Department of Mechanical Engineering
Powder Coating Oven
Verina Abdelmesih
Hussain Alismail
Desiree Dee
ME 486C-001

To: David Willy

From: Powder Coating Oven – Verina Abdelmesih, Hussain Alismail, Desiree Dee

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Re: Finalized Testing Plan

The powder coating team is required to conduct various testing with the final product of the design to ensure it functions efficiently and properly. To achieve the testing plan for the engineering design process, the team must analyze each design requirement of the quality functional deployment (QFD). The team created a testing plan going into detail about each testing plan with specification sheet preparations.

1. Design Requirement Summary

The engineering requirements and customer requirements from the house of quality are listed below:

Engineering Requirements:

- ER 1: Rack Holding Weight < 200 pounds
- ER 2: Volume (4 x 4 x 8ft)
- ER 3: Material Cost < $1,500
- ER 4: Heat Loss < 6 W/m^2
- ER 5: Heat Output of 400° Fahrenheit

Customer Requirements:

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

2. Top Level Testing Summary

From the design requirement summary, the tests that the team plans to perform are listed below with the corresponding design requirements that meet the criteria.

Table 1: Test Summary Table

Experiments/Tests	Relevant DRs
Ex 1: Heating Transfer of Composite Wall	ER4, CR1, ER2, CR4
Ex 2: Ventilation and Circulation Test	ER5, CR2, CR6, CR7
Ex 3: Powder Coating Technique Test	ER1, ER5, CR2, CR4

Ex 4: Rack Weight Test	CR5, ER1
Ex 5: Budget Plan Test	ER3, CR3

3. Detailed Testing Plan

3.1 Testing Plan One: 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.

3.1.1 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.

3.1.2 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) [1].
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.

3.1.3 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:

$$q" = \frac{T_{\infty} - T_s}{R_{tot}}$$

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 T_s is the temperature of the surface, the inside of the wall at thermocouple 1. R_{tot} is the summation of the R values. The equations used to determine the R values can be found below:

$$R_{tot} = 2R_{steel} + R_{Insulation} + R_{air}$$

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.

$$R_{steel} = \frac{L_{steel}}{k_{steel} * A}$$

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.

$$R_{insulation} = \frac{L_{insulation}}{k_{insulation} * A}$$

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].

$$R_{air} = \frac{L_{air}}{k_{air} * A}$$

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.

3.1.4 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.

3.2 Testing Plan Two: 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.

3.2.1 Test/Experiment 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.

3.2.2 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.

3.2.3 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.

3.2.4 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.

3.3 Testing Plan Three: Powder Coating Technique Test

The main purpose of this test is to ensure that items hooked on to the rack are subject to uniform heat flow and powder coat evenly. In order for an object to be powder coated it must be grounded or the powder will not stick to the object. This test will ensure that the grounding mechanism is in working order by conducting multiple trials with different pieces of scrap metal.

3.3.1 Test/Experiment Summary

For this test the team will be using the rack system to powder coat a piece of steel. The design requirements being tested are ER1, ER5, CR2 and CR5. ER1 ensures that the rack system hold can hold up to a weight of 200 pounds. ER5 ensures that the heat output of the oven can reach 400° Fahrenheit. CR2 ensures that there is even heat distribution throughout the oven. CR5 ensures that the rack system is retractable from the oven. No measurements or calculations will be required for this test. The materials that are required to conduct the test are the following:

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

No measurements or calculations are required for this test.

3.3.2 Procedure

The steps taken to conduct this test are as follows:

1. The team starts by sanding down the scrap metal removing impurities.

2. The team then wiped down the scrap metal 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 scrap metal.
6. The team then spray the scrap metal with the powder.
7. The team then closes the oven and runs the oven at 375 ° Fahrenheit for 15 minutes.
8. The scrap metal is then left for 24 hours to cool upon inspection of the interior.

3.3.3 Results

Upon letting the scrap metal cool down for at least 24 hours the team will then inspect it. The team will inspect all the corners and groves to ensure that the powder has cured without any chips or inconsistencies. This will show that the grounding mechanism used for the rack system works without causing curing inconsistencies of any kind. It will also confirm that there is uniform flow in the center of the oven and that the control system is in working order.

3.3.4 Conclusion

The team will use powder coating scrap metal to assess the grounding mechanism used for the rack system. If the scrap metal has no form of exterior imperfections after 24 hours this will confirm that the grounding mechanism has successfully electrostatically applied the powder to the bumper for curing.

3.4 Testing Plan Four: Rack Weight Test

The main purpose of this test is to ensure that the rack system can withstand the weight of 200 pounds. For the team to complete this test they will be taking a front bumper from the Bumper capstone team that weighs between 160 to 200 pounds for this test. This test will ensure that the rack system will not buckle when powder coating the remaining bumpers for the Bumper capstone team.

3.4.1 Test/Experiment Summary

For this test the team ensured that the rack system can withstand a weight of up to 200 pounds. The design requirements being tested are ER1 and CR5. ER1 ensures that the rack system can withstand a weight of up to 200 pounds. CR5 ensures that the rack system is a retractable rack system. The materials required for this test are shown below:

1. Powder coating oven
2. Oven rack system
3. Functional control system
4. White powder coating powder
5. All prep (iron phosphate)
6. Sander
7. Grounding wire
8. Air compressor
9. Power and flow control unit
10. Front bumper

3.4.2 Procedure

The steps taken to conduct this test are as follows:

1. The team starts by sanding down the front bumper removing impurities.
2. The team then wiped down the front bumper 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 white powder coating power.
5. Upon filling the bottle with the powder, the team, the connects the other side of the ground wire to the front bumper.
6. The team then spray the front bumper with the powder.
7. The team then closes the oven and runs the oven at 375 ° Fahrenheit for 15 minutes.
8. The front bumper is then left for 24 hours to cool upon inspection of the interior.

3.4.3 Results

Upon letting the front bumper cool down for at least 24 hours the team will then inspect the rack system. The team will inspect the s hook and eye socket along with the trusses in order to ensure that no deformation has occurred. This will show the rack system is in fact stable enough to tolerate 200 pounds of weight.

3.4.4 Conclusion

The team will use the front bumper as a method in which to assess the structural stability of the rack system. If the rack system shows no sign of deformation after 24 hour this will confirm the structural stability of the oven.

3.5 Testing Plan Five: Budget Plan Test

The main purpose of this test is to ensure that the team stays within the budget provided by the client. The client has provided the team with a budget of $1,500. This budget will be used to purchase all the materials required to complete the project.

3.5.1 Test/Experiment Summary

For this test the team will be inspecting the bill of materials (BOM) in order to ensure that the team stays within the designated budget. The design requirements being tested are ER3 and CR3. Both design requirements ensure that the team stays within the budget of $1,500. The materials required for this test are shown below:

1. Bill of Materials

3.5.2 Procedure

The steps taken to conduct this test are as follows:

1. Create a list of materials required to build the oven and rack system.
2. Obtain all prices and sources for the required items.
3. Place all items in an excel sheet.
4. Use the SUM function to determine the total amount spent.

3.5.3 Results

Upon inspection of the bill of materials the team found that they were projected to be over budget by $1,118. The team then fundraised $800 for miscellaneous project items and $465.18 for the materials required to construct the control system and the rack system.

3.5.4 Conclusion

The team was able to stay within budget due to multiple donations and the team's effort to fundraise all the residue required costs.

4. Specification Sheet Preparations

Table 2: 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

Table 3: 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

5. QFD

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.

Conclusion

The team must complete the testing plans listed to show the powder coating oven operated correctly to the client’s needs. The engineering requirements have technical targets to be met, such as the oven must reach a temperature of 400 degrees Fahrenheit or that the rack system must hold the weight of 200 pounds. Each testing plan corresponds to one or more of the engineering and client requirements found in the QFD. The team must complete the finalized testing plan with the data and observations to show in the poster and PowerPoint for the UGRADS presentation and the end of the semester.

References

[1] Northern Arizona University, "ME 495 – Intro to Data Acquisition with NI & Arduino," Flagstaff, AZ, 2022

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

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

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

Appendix:

Appendix A:

Table 1.A: Thermal Resistive Network for 3.5” Insulation

k_steel	0.5	[W/mK]	R_Steel	0.61
k_insulation	0.41	[W/mK]	R_insulatio	32.92
T_avg (ins)	133.67	[F]	R_air	0.07
	329.63	[K]		
h_air	13.75	[W/m^2K]	R_tot	34.21
A_insulation	35	[in^2]		
	0.023	[m^2]	q" [1-5]	-2.09
L_steel	0.3048	[m]	q" [4-5]	-14.83
L_insulation	0.254	[m]	q" [1-2]	31.88

Table 2.A: Thermal Resistive Network for 4” Insulation

k_steel	0.5	[W/mK]	R_Steel	0.61
k_insulation	0.41	[W/mK]	R_insulation	28.81
T_avg (ins)	134.23	[F]	R_air	0.07
	329.95	[K]		
h_air	13.75	[W/m^2K]	R_tot	30.10
A_insulation	40	[in^2]		
	0.026	[m^2]	q" [1-5]	-2.40
L_steel	0.3048	[m]	q" [4-5]	-3.07
L_insulation	0.254	[m]	q" [1-2]	52.10