Bioengineering Devices Lab Compact Vessel Cleaner and In-Vitro Flow Model Development

Final Proposal

Steven Schwartz II
Mason Minitti
Milo Gubler
Muath Nasrallah

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Project Sponsor/ Advisor: Dr. Tim Becker
Sponsor Mentor: Mana Alyami
Instructor: Dr. Carson Pete

DISCLAIMER

EXECUTIVE SUMMARY

In order to fulfill their Senior Design requirements, the Spring 2022 Group 2 Capstone team was tasked to create a compact pump system capable of cleaning three-dimensional (3D) support material from 3D printed vasculature models. This project is sponsored by Dr. Tim Becker, NAU Faculty and Principal Investigator (PI) of the Bioengineering Devices Laboratory (BDL) at Northern Arizona University (NAU). Using the specified Customer and Engineering requirements, the team developed a functional decomposition model to identify each subsystem of the device. Furthermore, the team could identify different safety codes they needed to follow throughout the development of their prototype. By determining the device's subsystems, they could further identify the failure mode effect analysis which would interrupt or damage the device's functionality. Between the elements of this proposal and the Preliminary proposal, the team proposed a final design concept for their prototyping phase. While the team is currently behind schedule on their prototyping, a preliminary model was developed before the beginning of the semester which serves as the team's proof of concept. Furthermore, the team has developed a testing plan in conjunction with their ME 495 course to optimize their design. This semester will end with a prototype of their design in preparation for their final phase of their senior design course (ME 486C).

TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

The overall objective of this project is to enhance an In-Vitro (within the lab environment) Flow Model developed by the NAU Bioengineering Devices Lab (BDL). The In-Vitro flow model is a Circle of Willis model meant to simulate the physiological conditions of human brain vasculature subjected to aneurysms, which makes it suitable for device deployment prior to In-Vivo (within the body) testing and treatment. Due to similarities in material properties, the vasculature model is created from three-dimensional (3D) printed materials. The objective of this project is to develop a Compact Vessel Cleaning (CVC) pump-system to efficiently clear out the 3D support material. In the previous report, it was indicated that the team will be responsible for upgrading the flow model's physiological conditions. However, the capstone team will focus on the CVC device, while Steven will develop the flow model for his personal research obligations.

The BDL specializes in biomaterials research and aneurysm treatment/prevention [1], which makes the flow model an important cornerstone of their research. Therefore, Goal #1 is needed for the effective replacement of any damaged or expired Circle of Willis models, and Goal #2 is necessary for comprehensive evaluation of various medical devices such as Balloon Stents, Liquid Embolics, and various guide catheters. The sponsor of our project is Dr. Tim Becker, the BDL's Principal Investigator (PI), who is the primary stakeholder of this project. However, the stakeholders with the greatest risk are victims of stroke. According to the Brain Aneurysm Foundation, 500,000 people die from brain aneurysms each year, and roughly 66% suffer from long-term neurological deficit [2].

1.2 Project Description

The following objective of the project is provided by the sponsor:

> The scope of this project is to design, build, and test a compact cleaning system for 3D models. This system will provide an efficient way of cleaning 3D models. The goal is to develop a simple design, easy to use, and portable.

2 REQUIREMENTS

To meet the goal of designing a portable model cleaning system, a list of specifications provided by the customer was used. The provided specifications, customer requirements, are listed in section 2.1. To meet these objectives, engineering requirements were set to regulate and ensure compliance with the customer's specifications by establishing measurable specifications to each requirement.

2.1 Customer Requirements (CRs)

The customer requirements reflect the qualitative objectives associated with a project. With the exception of cost and some physical dimension, these requirements are based off non-engineering qualities as listed below.

- Cost within budget: $1,500
- Durable and Robust design: Product is expected to be transported and still functioning within size parameters
    - Length: 24 to 30 inches
    - Width: 10 to 16 inches
    - Height: 8 to 10 inches
- Reliable Design: Usable for cleaning cycles
- Safe to Operate: High-temperature and pressure water, and complex circuitry should not harm users or surrounding equipment/lab space
- Pressure Gauge: Must measure based on medical standards (millimeters of mercury, mmHg)
- Temperature Gauge: Must be highly responsive and read in degrees Celsius
- Switch On/Off: One for heat and one for entire system to maintain safety
- Mesh Filtration: Remove support material and be easily removable for cleaning
- Universal Connectors: Allow for use on multiple models (Control and Circle of Willis)
- Water Reservoir: Primary water source for easy refilling
- Timer: Track cleaning time
- Water Pump: Pulsate or constant flow for different cleaning methods
- Adjustable setup: Leveling or system balance

2.2 Engineering Requirements (ERs)

- Water Temperature: Max water temperature, 80°C.
- Flow Rate: Max flow rate, needs testing, general value (100mL/s).
- Water pressure: Max water Pressure, 200 mmHg.
- Reservoir Volume: Max Volume, General value (10in by 10in by 10in).
- Water heater Volume: Max Volume, General value (10in by 10in by 10in).
- Frame Length: Max value, 3ft.
- Frame Width: Max value, 2ft
- Frame Height: Max value, 0.83ft.
- Frame Durability: Total Load Capacity, 50lbs-100lbs.
- Filtration Size: Design Goal; Must separate support material from fluid. Size requirement; Must fit in frame and system, testing required for final max size (Predicted size: 5in by 5in, Mesh Size: 2 - 3 mm/0.07 - 0.11 in.)

2.3 Functional Decomposition

Due to the customer requirements, there have been no changes made to the black box or functional decomposition model since the last report.

2.3.1 Black Box Model

Based on the Customer Requirements, discussed in Chapter 2.1, the inflows and outflows were simplified using a black box model in Figure 1. The bold arrows represent the materials, the light-weight arrows represent the system's energy, and the dashed arrows represent the signals throughout the system. The arrows pointing toward the black box are the inflows (materials, signals, energy) going into the system. The arrows pointing away from the box are the outflows. The overall objective of the black box is contained within the box itself. The black box model aided the team in developing a more advanced breakdown, known as the Functional Decomposition model in Section 3.3.2.

Figure 1. CVC Black Box Model

2.3.2 Functional Model

Due to the array of various processes throughout the system, a simple flowchart would not suffice. Using the black box model in Chapter 3.3.1, a Functional Decomposition model was developed (see Appendix A). The functional decomposition model uses the same notation as a black box model, but creates a breakdown of each step throughout the device's process. Each step was conceived from the customer requirements and the preliminary vessel cleaner design. Using the functional decomposition, the team created several preliminary designs for their concept generation phase in Chapter 4.

2.4 House of Quality (HoQ)

The house of quality (Appendix A) is used to relate the customer requirements and the engineering requirements. The customer requirements are each given a weight/importance score, this score will help the team balance the final score to ensure the clients most desired or attainable requirements are sure to be met. When comparing the customer requirements and engineering requirements the values 1, 3, 9 are used to quantify the relationships, a blank space means that there is no relationship between the two requirements. A 1 represents a weak relationship between the requirements, a 3 represents a medium relationship between the requirements, and a 9 represents a strong relationship. One strong relationship in our HoQ is the customer need for fast cleaning and the flow rate has a strong relationship. The HoQ also compares the project to other companies designs for cleaning 3D printed vessels. The HoQ also compares the effects of each engineering requirement on the others. For example, as flow rate increases it will cause water pressure to increase.

2.5 Standards, Codes, and Regulations

To develop a safe and efficient design, the team will use a set of standards and regulations as listed in Table 1. IEEE/ 13.26029.020 will be used to protect the users from harm caused by use of electrical. IEEE/ Standard 2700-2014 provides a consistent framework for sensor performance specification vocabulary, units, circumstances, and limits. 10.1109/IEEESTD.1975.81090 gives standards for the application of temperature-measurement techniques in monitoring the operating temperature and temperature rise of commonly used electrical machines, instruments, and apparatus.

Table 1: Standards of Practice

Standard Number or Code	**Title of Standard**	**How it applies to Project**
IEEE/ 13.260 29.020	Draft National Electrical Safety Code(R) (NESC(R))	Electrical Safety Precautions are needed to minimize risk when manufacturing this device.
IEEE/ Standard 2700-2014	Standard for Sensor Performance Parameter Definitions	Helps in measuring the performance of our project design.
10.1109/IEEE STD.1975.810 90	Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus	Helps in temperature measurements in this project.

3 Testing Procedures (TPs)

The team has decided that two testing procedures are necessary to fulfill the engineering requirements. These tests will verify the pressure, flow rate, and temperature engineering requirements. Below the objective, resources and schedule for each testing procedure will be outlined.

3.1 Testing Procedure 1: Flow Rate Reduction: Head Loss

This test will be influential in deciding the flow rate and pump needed by the system. This test will allow the team to meet the engineering requirements of flow rate and pressure. The test will be developing a worst and simplest representation of the system flow, then measuring the inlet pressure and outlet pressure to find the total head of the system. These pressures will be measured with transducers.

3.1.1 Testing Procedure 1: Objective

This test will be run to find the pump curve of the system in order to evaluate the pump needed for the product. A worst case flow system with minimum of six connectors, height change of 1 foot, 5 diverging tubes, and multiple bends will be tested. A simplest case of 3 connections, no height change, no diverging tubes, and minimal bends will be tested. These will simulate all potential flow system models that or product can be used with. Measuring the outlet pressure will also allow us to see if our ER of 200mmHg for the maximum pressure can be met under worst case and simplest case conditions.

3.1.2 Testing Procedure 1: Resources Required

The resources required for this test is the ME 495 Lab, two pressure transducer sensors, LabView, tubing, tubing connectors. In the lab the water flow can be provided as well as the LabView.

3.1.3 Testing Procedure 1: Schedule

Over three weeks this test will be conducted during specified times in the EGR lab 111. Each week a different objective will be completed. The first week will be dedicated to calibrating the pressure transducers and developing the LabView code. The second week will be dedicated to collecting pressure data for the worst case flow. Finally the third week will be dedicated to collecting pressure data from the simplest flow conditions. During the third week there will be calculations, data and uncertainty analysis for the test in order to finalize a pump curve that will be used to choose a pump.

3.2 Testing Procedure 2: Water Heating

A water heating system with the same heating element, radial size, but with elongated length will be used to test the ability of the system to heat water to the desired 80°C while water flows through. Through testing, the temperature control circuit will be built, the efficiency of the heater in the radial direction will be found, and the optimal length of the heating tank will be determined.

3.2.1 Testing Procedure 2: Objective

To test the heating system, six thermocouples will be placed evenly spaced along the length of the tank and varying radial positions. A seventh thermocouple will be placed outside of the tank to collect data on the temperature of the air surrounding the tank. With a voltage controller, the voltage to the water heating unit will be increased by 5V to calibrate the thermocouples, and find the maximum voltage to achieve the desired temperature. During testing, a water table will pump water into the tank to completely evacuate the air, then the flow rate will be reduced to mimic the estimated rate at which the water will be pumped during the cleaning devices operation. For further analysis and understanding, the flow rate of the table will be found through the bucket-timer method. During this time, an initial temperature of the water will be recorded. Then, the heating system will be turned on and a continuous measurement of the temperature will be recorded. Through analysis, the rate at which the heating element heats the water radially, the efficiency, will be reported, and the initial position along the length of the tank where the heating element begins to greatly increase the temperature of the water will be reported. For ease of operation, the voltage at which 80°C is achieved will be marked on the controlling device. This test will be run at least three times for statistical analysis of validity.

3.2.2 Testing Procedure 2: Resources Required

This test will be conducted in EGR Lab 111 as an ME 495 final project. This lab contains the water table, the seven thermocouples, and LabVIEW© software to run and analyze the data collected. Provided by the three people in the ME 495 lab team will be the heating element, the tank, the voltage controller, and all required wires/cables.

3.2.3 Testing Procedure 2: Schedule

Each test is expected to take under 20 minutes to complete, however the exact time required for sufficient heating will be tested so the time to complete the entire heating test is unknown. The test is expected to be run on 11 Apr, however the arrival of materials can delay the testing date. Ideally the testing will be completed by 15 Apr at the latest. Following the testing, analysis will be used to determine if further testing or fine-tuning of the heating equipment is required. Upon completion of this testing, the heating system will be completely built, and the water tank can be manufactured.The circuit controlling the heating element and water tank must be assembled prior to testing. The other materials, provided by Lab 111, will be set aside for use when testing can be completed.

4 Risk Analysis and Mitigation

In order to analyze the potential failures of our system, the team conducted a failure modes effect analysis (FMEA) which can be found in Appendix C. The team found ten failures for each of the four subsystems, resulting in a total of 40 failures. Each failure was given a score called the RPN; the highest RPN valued failures are considered the highest risk failures. Failures around a score of 30 are considered normal, while anything above should be tended too during the prototyping and testing phase. The goal of testing is to mitigate these high RPN failures. After testing the RPN for each function of the product should be low enough to consider the product complete.

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Mesh Filter Blockage

If the support material is not removed from the mesh filtration system, the support will congregate, causing blockage of flow. This scored a RPN of 180 this can be lowered by testing ways to clear support material from the filter.

4.1.2 Potential Critical Failure 2: Pump Damage due to Support Material

This failure is caused by the mesh filter sustaining thermal fatigue which causes the mesh size to increase. The result of this is that support material will pass through the mesh filter and damage the pump. This could lead to the pump needing to be replaced. This can be avoided by testing and material selection.

4.1.3 Potential Critical Failure 3: Water surpasses max temperature

This failure is caused by the water heating element receiving too much voltage. The water would heat past the maximum temperature of the system and cause damage to the vessel model. This will be tested by seeing the voltage to temperature relation.

4.1.4 Potential Critical Failure 4: Excess Pump Flow

If the pump provides excess flow, the system will surpass the maximum pressure and damage the vessel model. This will be tested by pump sizing.

4.1.5 Potential Critical Failure 5: Heating Element short circuits

This failure is caused by water getting onto the electronic controls of the water heater. The effects of this failure is that the heating system will stop working. This failure can be mitigated with proper assembly of all components ensuring there are no leaks.

4.1.6 Potential Critical Failure 6: Pump short circuits

This failure is caused by water intersecting the electronic controls of the water pump, which can disrupt the . This failure can be mitigated with proper assembly of all components ensuring there are no leaks.

4.1.7 Potential Critical Failure 7: Pump overheats

This failure will be caused by leaving the pump on for too long. This will cause the pump to need to be replaced. This can be mitigated by selecting a pump with a long life and by having a proper shut off procedure.

4.1.8 Potential Critical Failure 8: Pump can not handle water temperature

This failure is caused by the pump undergoing thermal fatigue. The effects of this failure is there will be improper flow in the system or the pump needs to be replaced. This can be mitigated by selecting a pump that has the proper temperature specifications.

4.1.9 Potential Critical Failure 9: Pump damage to to air

This failure is caused because the pump is turned on while not fully submerged in water or from air getting into the system. The effects of this failure is pump damage and could lead to the part needing to be replaced. To reduce the risk of this failure, the pump should never be turned on while not in the system and all connections must be airtight.

4.1.10 Potential Critical Failure 10: Water heating element damage

This failure would be caused by over using the water heater. Consequences of this failure include part replacement or insufficient temperatures. The way to mitigate this failure is to choose and test a water heating element that has the proper specifications.

4.2 Risks and Trade-offs Analysis

After completing the FMEA the team conducted a risk vs tradeoff analysis discussion. In this discussion we see the correlation between mitigating certain risks and the effects on whether it will make it harder to mitigate a different risk. One of the main correlations that we saw that could have potential impacts on the system is the placement of the pump. In order to avoid thermal fatigue on the pump it would be ideal to not place the pump in the water heating system. This could lead to complications with the flow. This correlation will need to be tested to see if the flow will meet the requirements depending on the placement. Another risk that has a direct correlation is the relation between build up on the water heating element and the cost and difficulties of implementing a water filter to the product. The water heating element can avoid any build up if the water being heated is pure and filtered. The cost of the water filter is not that much of a problem since we have the potential budget for it, however these types of filters are usually slow at filtering water, and therefore could lead to complications with full system flow. It would be ideal to test the flow rate through a water filter to see if it would lead to complications, but we have decided to test the water heater first to find out if build up will occur.

5 DESIGN SELECTED – First Semester

This chapter explains the design process following the initial design throughout the first semester. Starting with several concept drawings and CAD models, the team developed a foundation for their design for their subsystems as well as their overall system design. Based on feedback from their Capstone instructor, sponsor mentor, and their client, they were able to incorporate feedback for a finalized design choice.

5.1 Design Description

5.1.1 Proposed Design

By developing a series of concept models (Appendix E), the team formulated a proposed design. The initial design features a 9 in. diameter water heating tank connected to a pulsatile pump that is already used for cleaning 3D models. After being pumped, the heated water flows through an attached model to a filter. This filtration unit features an angled mesh to contain the removed support material while the water continues to flow. The filter is separable for easy removal of the support material post cleaning. The water post filtration moves to a water reservoir that fills the heating tank. This extra reservoir allows for the water used in the closed system to be easily maintained via a fill port at the top.

5.1.2 Changes Made during Prototyping

Through feedback from the team mentor, the initial design was acceptable; however, the planned pump could not be used. To ensure the budget is maintained, a cheap fountain pump was considered in place of a pulsatile pump. To regulate the pressure in the system, a set of clamps will be used before the sphygmomanometer to ensure the final pressure before the model is within safe levels. For this design, the maximum sized frame was removed and the final frame will be built around the system once all parts are built.

5.1.3 Engineering Calculations

All engineering calculations are based on the testing procedures listed in Section 3, and can be found in Appendix D. Each of these calculations were selected based on the testing procedures formulated in the testing procedures section (Chapter 3). Further engineering calculations may have to be modified and selected depending on any further design changes later on in the device's development.

5.2 Implementation Plan

To minimize the budget spending necessary for this project, the team will utilize parts and resources from the BDL, Thermal Fluids (495) laboratory (Bldg, 69, Rm. 111), and NAU Machine Shop. In order to test and prototype the device, the team will utilize the 495 lab and the BDL. Most of the resources included in the Bill of Materials (Appendix F) will be provided by Dr. Becker within the BDL, but some resources might have to be outsourced and purchased, such as the fountain pump and the fluid reservoir. Finally, the Machine shop will be the source of the system's frame manufacturing depending on the progression of the prototype.

Mason and Steven will develop a LabVIEW code in the BDL to aid their testing procedures for section 3.1. Furthermore, Milo and Steven will also develop a LabVIEW code to aid their testing procedures in section 3.2. Additionally, the team will develop Arduino codes for thermocouples they may use for temperature. Finally, Milo will utilize Solidworks to develop future CAD models as required for later deliverables in the course.

A comprehensive overview of all implementation activities is contained within a Gantt Chart (Appendix

G). From the end of March until Week 12 at the latest, the team is prototyping and testing the device. Furthermore, the team is considering an extensive timeline for different long-term objectives such as the website and the final deliverables.

6 CONCLUSIONS

The BDL capstone team has been tasked with designing and building an automated cleaning system to clean the support material from varying advanced 3D models of blood vessels. Through provided customer requirements, multiple designs were created then rated to establish a final design for approval. Despite setbacks in prototype development, the team has a foundation for their testing process. This semester has been oriented towards establishing a final design and testing components to ensure customer satisfaction is met. However, as per the recent curriculum change in the senior design course, the team will be required to have a working prototype completed by the end of their semester.

7 REFERENCES

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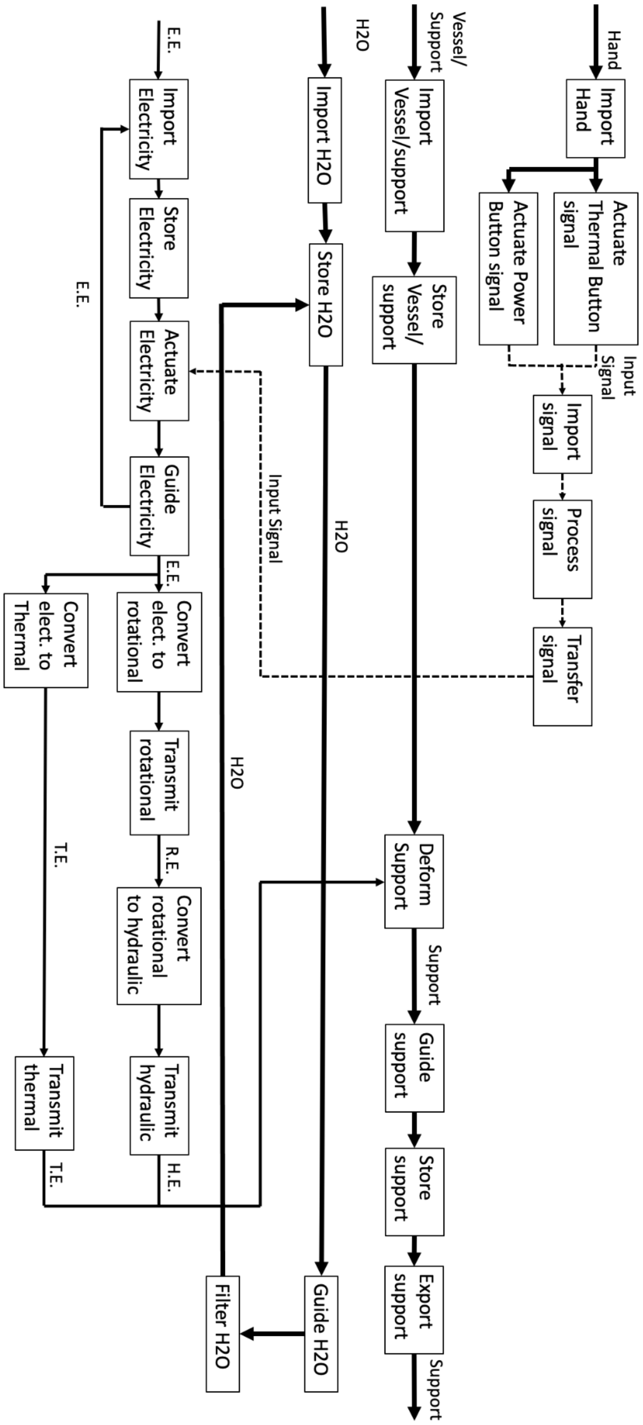
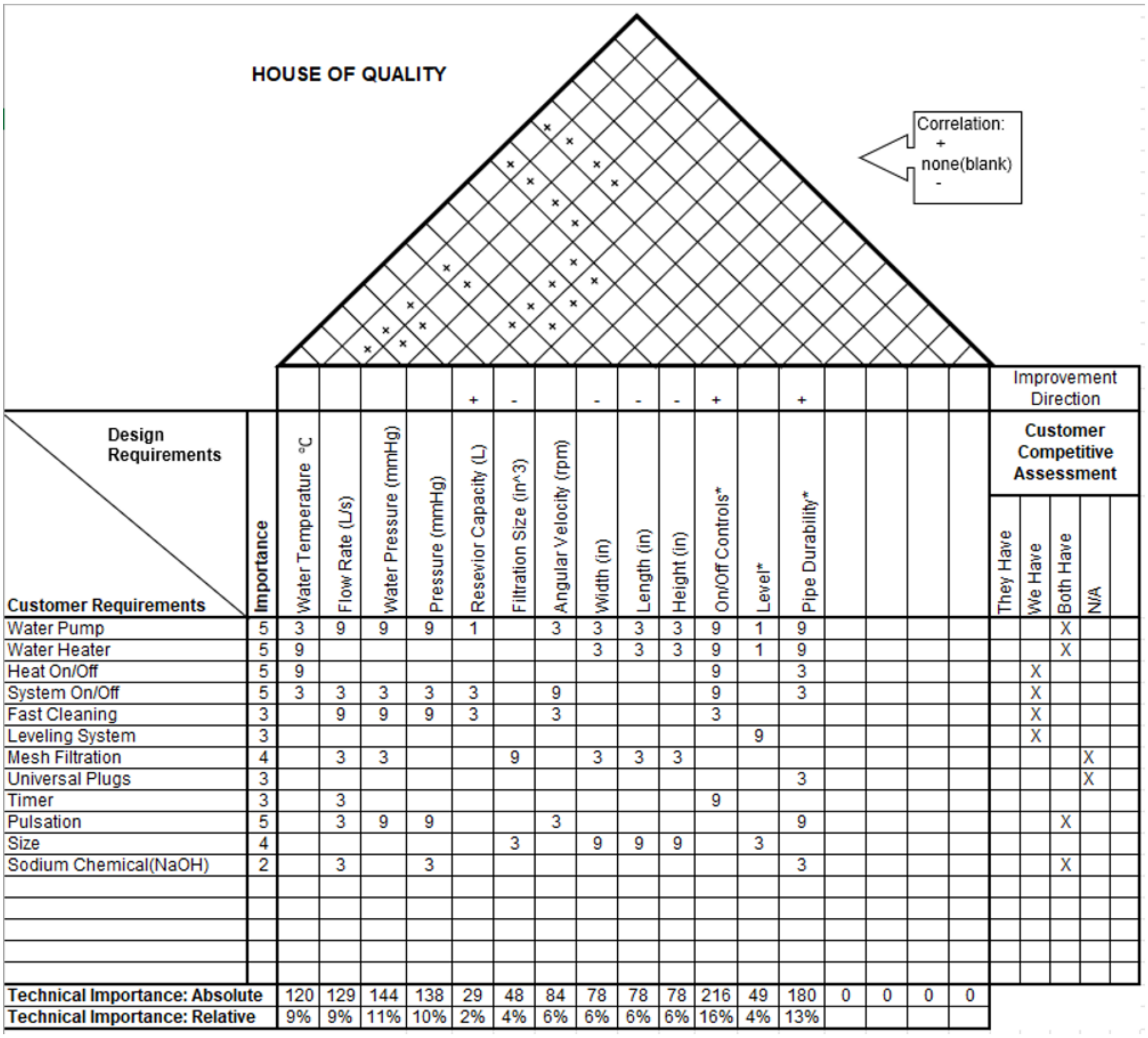
8 APPENDICES

8.1 Appendix A: Functional Decomposition Model



8.2 Appendix B: House of Quality



Design Requirements																			Customer Competitive Assessment				
Improvement Direction						+	-		-	-	-	+		+									
Customer Requirements	**Importance**	Water Temperature °C	Flow Rate (L/s)	Water Pressure (mmHg)	Pressure (mmHg)	Resevior Capacity (L)	Filtration Size (in^3)	Angular Velocity (rpm)	Width (in)	Length (in)	Height (in)	On/Off Controls*	Level*	Pipe Durability*					They Have	We Have	Both Have	N/A	
Water Pump	5	3	9	9	9	1		3	3	3	3	9	1	9							X		
Water Heater	5	9							3	3	3	9	1	9							X		
Heat On/Off	5	9										9		3						X			
System On/Off	5	3	3	3	3	3		9				9		3						X			
Fast Cleaning	3		9	9	9	3		3				3								X			
Leveling System	3												9							X			
Mesh Filtration	4		3	3			9		3	3	3											X	
Universal Plugs	3													3								X	
Timer	3		3									9											
Pulsation	5		3	9	9			3						9							X		
Size	4						3		9	9	9		3										
Sodium Chemical(NaOH)	2		3		3									3							X		
Technical Importance: Absolute		120	129	144	138	29	48	84	78	78	78	216	49	180	0	0	0	0					
Technical Importance: Relative		9%	9%	11%	10%	2%	4%	6%	6%	6%	6%	16%	4%	13%									

8.3 Appendix C: Failure Modes and Effects Analysis

Product Name	BDL CVC	Development Team	Spring 2022 BDL CVC capstone			Page No 1 of 1			
System Name						FMEA Number 1			
Subsystem Name						Date 04/08/2022			
Component Name									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1- heats water	Thermal Fatigue	heating system fail, part replacement	8	over voltage	4	Temperature Reading	3	96	Testing
1-heats water	Corosive Wear	Improper water temp.	3	build up from water not cleaned off	5	Temperature Reading	4	60	Add water filter.
1-heats water	high cycle fatigue	heating system fail, part replacement	8	left on too long, over voltage	3	Temperature Reading	3	72	Testing
1-heats water	Thermal Fatigue	heating system fail, part replacement	9	Left on while tank has no water	2	Temerature Reading	4	72	Proper shut down procedure
2-Holds hot water	Thermal Fatigue	Leaking, Tank needs replacement, Potential system failure	8	Not proper material to withstand temperature	1	Visual	2	16	Material selection
2-Holds hot water	Fatigue from use	Leaking, Tank needs replacement, Potential system failure	5	improper construction	3	visual	1	15	testing
2-Holds hot water	Evacuated tank	heating element sustains dammage, tank sustains gammage	6	improper size	3	Visual	2	36	testing
3-Reads temperature outside tank	No power	no temperature reading	5	turn on procedure not followed, improper set up	2	Visual	1	10	proper set up and turn on procedure
2-Holds hot water	sizing	restricts flow of system	6	improper sizing or connection	2	pressure reac	1	12	testing all components together
1-heats water	fracture	no hot water	7	imporper assembly	1	temp reading	1	7	proper assembly
5-pressure reading	Forein substance dammage	no pressure reading, part replacement	7	water dammages sphygomanometer	2	visual	3	42	Propper assembly, good care
6-moves water through system	Forein substance dammage	no water movement, pump breaks, total failure	9	air gets into the system	4	visual	3	108	Testing, proper assembly
6-moves water through system	over voltage	surpass max pressure, dammage vessel model	8	flow is not controled properly, pump gets too much power	5	pressure reading	2	80	testing, pump sizing
6-moves water through system	thermal fatigue	pump stops working	9	pump not suitable for hot water	5	visual	2	90	testing with pump and hot water
6-moves water through system	high cycle fatigue	pump stops working	9	pump over worked, left on for too long	2	visual	2	36	testing, pump specs
6-moves water through system	over heating	pump slows down the flow, not correct pressure	8	pump not meant to be kept on too long, gets too much power	4	pressure reading	3	96	testing , pump specs
6-moves water through system	under perfomance	vessel will not be cleaned, prodect failure, under desired pressure	9	pump not properly sized	2	pressure reading	2	36	testing, pump sizing
6-moves water through system		pump breaks	9	not fully submerged in water, turned on while in air, pumping air not water, empty system	1		1	9	proper turn on conditions

6-moves water through system		makes a mess of water	7	not turned off properly	1		1	7	proper turn off procedure
6-moves water through system	assembly	makes a mess of water, electrical hazard	6	not assembled properly, system is leaking anywhere	3	visual	1	18	proper assembly
7-removes support material from fluid	thermal fatigue	mesh size increases, pump gets dammaged by support material	9	hot water increases the mesh size and material is able to pass through	5	visual	3	135	material properties, testing,
7-removes support material from fluid	corosive wear	mesh size increases, pump gets dammaged by support material	9	water corodes the material making mesh size bigger	3	visual	2	54	material properties, testing,
7-removes support material from fluid	fracture	support material getstrough the fracture, pump dammage	9	impropper assembly, bad care	2	visual	1	18	proper assembly and good care of component
7-removes support material from fluid		fluid blockages	9	support material build up on the filter	5	visual	4	180	testing
7-removes support material from fluid	sizing	sup. Mat. Gets pushed through	9	pressure too high, mesh wrong size	4	visual	2	72	testing
8-collects sup. Mat. Waste		fluid back up	7	waste not emptied often enough, collection system too small	2	visual	2	28	Testing
9-Removes impurities from water	corosive wear	water heater acquires build up.	8	water filter is worn down and not filtering properly	2	water heater performance	2	32	Often maintenance
9-Removes impurities from water	high cycle fatigue	water heater acquires build up.	8	filter needs replacement	1	recommended filter life	1	8	Fiter specs
9-Removes impurities from water	thermal fatigue	water heater acquires build up.	8	filter gets dammaged by hot water	1	recommended filter temp	1	8	Fiter specs
9-Removes impurities from water		fluid blockages	8	improper assembly, doesn't filter fast enough	3	visual	2	48	Testing
1-heats water	over voltage	heats water past max temp	9	too much power	5	temp reading	3	135	Testing voltage to temp
6-moves water through system	over voltage	too much flow in system surpasses max pressure	9	too much power	5	pressure reading	3	135	testing pump
10-Controls electronics	short circuits	no control of data	7	water gets on arduino	4	no electonic signals	2	56	Keep away from water, avoid leaks
3-Reads temperature	short circuits	no temperature reading	6	water gets on thermocouple	4	no temp reading	2	48	Keep away from water, avoid leaks
6-moves water through system	short circuits	no flow	8	water gets on electrical components of pump	5	visual	2	80	proper assembly
10-Controls electronics		system left on, dammage to all components	8	not turned off properly	1	visual	1	8	proper shut off procedure
10-Controls electronics	electrical connections	product will not work	9	Arduino not connected properly	3	visual	2	54	proper assembly

All components	short circuits	product will not work	9	product requires too much power	2		2	36	testing all components together
1-heats water	short circuits	component will not work	9	water gets on electrical components of heater	5	temp reading	3	135	proper assembly
All components		product will not work	9	components not connected correctly	3	visual	2	54	proper assembly

8.4 Appendix D: Head Loss Equation Calculations

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

$h_f \rightarrow$ *Head loss due to Flow*

$f \rightarrow f\left(Re, \frac{\varepsilon}{D}\right)$, *the Moody, Darcy, or Stanton friction*

$D \rightarrow$ *diameter of the pipe*

$L \rightarrow$ *length over which the pressure drop occurs*

$\varepsilon \rightarrow$ *roughness factor for the pipe, and other symbols are defined as before*

$$f = 0.018$$

$$L = 5\ feet = 1.524\ m$$

$$D = 0.001m$$

$$average\ velocity = 0.02\frac{m}{s}$$

$$g = 9.81\frac{m}{s^2}$$

$$hf = 5.78e - 4\ m$$

8.5 Appendix E: Engineering Concepts, CAD, & Prototypes

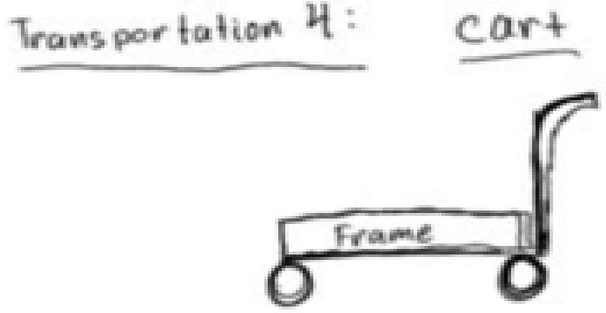


Figure 2. Transportation Subsystem Concept Selection.

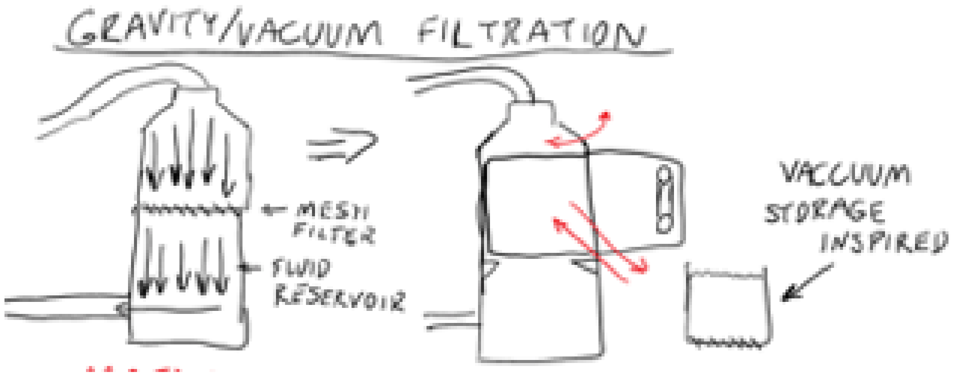


Figure 3. Filtration Subsystem Concept Selection

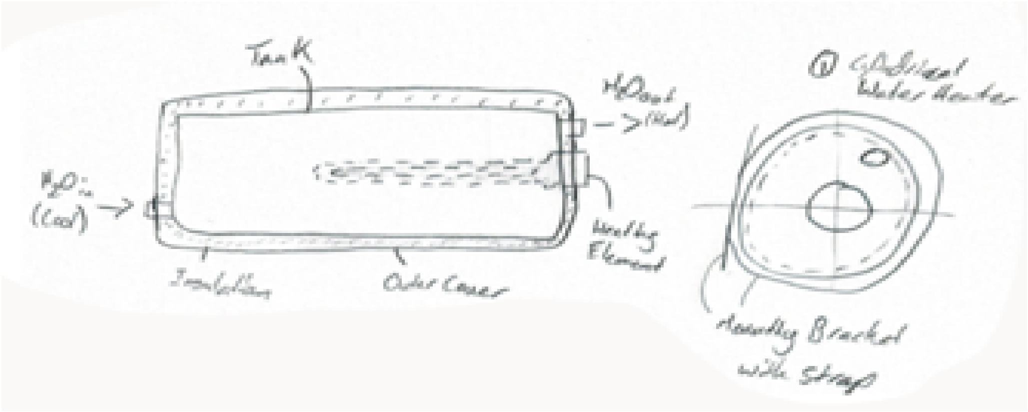


Figure 4. Heating Element Subsystem Concept Selection

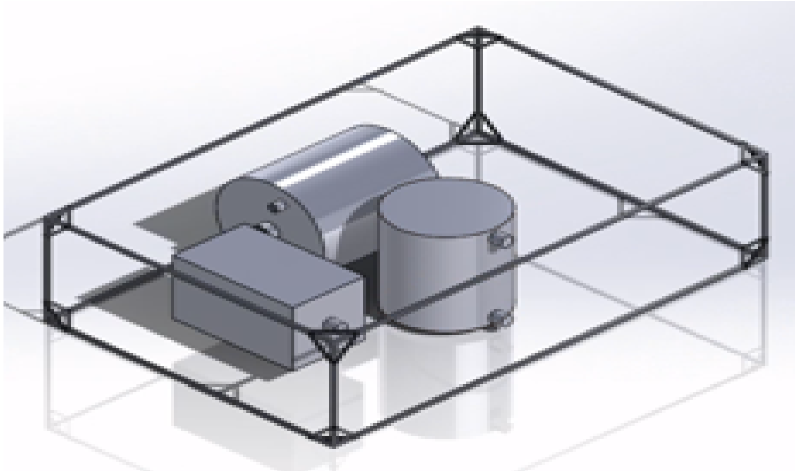


Figure 5. Preliminary CAD Model (Isometric View)

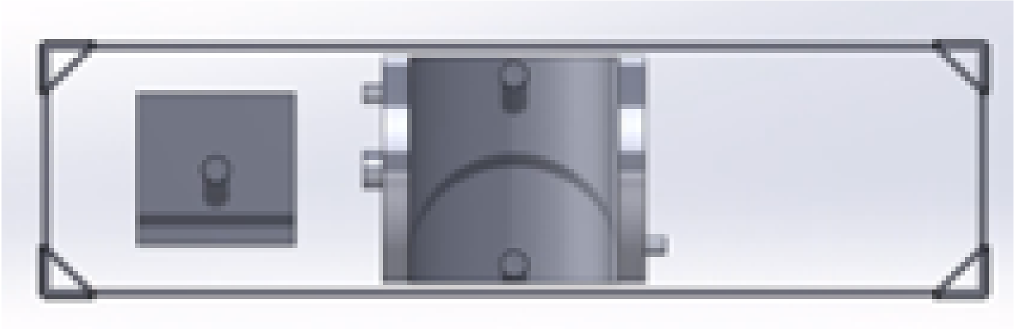


Figure 6. Preliminary CAD Model (Front View)

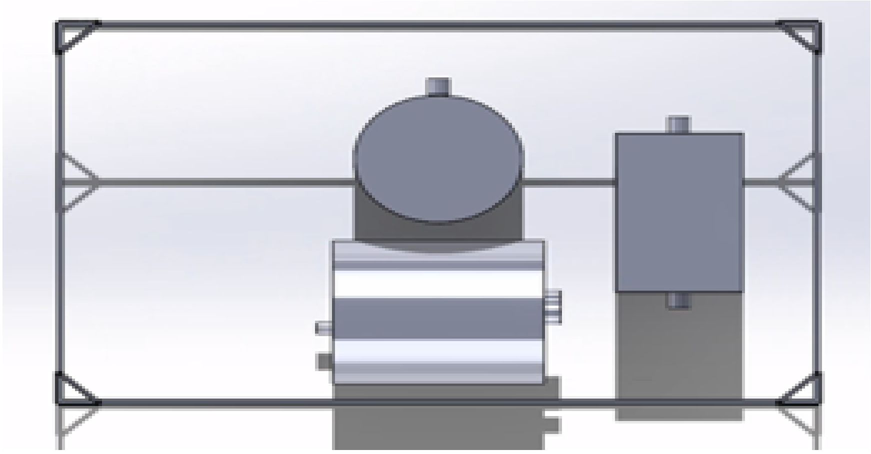


Figure 7. Preliminary CAD Model (Top View)

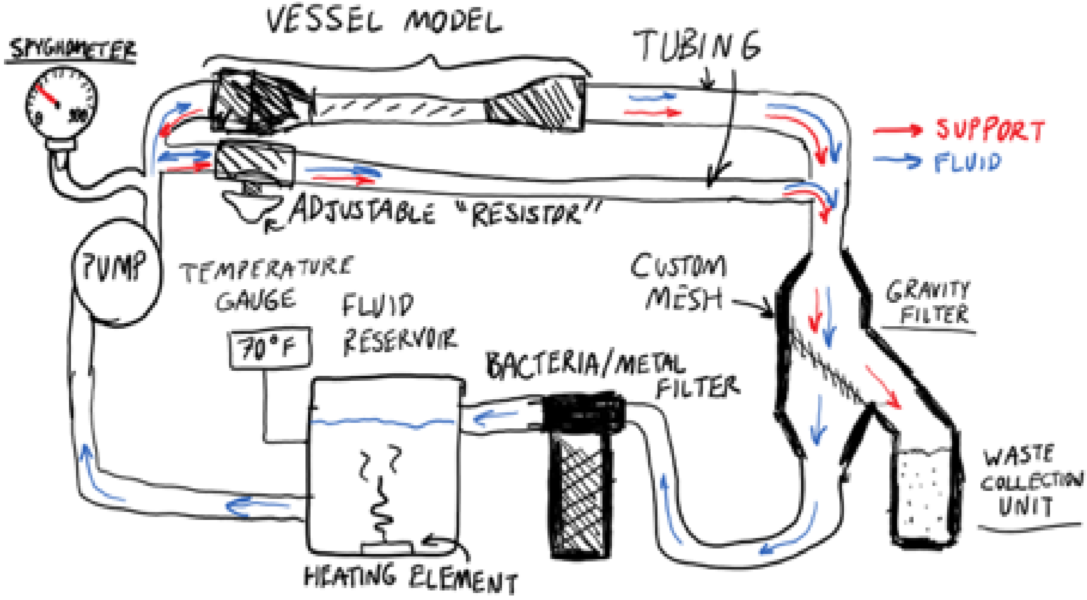


Figure 8. Proposed Concept Design

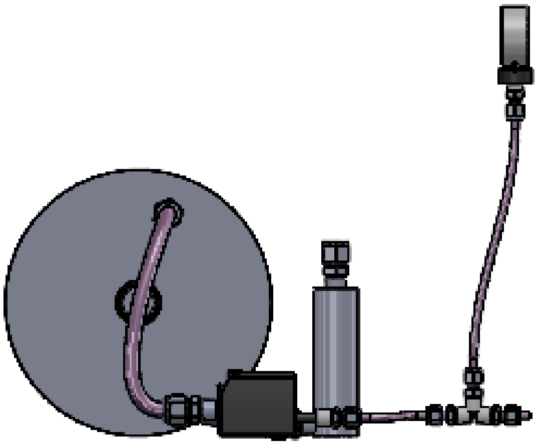
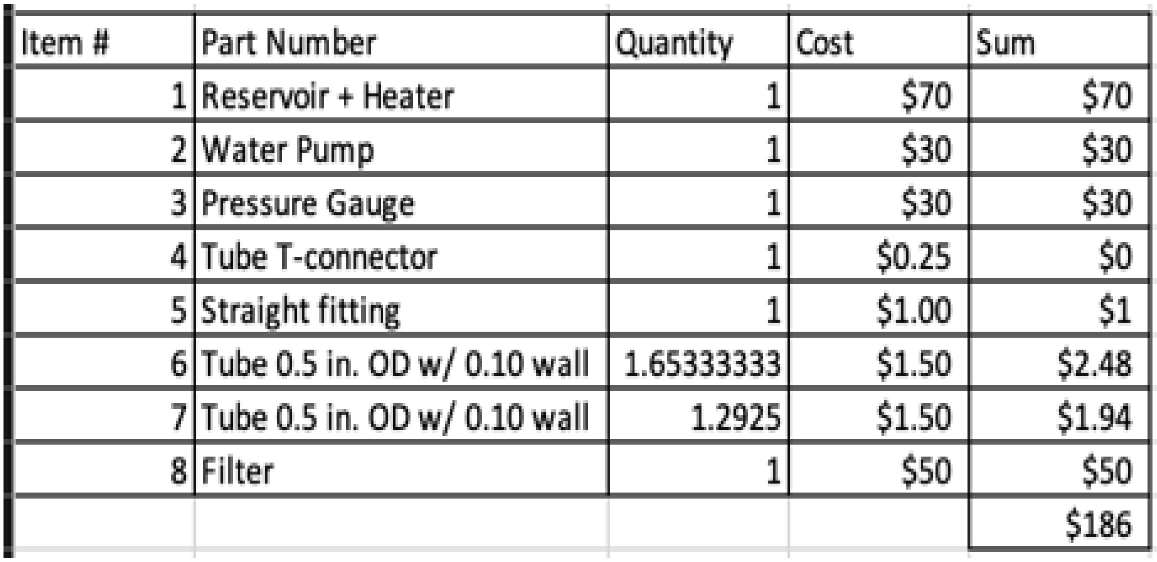


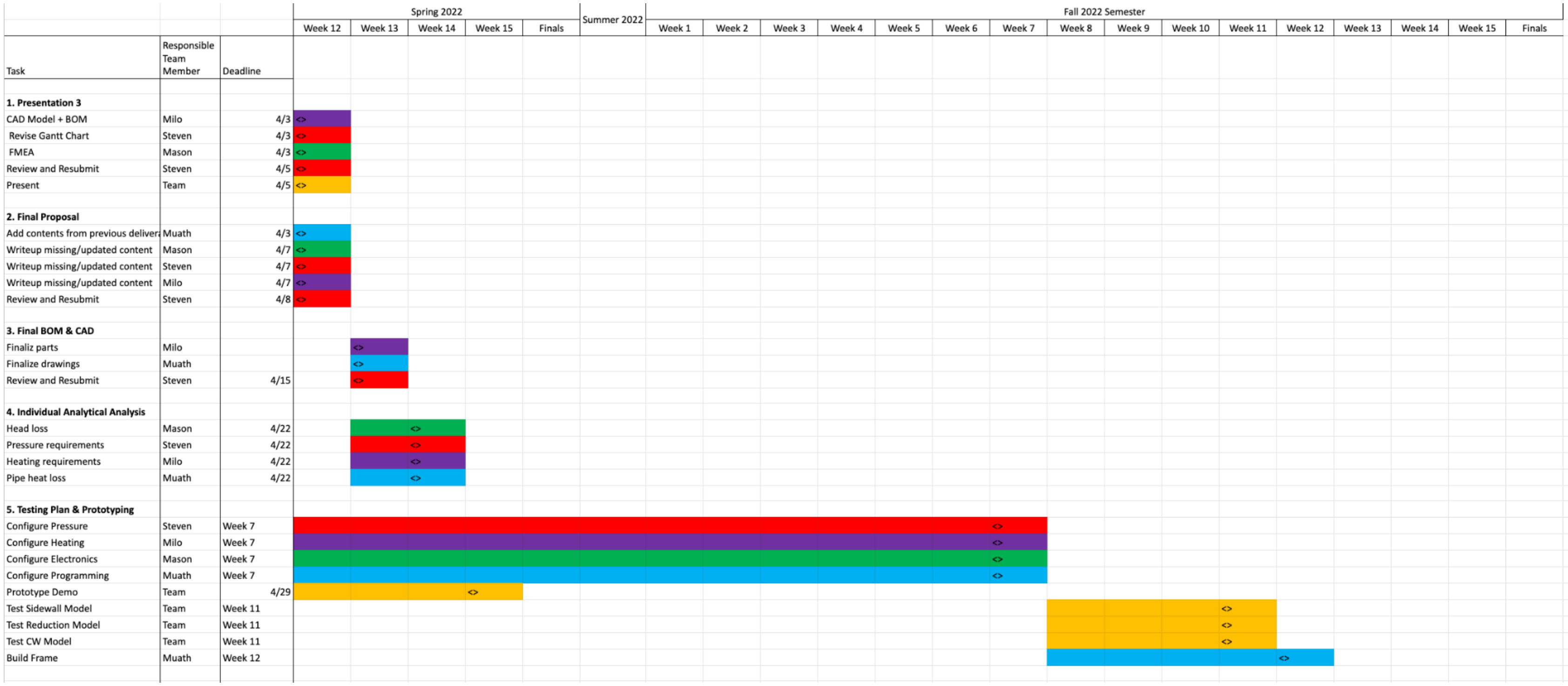
Figure 9. Proposed CVC CAD Model

8.6 Appendix F: Bill of Materials

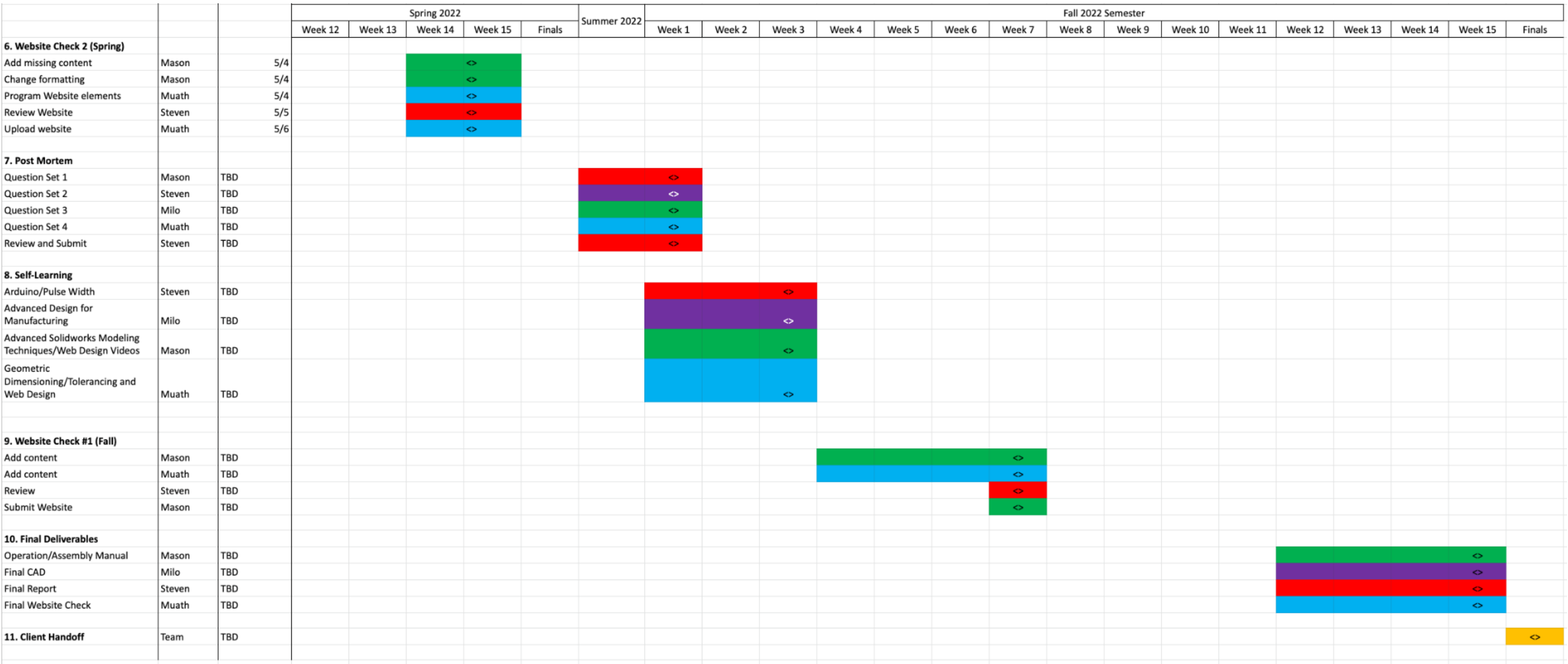


Item #	Part Number	Quantity	Cost	Sum
1	Reservoir + Heater	1	$70	$70
2	Water Pump	1	$30	$30
3	Pressure Gauge	1	$30	$30
4	Tube T-connector	1	$0.25	$0
5	Straight fitting	1	$1.00	$1
6	Tube 0.5 in. OD w/ 0.10 wall	1.65333333	$1.50	$2.48
7	Tube 0.5 in. OD w/ 0.10 wall	1.2925	$1.50	$1.94
8	Filter	1	$50	$50
				$186

8.7 Appendix G: Implementation Schedule (Gantt Chart)



			Spring 2022					Summer 2022	Fall 2022 Semester															
			Week 12	Week 13	Week 14	Week 15	Finals		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Finals
Task	Responsible Team Member	Deadline																						
1. Presentation 3																								
CAD Model + BOM	Milo	4/3	🟪 <>																					
Revise Gantt Chart	Steven	4/3	🟥 <>																					
FMEA	Mason	4/3	🟩 <>																					
Review and Resubmit	Steven	4/5	🟥 <>																					
Present	Team	4/5	🟨 <>																					
2. Final Proposal																								
Add contents from previous deliver	Muath	4/3	🟦 <>																					
Writeup missing/updated content	Mason	4/7	🟩 <>																					
Writeup missing/updated content	Steven	4/7	🟥 <>																					
Writeup missing/updated content	Milo	4/7	🟪 <>																					
Review and Resubmit	Steven	4/8	🟥 <>																					
3. Final BOM & CAD																								
Finaliz parts	Milo			🟪 <>																				
Finalize drawings	Muath			🟦 <>																				
Review and Resubmit	Steven	4/15		🟥 <>																				
4. Individual Analytical Analysis																								
Head loss	Mason	4/22		🟩	🟩 <>																			
Pressure requirements	Steven	4/22		🟥	🟥 <>																			
Heating requirements	Milo	4/22		🟪	🟪 <>																			
Pipe heat loss	Muath	4/22		🟦	🟦 <>																			
5. Testing Plan & Prototyping																								
Configure Pressure	Steven	Week 7	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥 <>									
Configure Heating	Milo	Week 7	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪 <>									
Configure Electronics	Mason	Week 7	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 <>									
Configure Programming	Muath	Week 7	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦 <>									
Prototype Demo	Team	4/29	🟨	🟨	🟨	🟨 <>																		
Test Sidewall Model	Team	Week 11														🟨	🟨	🟨	🟨 <>					
Test Reduction Model	Team	Week 11														🟨	🟨	🟨	🟨 <>					
Test CW Model	Team	Week 11														🟨	🟨	🟨	🟨 <>					
Build Frame	Muath	Week 12														🟦	🟦	🟦	🟦	🟦 <>				



			Spring 2022					Summer 2022	Fall 2022 Semester															
			Week 12	Week 13	Week 14	Week 15	Finals		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Finals
6. Website Check 2 (Spring)																								
Add missing content	Mason	5/4			🟩	🟩◇																		
Change formatting	Mason	5/4			🟩	🟩◇																		
Program Website elements	Muath	5/4			🟦	🟦◇																		
Review Website	Steven	5/5			🟥	🟥◇																		
Upload website	Muath	5/6			🟦	🟦◇																		
7. Post Mortem																								
Question Set 1	Mason	TBD						🟥	🟥◇															
Question Set 2	Steven	TBD						🟪	🟪◇															
Question Set 3	Milo	TBD						🟩	🟩◇															
Question Set 4	Muath	TBD						🟦	🟦◇															
Review and Submit	Steven	TBD						🟥	🟥◇															
8. Self-Learning																								
Arduino/Pulse Width	Steven	TBD							🟥	🟥	🟥◇													
Advanced Design for Manufacturing	Milo	TBD							🟪	🟪	🟪◇													
Advanced Solidworks Modeling Techniques/Web Design Videos	Mason	TBD							🟩	🟩	🟩◇													
Geometric Dimensioning/Tolerancing and Web Design	Muath	TBD							🟦	🟦	🟦◇													
9. Website Check #1 (Fall)																								
Add content	Mason	TBD										🟩	🟩	🟩	🟩◇									
Add content	Muath	TBD										🟦	🟦	🟦	🟦◇									
Review	Steven	TBD													🟥◇									
Submit Website	Mason	TBD													🟩◇									
10. Final Deliverables																								
Operation/Assembly Manual	Mason	TBD																		🟩	🟩	🟩	🟩◇	
Final CAD	Milo	TBD																		🟪	🟪	🟪	🟪◇	
Final Report	Steven	TBD																		🟥	🟥	🟥	🟥◇	
Final Website Check	Muath	TBD																		🟦	🟦	🟦	🟦◇	
11. Client Handoff	Team	TBD																						🟨◇