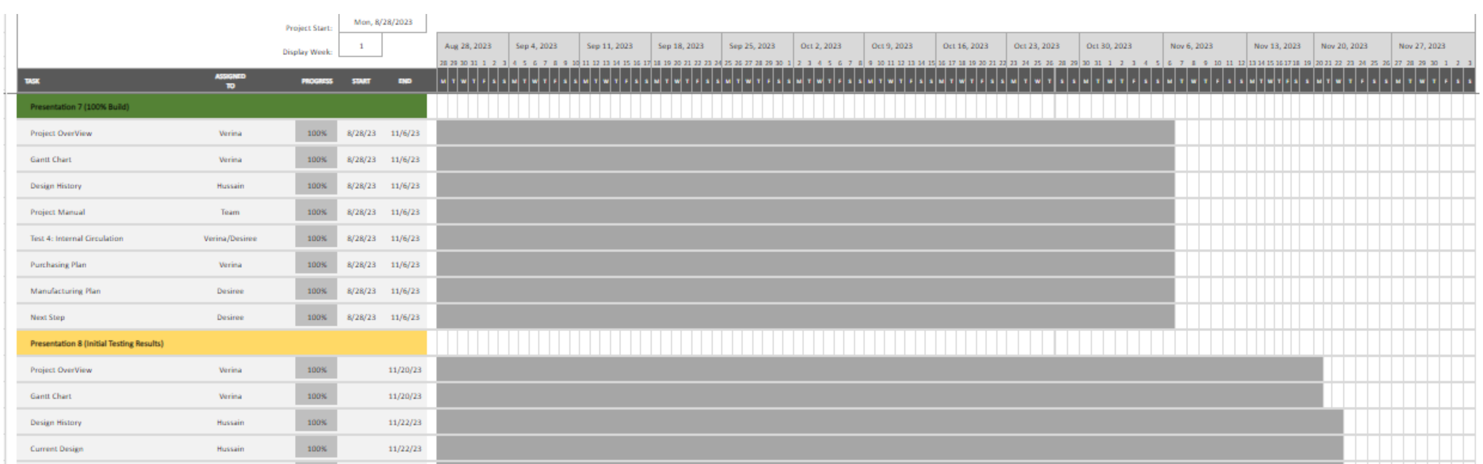


Figure B.3 : Gantt Chart Part 3

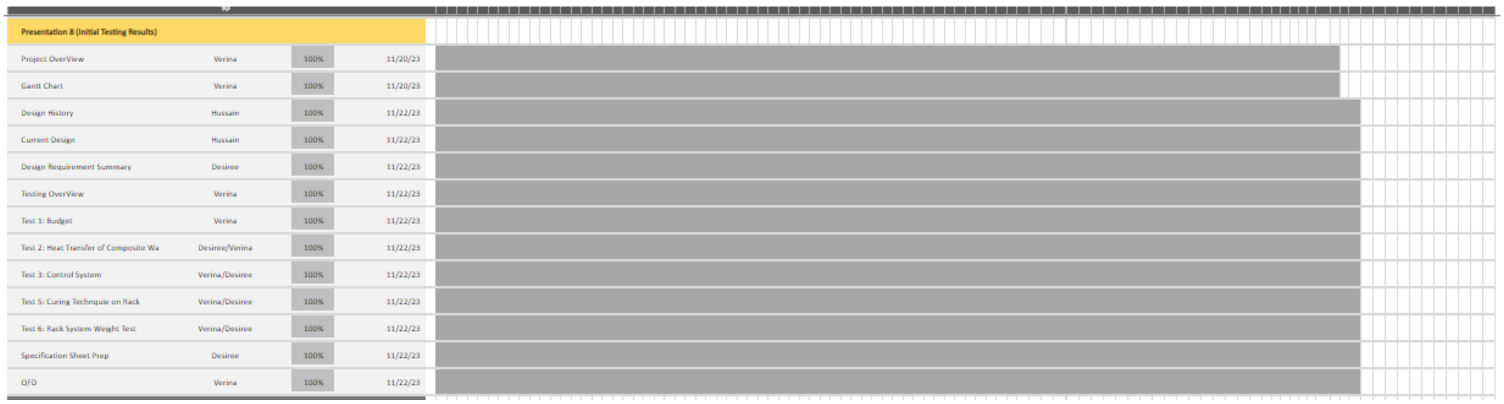


Figure B.4 : Gantt Chart Part 4

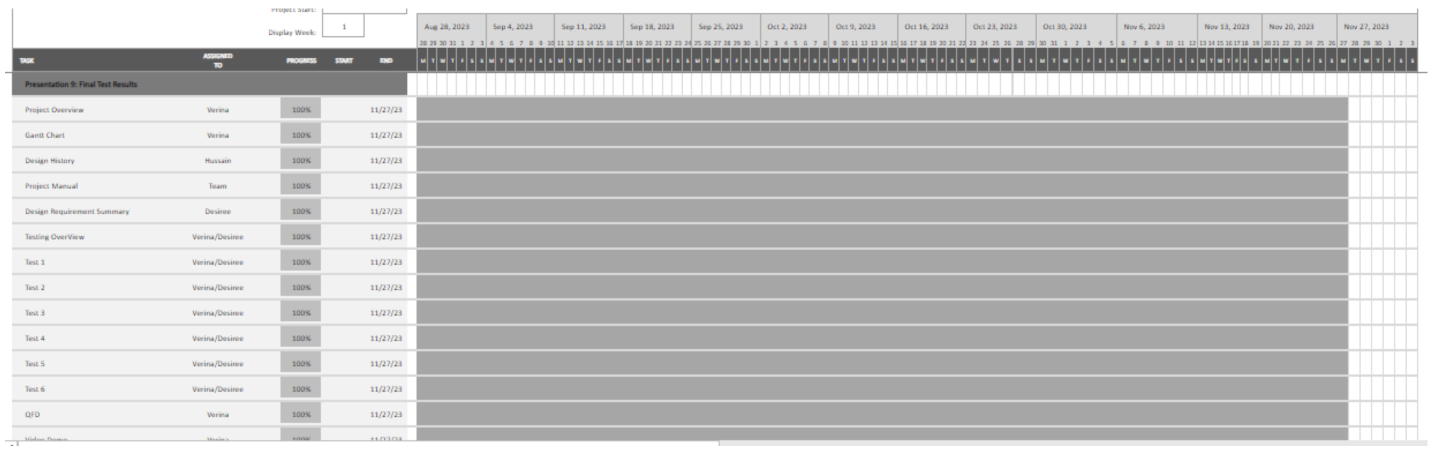


Figure B.5 : Gantt Chart Part 5

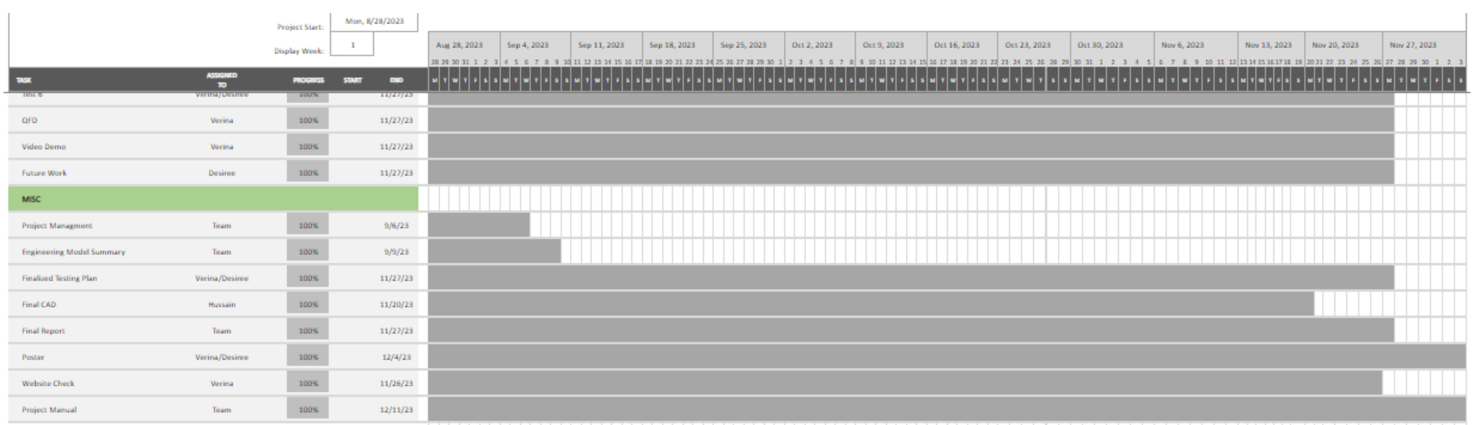


Figure B.6 : Gantt Chart Part 6

13.3 Appendix C : BOM

	No.	Material:	Product Dimensions:	Project Dimensions	Quantity Per Pack	Quantity Needed	Cost per unit	Total Cost:	Purchased By:	Source:	Link:	Purchase?	Arrived	Manufacturing Time
For the Oven	1	20 gauge sheet metal	4 ft x 8 ft	4 ft x 8 ft	1	11	$80	$880	Carson/Verina	Artisan Metal Works	N/A	Yes	Yes	
	2	25 gauge steel stud	25 3-5/8 in x 10 ft	4 ft x 8 ft	1	24	$14.98	$359.52	Carson	Home Depot	https://www.homedepot.c	Yes	Yes	
	3	piano hinge	12 in x 1.18 in	8 ft	2	7	$11.99	$47.96	Carson	Amazon	https://www.amazon.com/	Yes	Yes	Frame Assembly: 37.5 Hours
	4	rivets	3/16 in x 1/8 in	3/16 in x 1/8 in	50	300	$7.27	$43.62	Verina	Home Depot	https://www.homedepot.c	Yes	Yes	
	5	rustoleum paint	300 sq ft	144 sq ft	1	1	$26.98	$26.98	Verina	Home Depot	https://www.homedepot.c	Yes	Yes	
	6	wheels	6 inches	6 inches	4	4	$58.99	$58.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
	7	R15 wool insulation	15in x 47 in	15in x 47 in	1	3	$69.68	$209.04	Verina/Carson	Home Depot	https://www.homedepot.c	Yes	Yes	
	8	Oven Gasket	30ft	24ft	2	1	$13.99	$13.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes	Over All Oven Assembly: 20 hrs
	9	Door Latch and Screws	N/A	N/A	4	4	$20.98	$20.98	Carson	Amazon	https://www.amazon.com/	Yes	Yes	
	10	Oven Window Glass	10 in x 10 in	10 in x 10 in	1	1	$65.19	$65.19	Verina	One Day Glass	https://proxy.onedayglass.	Yes	Yes	
	11	High Temperature Sealant	N/A	N/A	1	2	$7.68	$15.36	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
For the Rack	12	Steel rods	10ft	50ft	1	5	$1.79	$105.22	Carson	Mayorga's Welding	N/A	Yes	Yes	
	13	Eye Hooks	N/A	N/A	1	1	$4.65	$4.65	Verina	Home Depot	N/A	Yes	Yes	Rack Assembly: 6 hours
	14	wheels	2 inches	2 inches	4	4	$16.99	$16.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
For the Control System	15	k thermo	3M	N/A	1	3	13.99	41.97	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
	16	PID	N/A	N/A	1	1	62.98	62.98	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes	
	17	Box	N/A	N/A	1	1	99.98	81.98	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes	
	18	E stop	N/A	N/A	1	1	6.99	6.99	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes	
	19	Toggle switch	N/A	N/A	1	1	3.4	3.4	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes	
	20	alarm light	N/A	N/A	1	1	6.95	6.95	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes	
	21	ON/OFF switch	N/A	N/A	1	3	9.98	29.94	Verina	Auber Insturments	https://www.auberins.com	Yes	Yes	
	22	Wiring	20 ft	20 ft	1	1	$7.21	$7.21	Verina	Home Depot	N/A	Yes	Yes	Control System Assembly: 8 hours
	23	Lamp Holder	3-1/4 in	N/A	1	1	$3.99	$3.99	Verina	Amazon	https://www.amazon.com	Yes	Yes	
	24	Lightbulb	N/A	N/A	1	1	$1.39	$1.39	Verina	Walmart	N/A	Yes	Yes	
	25	duct cap	6in	N/A	1	2	$21.99	$43.98	Verina	Amazon	https://www.amazon.com	Yes	Yes	
	26	duct connector	6 in	N/A	1	1	$11.99	$11.99	Verina	Amazon	https://www.amazon.com	Yes	Yes	
	27	Switch Wire		N/A	6	6	11.99	11.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
	28	120 V Cable Plug	6 ft	N/A	1	1	20.99	20.99	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
Misc	29	Propane Heater	N/A	N/A	1	1	$279.99	$279.99	Carson	Amazon	https://www.amazon.com/	Yes	Yes	
	30	Duct Elbow	8 in	8 in	1	1	$10.98	$10.98	Verina	Home Depot	https://www.homedepot.c	Yes	Yes	
	30	Heater Duct Connector	8 in	8 in	1	1	$19.60	$19.60	Verina	Home Depot	https://www.homedepot.c	Yes	Yes	
	31	Oven Vent	N/A	N/A	1	1	$29.85	$29.85	Verina	Amazon	https://www.amazon.com/	Yes	Yes	
	32	30 lb steel propane tank	N/A	N/A	1	1	$72.99	$72.99	Carson	Amazon	https://www.amazon.com/	Yes	Yes	
							Running Total	$2,618						
											Number of Parts	397		
							Capstone Fund	1500			Parts On Hand	397		
							Fundraised	$800						
							Donated	$465.18			Percent of Parts Ordered	100.00		
							True Budget	2765.18						

Figure C.1 : Bill of Materials

13.4 Appendix D: FMEA

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
AI-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

Figure D.1 : Gantt FMEA