

FULLY AUTOMATED BEER COOLING AND DISPENSING SYSTEM

By

NICOLE MARIE ROJAS

A Thesis Submitted to The Honors College

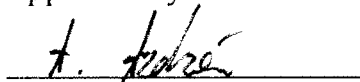
In Partial Fulfillment of the Bachelors degree
With Honors in

Mechanical Engineering

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MAY 2013

Approved by:

A handwritten signature in black ink, appearing to read "A. Arabyan", is written over a horizontal line.

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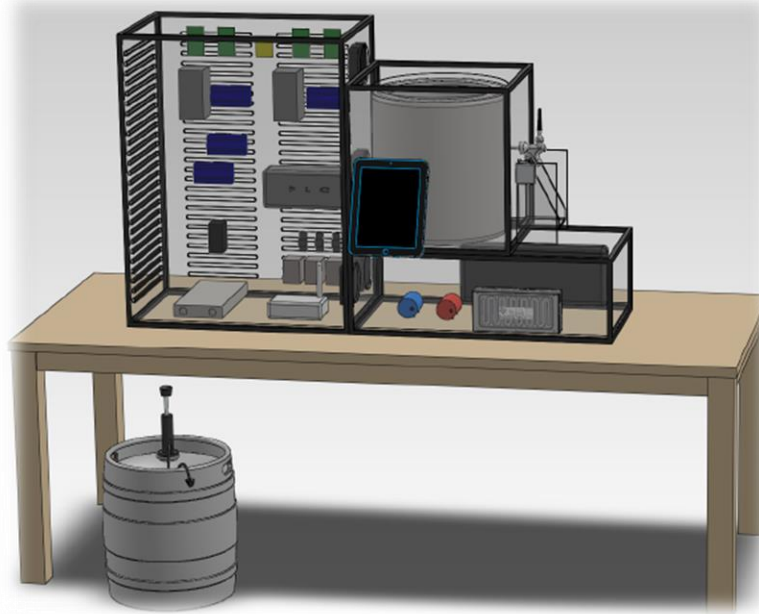
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FULLY AUTOMATED BEER COOLING AND DISPENSING SYSTEM



CAPSTONE REPORT

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Abstract

Texas Instruments is the world leader in digital signal processing and analog technologies. In order to showcase two new products (the ADS1220 and DAC8760), the company created a project to cool and dispense beer automatically. The ability to successfully display the accuracy and precision of their new technologies is key in the design and manufacture of loop powered sensor field transmitters, utilizing high precision data converter integrated circuits. These transmitters are used to monitor temperatures at different locations within the beer cooling system through the use of Resistance Temperature Device (RTD) sensors. The sensors, along with other industrial instrumentation, interface with a Programmable Logic Controller (PLC) to dispense beer at the appropriate temperature and fill a receptacle to the desired level. The water, cooled by the Thermal-Electric Coolers (TECs), is re-circulated through a water bath that houses the beer coil and absorbs the heat dissipated by the beer at a rate of 37°F/hr. Additionally, system status and settings can be seen and changed by a user through an iPad GUI application. This temperature control application highlights TI's accurate and precise technologies for designers in the process control industry.

Table of Contents

- Abstract 2**
- Table of Contents 3**
- Table of Figures 6**
- Table of Tables 8**
- 1.0 Introduction 9**
 - 1.1 Scope of the Document.....9
 - 1.2 Background Information9
 - 1.3 Scope of the Project9
 - 1.4 Project Functionality 10
 - 1.5 Stakeholders..... 11
- 2.0 System Requirements12**
- 3.0 Post Preliminary Design Review Modifications14**
 - 3.1 Three Design Concepts..... 14
 - 3.2 Trade-Off Study and Sensitivity Analysis 14
 - 3.3 Changes since Critical Design Review 15
- 4.0 Top-Level Design.....17**
 - 4.1 Key Terminology..... 17
 - 4.2 Overview of Total System..... 17
 - 4.3 System Architecture 18
 - 4.4 Subsystems and Components 18
- 5.0 Subsystems and Interface Design21**
 - 5.1 Enclosure Subsystems 21
 - 5.2 Cooling Subsystem 22
 - 5.3 Beer Dispensing Subsystem 24
 - 5.4 Electronic Component Subsystem 28
 - 5.4.1 Temperature Sensor Layout and Wiring Subsystem..... 28
 - 5.4.2 Transmitter Design 30
 - 5.4.2.1 PCB Layout..... 33

5.5 Programmable Logic Controller Subsystem	37
6.0 Algorithm Description and Interface Document.....	39
6.1 Microcontroller Modules	39
6.1.1 ADS1220 Code	39
6.1.2 DAC8760 Code.....	41
6.2 Microcontroller Flow Diagram	41
6.3 Microcontroller Trade Study	42
6.4 Programmable Logic Controller Flow Diagram	43
6.5 Graphical User Interface	45
7.0 Analysis	47
7.1 Heat Transfer Analysis.....	47
7.2 Pipe/Water Bath Analysis.....	49
7.3 Tilting Mechanism Analysis	51
8.0 Development Plan	52
8.1 First Build: RTD Structure	52
8.2 Second Build: Water Bath Enclosure.....	52
8.3 Third Build: Totalizer Method	53
8.4 Fourth Build: Graphical User Interface.....	53
9.0 Budget and Suppliers	54
10.0 Requirements Review/Acceptance Test Plan	57
10.1 Requirements Review	57
10.2 Acceptance Test Plan	59
11.0 Summary of Risk Analysis and Mitigation Plan.....	60
12.0 Project Management Update	63
13.0 Closure	64
References	65
Appendix A.....	66
Individual Contributions.....	66
Appendix B.....	68

Hardware Drawings for Assemblies	68
Appendix C.....	73
Calculations	73
Appendix D	76
Functional Diagrams.....	76
Appendix E.....	78
Control Panel and High Level Wiring Diagram	78
Appendix F	80
Preliminary Implementation Timeline	80

Table of Figures

3.1.1 Three Design Concepts Diagram.....	14
4.3.1 System Architecture.....	18
4.4.1 Enclosure Subsystem	19
4.4.2 Thermo-Electric Water-Cooling System.....	19
4.4.3 RTD/T-Fitting Subsystem	20
4.4.4 Flow Meter.....	20
5.1.1 System Enclosure SolidWorks Diagram	21
5.1.2 System Parts Assembly	22
5.2.1 Stainless Steel Coil	23
5.2.2 TEC Water-Cooling Channels	24
5.3.1 D-System Keg Tap	25
5.3.2 CO ₂ Regulator.....	25
5.3.3 RTD with T-Fitting	26
5.3.4 Infrared Flow Meter.....	26
5.3.5 Infrared Flow Sensor	27
5.3.6 Solenoid Valve.....	27
5.4.1.1 PCB Board	29
5.4.1.2 RTD and ADS Schematic.....	30
5.4.1.2 ADS to MSP to DAC Wiring	30
5.4.2.1 ADS1220 Analog Input Voltage Pin (AVDD).....	32
5.4.2.2 DAC Analog Input Voltage (AVDD)	32
5.4.2.3 Voltage Regulator Analog Input Voltage Pin (IN)	33
5.4.2.1.1 PCB and Schematic Example of the Voltage Regulator	34
5.4.2.1.2 ADS Schematic	35
5.4.2.1.3 Microcontroller Schematic	35
5.4.2.1.4 DAC Schematic.....	36
5.4.2.1.5 Voltage Regulator	36
5.4.2.1.6 Transmitter Layout Design.....	37

6.1.2.1 ADS1220ReadRegister() Code.....	40
6.1.2.2 ADS1220ReadData() Code	40
6.2.1 Microcontroller Flow Diagram.....	42
6.4.1 Programmable Logic Controller Flow Diagram.....	43
6.3.1 S7-1200 GUI Application	46
7.1.1 Heat Removal for a Constant Water Temperature	47
7.1.2 Heat Transfer between Fluid Flowing Over and Passing through the Tube.....	48
7.1.3 Schematic of Helically Coiled Tube and Secondary Flow	48
7.1.4 Axial Temperature Variations for Heat Transfer on Constant Surface Temperature	49
11.1 Severity vs. Frequency	61
B.1 SolidWorks Drawing of Entire System	68
B.2 SolidWorks Drawing of Beer Coil	68
B.3 SolidWorks Drawing of System Enclosures	69
B.4 SolidWorks Drawing of RTD with T-fitting.....	69
B.5 SolidWorks Drawing of Thermo-Electric Water-Cooling Channel	70
B.6 SolidWorks Drawing of Water Bath Container	70
B.7 SolidWorks Drawing of Water Bath Tilting Mechanism Assmebly.....	71
B.8 SolidWorks Drawing of Water Exchange Assembly.....	71
B.9 SolidWorks Drawing of Electronics/Control Panel Assembly.....	72
B.10 SolidWorks Drawing of Tilting Mechanism Assembly	72
C.1 Heat Transfer/Pipe Analysis Calculations Page 1	73
C.2 Heat Transfer/Pipe Analysis Calculations Page 2	74
C.3 Tilting Mechanism Analysis Calculations Page 1	75
D.1 Operational Functional Flow Diagram Representation of the System	76
D.2 Maintenance Functional Flow Diagram Representation of the System	77
E.1 Control Panel Layout.....	78
E.2 High Level System Components.....	79
F.1 Gantt Chart Representation of the Timeline	83

Table of Tables

2.1 System Requirements	12
3.2.1 Trade-Off Study	15
3.2.2 Sensitivity Analysis	15
7.2.1 Acrylic Properties	51
9.1 Bill of Materials	54
10.1.1 Requirements Review	57
11.1 Four Major Risks	60
11.2 Four Major Risks' Solutions.....	62
F.1 Preliminary Implementation Timeline	80

1.0 Introduction

1.1 Scope of the Document

Texas Instruments will showcase at trade shows, in the United States and around the world, their two new innovations (the ADS1220 and DAC8760) in the automated beer cooling and dispensing system following the University of Arizona's Senior Design day on April 30th, 2013. This system exhibits breakthrough technology in the field of electrical engineering by demonstrating the high accuracy and precision performance of Texas Instruments' temperature sensor transmitters. This document elucidates the desired system and provides a brief background of the causes that lead to the creation of this project.

1.2 Background Information

Texas Instruments (TI) is a world class manufacture of temperature sensor transmitters, who would like to showcase these transmitters at trade-shows around the world. For this reason, TI funded a University of Arizona Capstone project that fully cools and dispenses beer automatically. A temperature sensor transmitter is a loop-powered sensor field transmitter that utilizes high-precision data-converter integrated circuits. The integrated circuits, which were incorporated within the transmitter, include Texas Instruments' ADS1220, DAC8760, and the MSP430F5528 microcontroller. This transmitter is attached to a temperature probe sensor to construct a resistance temperature detector (RTD). This RTD produces a 4-20 mA signal received by the Siemens S7-1200 programmable logic controller (PLC), which in turn linearly compares the signal to an established temperature range. This new determined value is used to monitor temperature within a section of the system. The use of this RTD demonstrates the accuracy, precision, and quality of Texas Instruments' temperature sensor transmitters.

1.3 Scope of the Project

This proposed project improves the understanding of constructing Texas Instruments' temperature sensor transmitters by utilizing them in an industrial system at trade-shows, both nationally and internationally, after the completion of Senior Design day at the University of Arizona. The RTDs are accompanied by numerous industrial devices, which include a flow meter, a flow valve, and thermo-electric coolers (TEC). These devices interface with the PLC, and through automation, the system is controlled to cool and dispense beer automatically. This system is controlled through a Graphical User Interface (GUI) to monitor and change values within the PLC, which controls temperature and flow out

of the system. Team 5348 has created a portable system capable of cooling and dispensing beer automatically through a GUI.

1.4 Project Functionality

For Texas Instruments to showcase its new products, they proposed this University of Arizona Capstone project. It is a system that automatically cools and dispenses beer. The system dispenses beer in varying user-specified size glasses (up to a pint), at changeable user-specified temperatures. For this to be achieved, the system uses industrial instrumentation and a Siemens PLC. The industrial instrumentation involved within this system consists of a flow meter, a flow valve, a thermo-electric cooler, and four temperature sensor transmitters. The entire system is controlled through a graphical user interface (GUI) by means of an iPad.

For the system to be cooled properly, it needs to use four temperature sensors and three TECs. Three temperature sensors are placed in the beer line and another sensor is placed at the in the middle of the cooler which houses the water. Utilizing the feedback from the sensors as a process variable, and using the TEC output as the control variable, the PLC uses a PID loop function to control the output signal to the TEC. This provides a constant temperature output into the water bath, thus enabling the system to cool the beer in the coil at a constant rate and at a user established temperature set-point. The two sensors at the inlet and outlet of the coil relay measure the temperature of the beer before and after the water bath to ensure the beer dispensed is at the proper temperature. This demonstrates the effectiveness of the system, along with showcasing Texas Instruments' transmitters.

Flow out of the system is monitored to ensure proper fill level in the glass. To achieve this, an infrared flow meter is utilized to measure the speed of the fluid through the pipe, along with two flow valves, to enable and disable flow out of the system. To ensure there is enough fluid filling the glass, a totalizer method is deployed with the flow meter, which monitors the liquid level in the glass. Once the glass is filled, the flow valve closes, resulting in a perfect beer pour.

Initially, a pushbutton was used to start and stop the dispensing. Given that Texas Instruments incorporated a graphical user interface (GUI) to write and monitor values within the PLC, the pushbutton was converted to an emergency-stop button, in the case of beer leakage. This GUI is the S7-1200 application for the iPad, which displays temperatures, fill level, and modes of the system. The GUI also has adjustable variables consisting of temperature set-points, fill level set-points, and mode selections. Creating a GUI for this system is beneficial in showcasing the temperature sensor transmitters, due to the use of a real-time temperature value display. With the ability to change the temperature set-point

from the GUI, the system demonstrates quick temperature changes, along with accuracy of the temperature sensor transmitters.

1.5 Stakeholders

The system's stakeholders are Texas Instruments' representatives, along with users at tradeshows around the world. Texas Instruments is planning on having a station at these tradeshows that will attract customers and vendors by demonstrating the accuracy and precision of its temperature sensor transmitters. These participants will have complete control to select their beer's desired temperature, along with their desired glass size (up to one liter). While the system is dispensing, the user can view the temperature in real-time, as well as the flow rate of the system, with the iPad S7-1200 application GUI.

While the participants of the demonstration are drinking their beer, Texas Instruments representatives will be able to illustrate the precision and performance of their new temperature sensor transmitters. Since crowds are drawn to entertaining and user-interactive demonstrations, this system should create a large crowd, giving Texas Instruments the attraction needed to showcase their products. This will create an easy way for the representatives to gain customers and expand their business worldwide.

2.0 System Requirements

To fully understand the aspects of this project, requirements were established to identify the capabilities and functions needed by the system in order to satisfy the customer's needs. The system requirements are sectioned off into six separate categories:

- **Functional Requirements:** Determine what the product must do, and distinguish between what the product must do and what would be desirable.
- **Technology Requirements:** Identify what specific technologies must be integrated into the system design.
- **Performance Requirements:** Illustrate how well the product must perform its required functions with metrics and some verification method.
- **Utilization of Resource Requirements:** Determine the dollar budget, along with the budget in mind and labor cost.
- **Trade-Off Requirements:** Define where there is a likely trade-off between requirements.
- **System Test Requirements:** Develop tests to verify the system performs as required.

As illustrated in Table 2.1 below, the system requirements for the proposed system were established.

Table 2.1 – System Requirements

Number	Type	Description
101	Functional	The system shall cool beer to a desired temperature based on beer type
102	Functional	The system shall dispense beer at a specified flow rate based on beer type
103	Functional	The system shall be limited to two power plugs (one per each compatibility)
104	Functional	The system shall be controlled through a graphical user interface (GUI)
105	Functional	The system shall disassemble and fit into, at most, three "Pelican 1690 Transport Cases" (30.01" x 25.02" x 15.00")
201	Technology	The system shall use a Siemens S7-1200 Series PLC to automate the system
202	Technology	The system shall utilize an RTD probe, plus an ADS1220 and the DAC8760 to create an RTD
203	Technology	The system shall utilize Thermo-Electric Coolers (TECs) to cool the beer
204	Technology	The system shall utilize a push button to start the dispensing system
205	Technology	The system shall use "see-through" tubes
206	Technology	The system shall utilize food-grade devices/equipment
207	Technology	The system shall utilize an iPad GUI application to control the system

208	Technology	The system shall be compatible with both 120V/60Hz and 220V/50Hz outlets
301	Performance	The temperature detector shall not consume more than 3.6mA each
302	Performance	The TEC device shall cool beer within a $\pm 1^{\circ}\text{C}$ accuracy
303	Performance	The TEC device shall cool beer utilizing the RTDs
304	Performance	The flow meter shall determine a level with an error rate of less than $\pm 2\%$
305	Performance	The system shall dispense beer into a $\frac{1}{4}$ pint, $\frac{1}{2}$ pint, and one pint glass
401	Utilization	The system shall not cost over \$3000
402	Utilization	The system shall be assembled in 30 minutes
403	Utilization	The system shall require, at most, two individuals to set up
404	Utilization	The system shall be light enough for two individuals to carry
405	Utilization	The system shall be reliable for intervals of at least 8 hours
406	Utilization	The system shall require one individual to operate the system
501	Trade-Off	The system shall use the following criteria for a trade-off analysis:
501.1	Trade-Off	Overall system performance is more important than Utilization of Resources
501.2	Trade-Off	Overall size of system is more important than cost in value
501.3	Trade-Off	Technology within the system is more important than cost in value
501.4	Trade-Off	Overall size of system is more important than aesthetics
601	System Test	The system shall be tested under the following criteria:
601.1	System Test	The system shall undergo a temperature analysis.
601.2	System Test	The system shall undergo a fill level analysis.
601.3	System Test	The system shall undergo a power consumption analysis.
601.4	System Test	The system shall be tested for weight constraint.
601.5	System Test	The system shall undergo a timed setup plan.

3.0 Summary of Preliminary Design Review Results

3.1 Three Design Concepts

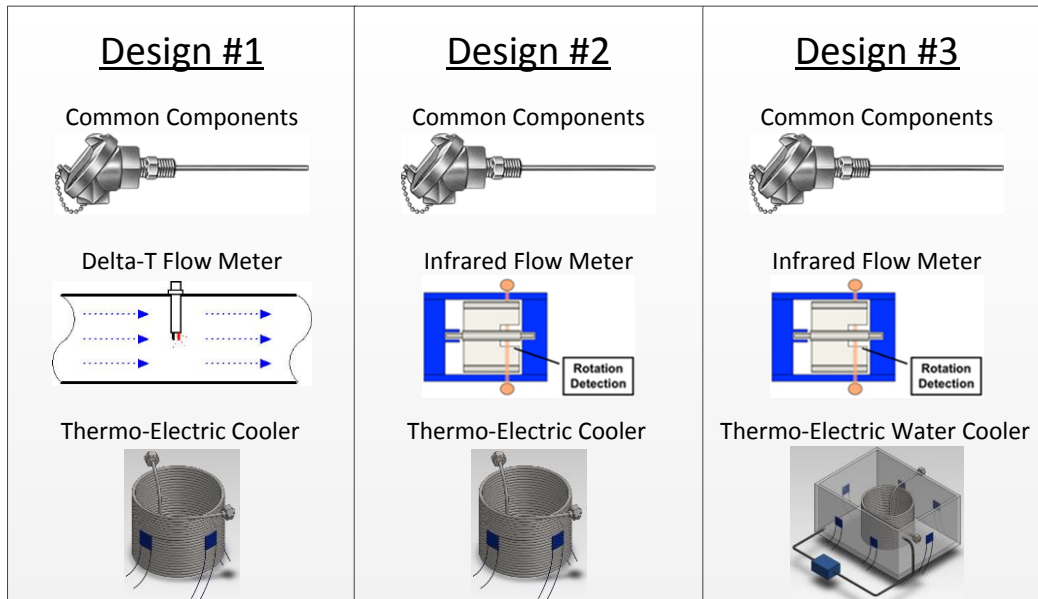


Figure 3.1.1 – This figure shows the three design concepts that were used in selecting the final product

For the preliminary design review, Team 5348 developed three separate design concepts of the proposed system, as displayed in Figure 3.1.1 above. This was done to determine a superior design of the developed project.

All three designs shared common components: four temperature sensors, a flow valve, and a programmable logic controller (PLC). These components remained constant throughout the three designs due to the lack of different options available. Design #1 included a flow meter, composed of two RTDs and the delta-T method. This design also included thermo-electric coolers attached directly to the beer coil. Design #2 used the same cooling method, but differed on the flow meter. The one used for this design was an infrared flow meter, which produces a high speed counting (HSC) signal. Design #3 used the same flow meter as design #2, but differed on the cooling method, by placing the beer coil in a water bath and using a TEC water cooler to recirculate the water within the bath, cooling the water that in turn cools the beer in the coil. This system is described as a heat exchanger.

3.2 Trade-Off Study and Sensitivity Analysis

To determine the best design, Team 5348 performed a trade-off study and sensitivity analysis. The trade-off study was used to assign weights to the evaluation criteria. The evaluation criteria were

weighted based on the need/importance from Texas Instruments. Team 5348 then evaluated a score for each design based on the satisfaction level of the evaluation criteria. The results are displayed in Table 3.2.1 below.

Table 3.2.1 – A table consisting of the trade-off study

Evaluation Criteria	Weight	Design 1	Design 2	Design 3
Cost	0.10	0.90	0.70	0.60
Technology	0.30	0.80	0.85	0.90
Performance	0.30	0.50	0.70	0.90
Size	0.20	0.80	0.80	0.65
Aesthetics	0.10	0.90	0.90	0.90
Total Scores	1.000	0.730	0.785	0.820

The results indicate design #3 as the best design for the proposed system. With the purpose of determining whether the trade-off study was considered accurate, a sensitivity analysis was conducted. The evaluation criteria weights were adjusted to determine if changing the weights could potentially change the outcome of the trade-off study. The results are displayed in Table 3.2.2 below. After the trade-off study and sensitivity analysis, Team 5348 selected design #3.

Table 3.2.2 – A table consisting of the sensitivity analysis

Evaluation Criteria	Weight	Design 1	Design 2	Design 3
Cost	0.20	0.90	0.70	0.60
Technology	0.25	0.80	0.85	0.90
Performance	0.25	0.50	0.70	0.90
Size	0.20	0.80	0.80	0.65
Aesthetics	0.10	0.90	0.90	0.90
Total Scores	1.000	0.755	0.778	0.790

3.3 Changes since Critical Design Review

Since the critical design review, there have been a few design changes within the system. In order to determine the most efficient, effective, and safe method to cool the beer, Team 5348 created a different method for cooling the beer. The method selected places the beer coil within a container filled with water and a recirculation pump that ensures the temperature of the water bath is evenly

distributed. Three TECs are used in a water-cooling channel and placed in the middle of two aluminum plates, one of which cools the water being re-circulated within the water bath, and the other which dissipates the heat generated by the TECs by means of a radiator recirculating system. This system creates a heat transfer between the water and the beer in the coil.

Taking notice of the amount of power consumption per TEC in the previous design and the inefficiency of having multiple TECs on the exterior of the container, Team 5348 decided to change the cooling method. The recirculation loop was kept, however a TEC water-cooling channel was added after the pump, within the recirculation line. The warm water exits at the bottom of the water bath through an insulated tube, proceeds through the recirculation pump and TEC water-cooling channel, and is injected back into the top of the water bath. This creates a vortex within the water bath, causing an even distribution of temperature within the system, while efficiently cooling the beer within the coil. This is the most effective, efficient, and safe cooling method for this project.

A tilting mechanism and a pressure switch are also incorporated in the dispense system. A motor, controlled through the PLC, provides the torque necessary to tilt a Plexiglas enclosure to provide a perfect dispense at a 45° tilt. The segment supporting the back of the glass can be manually adjusted up or down to provide enough space for a wider glass. The pressure switch is activated when a glass is placed on the enclosure, sending a signal to the PLC, which in turn enables the output of the motor to tilt the glass. Once the glass is filled half way of the desired set point, the current is reversed through the motor and the glass comes to the upright position for retrieval. This is done through a magnetic switch mounted within the enclosure allowing for the glass to return to the perfect position every time a beer is dispensed.

4.0 Top-Level Design of Final Concept

4.1 Key Terminology

- ADS – Analog-to-Digital Converter
- ADS – ADS1220, an Analog-to-Digital Converter
- GUI – Graphical User Interface
- PLC – Programmable Logic Controller
- RTD – Resistance Temperature Detector
- TEC – Thermo Electric Cooler

4.2 Overview of Total System

The mobile automated beer cooling and dispensing system cools and dispenses beer using industrial instrumentation within the system. This system consists of three separate Plexiglas/angled iron enclosures housing the pump, the TEC water-cooling channel, the PLC, temperature transmitters, a flow meter, a flow valve, and the water container housing the coil from which the beer is dispensed. This entire system is controlled through the S7-1200 iPad GUI application that displays all system temperatures, fill level, and modes of the system as well as temperature set-points, fill level set-points, and mode selection.

This system utilizes four temperature sensors, created using Texas Instruments' temperature transmitters together with a TEC water cooler system to cool the beer. One temperature sensor transmitter is placed at the inlet of the beer coil, along with one at the middle of the coil and one at the outlet. This subsystem is used together with a temperature sensor transmitter placed at the center of the water bath to monitor the temperature difference within the beer line. This determines if the beer flowing out of the system is at the desired temperature set by the user. The feedback from the four transmitters is sent to the PLC, and the system automatically controls the TECs to acquire the desired beer temperature out of the system.

Once a glass is placed on the tilting mechanism, the pressure switch sends a signal to the PLC that a glass has been placed on the holder. When the user selects to start the dispensing the beer, the PLC waits for a time of two seconds before enabling the output of the motor to tilt to the 45° angle. Once the glass reaches a 45° angle, the system waits for an additional second before enabling the flow valve to open. As the fill level reaches half of the fill level set point, the system enables the motor to return to the initial position, and continue the flow until the fill level reaches the set point. When the fill level is

reached, the flow valve is closed, and the final average temperature leaving the system is recorded, as well as the final fill level percentage for the user to view via the iPad. The flow out of the system is monitored to ensure a proper fill amount. The flow is measured by a flow meter at the inlet of the coil where the high-speed signal count is totaled within the PLC. Once the totaled count is equal to the fill level set point count amount, the system closes the flow valve, stopping the count of the flow meter. Flow speed is controlled by the carbon dioxide pressure inject at the entrance of the keg sub-system.

4.3 System Architecture

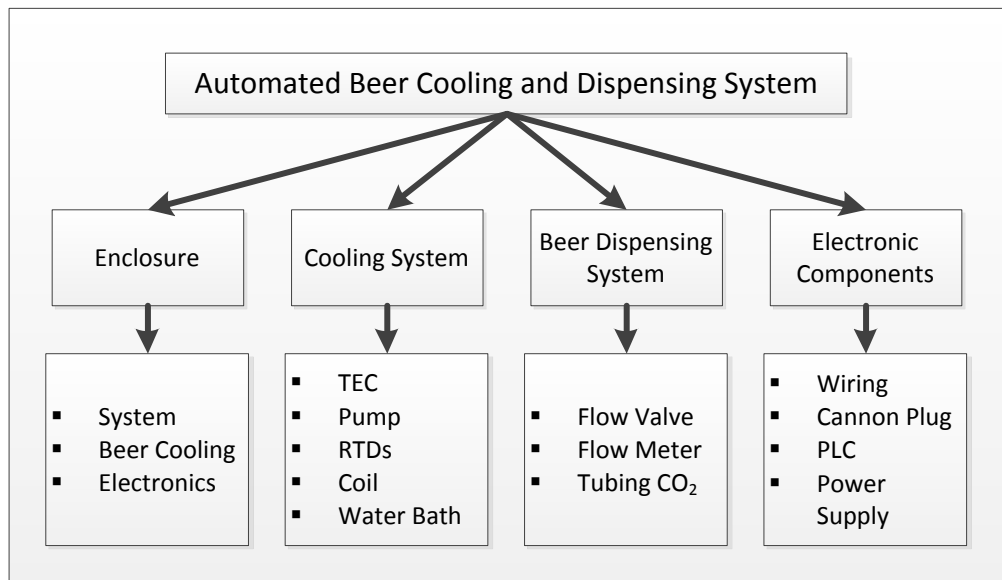


Figure 4.3.1 – The figure above displays the beer cooling and dispensing system architecture

4.4 Subsystems and Components

The three enclosures house the entire system, which are divided by the water bath/tilting mechanism, the pump/TEC components and the electronics section (Figure 4.4.1). These enclosures are placed on top of tables at tradeshows around the world where Texas Instruments will showcase the entire cooling and dispensing system.

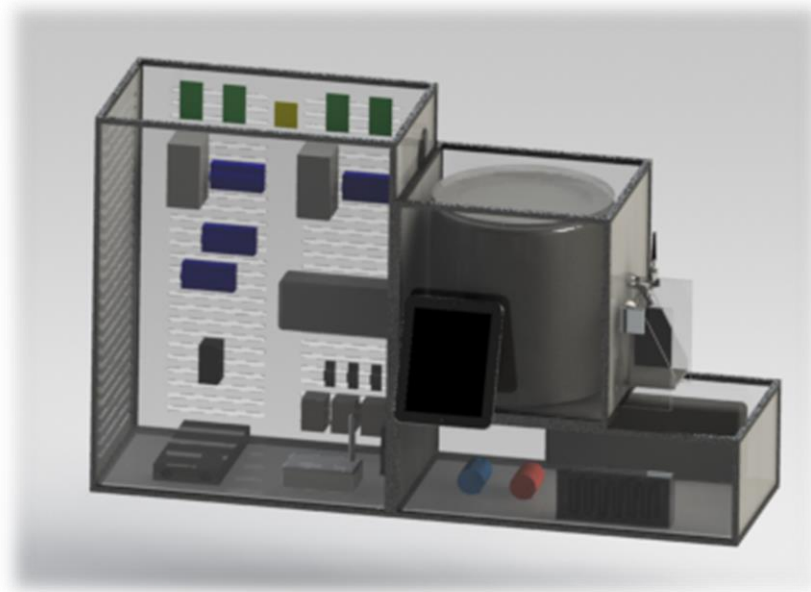


Figure 4.4.1 – This is an illustration of the minimum components of the enclosure subsystem

The cooling system is composed of a water bath storing the coil containing the beer, the RTDs placed on the coil in the middle of the water bath, the pumps, the radiator cooler, and the TEC water-cooling channel subsystem, which are placed outside of this subsystem and wired to the PLC. This subsystem is displayed in the figure above. The TEC water-cooling channel is used with the pump to cool the water stored in the water bath and recirculate it to provide a static temperature. The figure below details the TEC water-cooling channel that this subsystem uses. The red and blue colors signify the hot and cold portions of the channels, respectively.

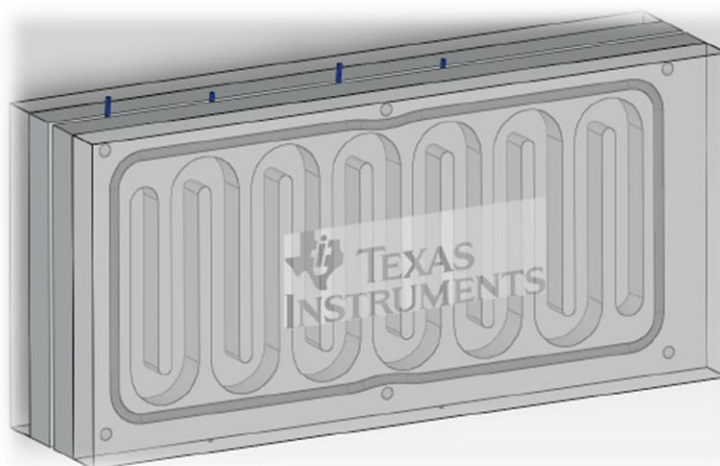


Figure 4.4.2 – This is the thermo-electric water-cooling channel which recirculates the cool water to the water bath on one side and the hot water to the radiator on the other side

The four RTDs (three utilized by the coil subsystem and one by the water bath subsystem) are connected independently to a PCB board that houses the temperature transmitter circuit. The other side of each RTD fits into a T-fitting in the beer line as depicted below.

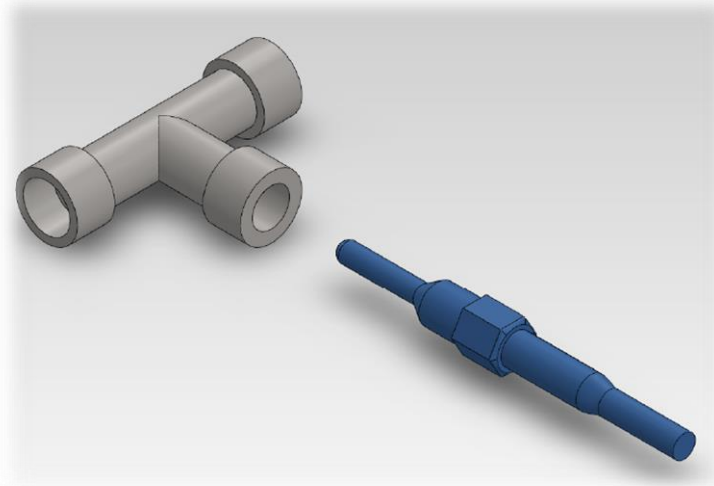


Figure 4.4.3 – The RTD above (in blue) fits into the beer line’s T-Fitting subsystem (grey)

The flow meter used in the beer line to provide a flow measurement is depicted in figure 4.4.4.



Figure 4.4.4 – The Swissflow flow meter measures the amount of fluid passed through the beer line to ensure the proper dispense amount

5.0 Subsystems and Interface Design

5.1 Enclosure Subsystems

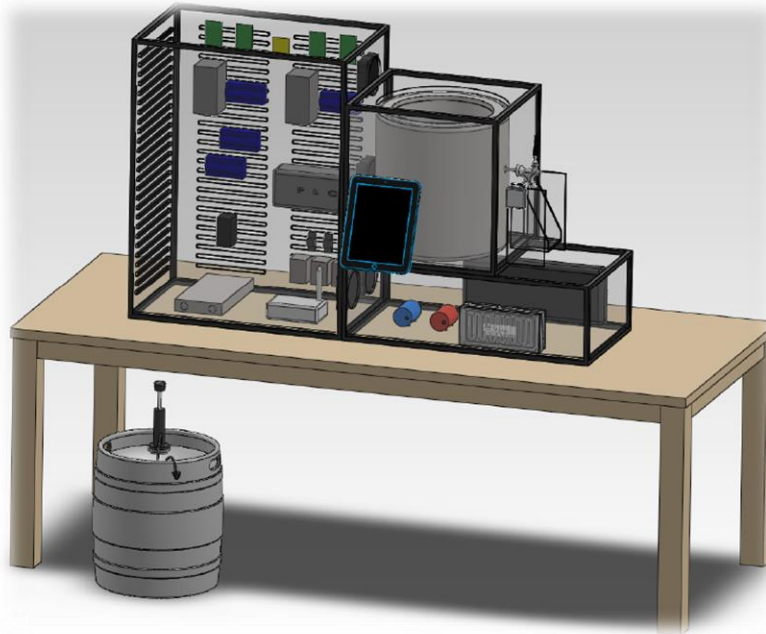


Figure 5.1.1 – This is the overall system that was modeled in SolidWorks and which shows the different compartments housing the water bath, the cooling subsystem and the electronics

The system is broken up into three separate enclosures made of angle iron with $\frac{1}{4}$ " to $\frac{1}{2}$ " Plexiglas. These enclosures are shown side-by-side above in Figure 5.1.1 for illustrations purposes. One compartment contains the electronics including the PLC, power supplies, and Texas Instruments components (Analog-to-Digital Converter, Microcontroller, and Digital-to-Analog Converter). The second compartment holds the beer cooling system, which includes the TEC water-cooling channel, the pumps, and the radiator. Finally, the third compartment houses the RTDs, the beer coil, the water bath cooler, and the tilting mechanism. This last enclosure also has a faucet on its side where the beer is dispensed and a removable tray that catches any beer that may overflow or miss the glass. Each container has a plug on the side where cannon plugs are used to connect all of the enclosures. The purpose of having separate enclosures is to adhere to size restraints for portability and shipping that were established in the aforementioned system requirements. The separate containers also provide a safer environment for the electronics, as they are in a separate case from the one containing liquids. Also, when in use, the TECs produce excess heat that does not affect the other electronics in their separate enclosure. Each enclosure has ventilation holes that allow the heat produced by the various

components to be vented out away from the system, allowing for a better system operating temperature. The system’s angled iron and Plexiglas construction allow users to see the components, being that the overall purpose of the system is to showcase the design and functionality of Texas Instruments’ components. A breakdown of the system enclosures and their components is depicted in Figure 5.1.2.

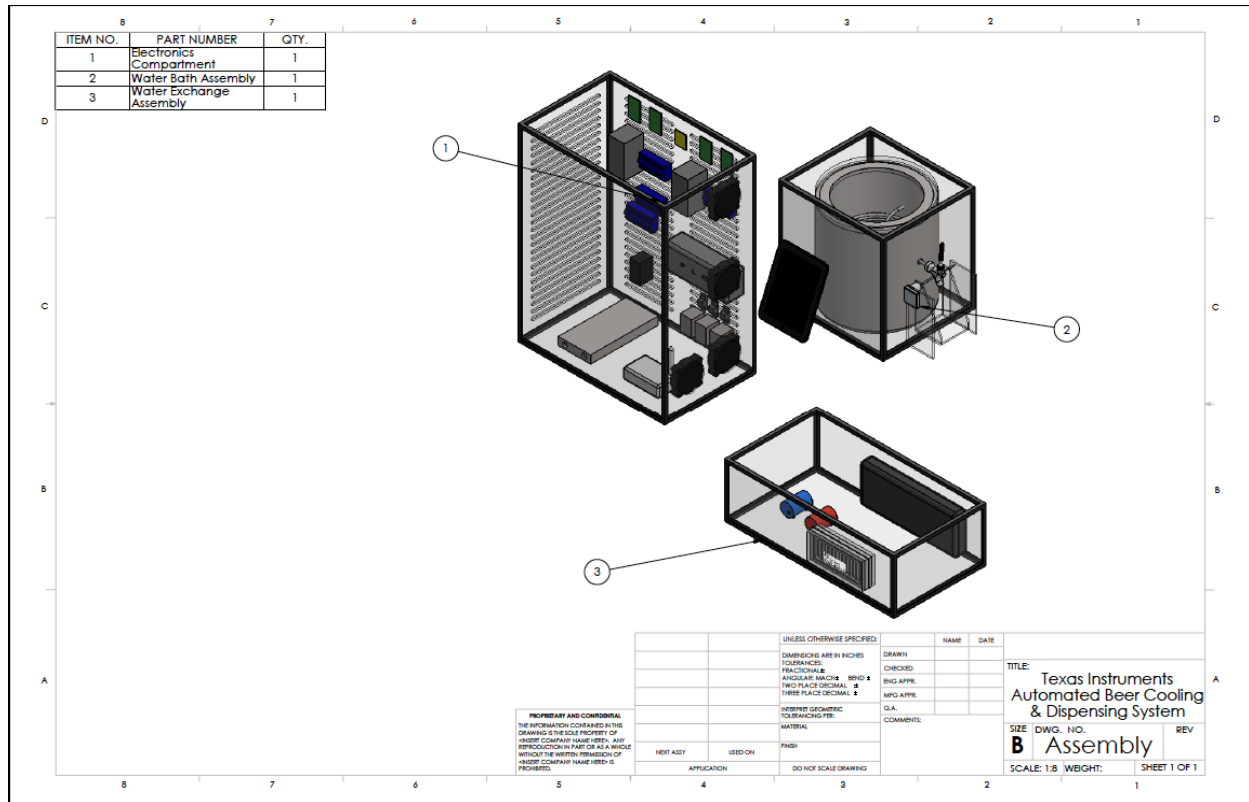


Figure 5.1.2 – This is the assembly of broken down system parts

5.2 Cooling Subsystem

To cool the beer down to the desired temperature, the beer passes through a heat exchange system before it reaches the tap where it flows out of system and into the glass. The heat exchange system is composed of stainless steel coiled tubing that is immersed in a water bath cooler. The coil is shown below in Figure 5.2.1.



Figure 5.2.1 – This is the stainless steel coil in which the beer flows and is cooled by the heat exchange system

The water bath is a square cube constructed of angled iron and Plexiglas containing an igloo cooler that houses the coil in which the beer passes through (Figure 5.1.2). When setting up the system, ice water is initially added to the water bath to provide a good thermal conductor for the coils to sit in. As the beer passes through the coils, a heat exchange occurs. The heat, from the warm temperature of the beer, dissipates until the system is in equilibrium with the water in the water bath. The beer reaches the coil at the temperature designated by the user. An RTD sensor monitors the input and output temperatures of the beer so the correct temperature can be set for the water bath. To control the temperature of the water bath, the water constantly cycles through the TEC water-cooling system by a pump (Figure 5.1.2 part 4). Another RTD is placed at the middle of the water bath to monitor the water temperature. When the water temperature rises above the desired temperature, the TECs turn on to begin the cooling process until the temperature is back in the desired range. When the TECs are on, one side of the channel becomes very cold while the other side becomes very hot. The water from the water bath is routed to the cooling side of the heat exchanger, and the water from the radiator is routed through the hot side as heat exchange occurs. Similarly, a heat exchange occurs for the beer in the coils that are submerged in the water bath. The cooling side of the TECs is shown in blue in Figure 5.2.2 below. To manage the heat generated by the opposite side of the TEC, a radiator is used to dissipate the heat, sending the excess hot water out of the system through the radiator to cool. The hot side of the TEC water-cooling channel is shown in Figure 5.2.3 below.

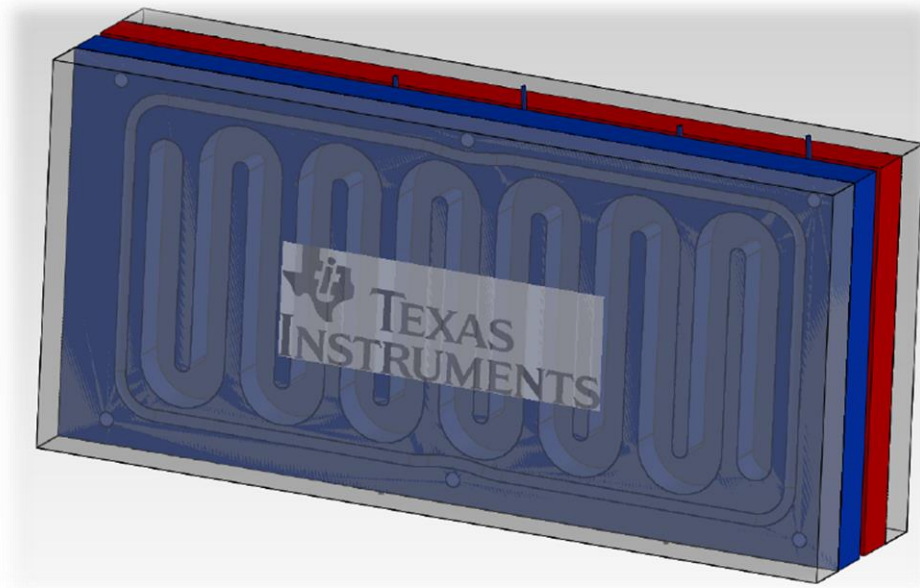


Figure 5.2.2 – TEC water-cooling channel displaying the cold channel and the hot channel sides

5.3 Beer Dispensing Subsystem

The system's beer supply was store bought, together with a rented keg that is set up next to the system and kept at room temperature. To connect to the keg to the dispensing system, a beer tap is used. The beer tap connects a CO₂ line to the system and has a tubing to allow the beer to flow out. The system comes with two taps for the most common beers on the market, but if a different type of keg tap is required, the team will rent it from the store where the beer is purchased. The most widely used tap in the United States is the D-system coupler (Figure 5.3.1), and in Europe the most common is the S-system coupler, which looks much like the D-system coupler but has different threading for European kegs. Other taps, some more specific for different breweries, are interchangeable with the system, but will have to be rented when the keg is rented.



Figure 5.3.1 – This D-system keg tap is used with the beer keg and the CO₂ tank as a means to allow the beer to flow into the system

A CO₂ tank needs to be rented with the keg at the time of purchase. The system includes a CO₂ regulator that attaches to the CO₂ tank and controls the pressure in the keg. The CO₂ regulator is seen below in Figure 5.3.2.



Figure 5.3.2 – CO₂ Regulator

The pressure assures that when the flow valve is open, beer leaves the keg, passes through the system, and dispenses into a glass. The regulator has 5/16" CO₂-resistant tubing, which connects to the keg. Each end of the tubing is secured with clamps. The standard pressure of the keg is 8 psi, per industry standards, but could use minor adjustments depending on the altitude where the system is being used. The regulator allows for manual adjustments to the keg pressure to prevent excessive foam when beer is dispensed. These manual adjustments are accomplished during the system's set up; after initial set-

up, the system does not need further adjustments unless the user wants to change the set-up parameters. The tubing connecting the keg to the system enclosure is 3/16" vinyl tubing. Vinyl tubing is used because it is food-grade quality and does not leach off-flavors into the beer. This tubing is secured to the keg and enclosure fitting by clamps for easy set up. Once in the enclosure, the beer passes through the first T-fitting that contains an RTD sensor and then into the stainless steel cooling coil. As the beer is being cooled, it passes through a second T-fitting placed in the middle of the coil as well as a third T-fitting when it leaves the coil. The third RTD sensor reads the final temperature of the beer before it is dispensed. There is also a fourth RTD placed in the water bath to monitor the water bath temperature. An RTD with its T-fitting is shown below in Figure 5.3.3.

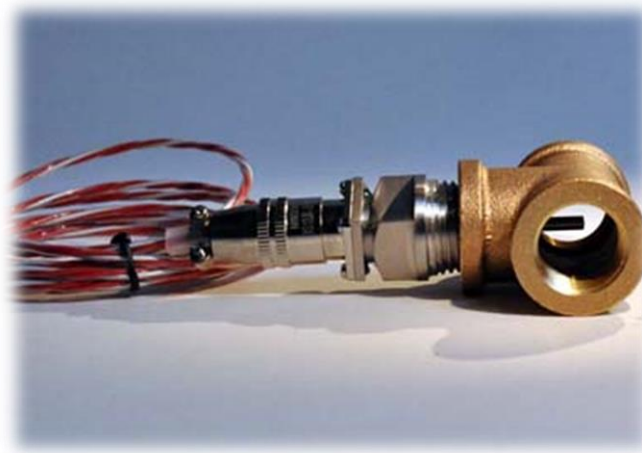


Figure 5.3.3 – This is an example of an RTD with its T-fitting. These RTDs are placed at the inlet, middle and outlet of the beer coil, as well as in the water bath, to monitor the temperatures of the water and beer within the system

After flowing through the T-fitting, the beer goes through the flow valve before reaching the spout. All fittings are connected with stainless steel food-grade connectors. The flow valve, and faucet used are also food-grade quality so the beer is never in contact with any surface that could cause it to be deemed unsuitable to serve to the public. To control the amount of liquid passing through the system, an infrared flow sensor (also known as a meter) is used. The flow sensor is shown below in Figure 5.3.4.



Figure 5.3.4 – The infrared flow meter is used within the beer line to provide beer flow accurate measurement

As beer passes through the flow sensor, it causes the blade inside the meter to spin. This blade has a marker on it that causes it to be picked up by the infrared sensor seen below in Figure 5.3.5.

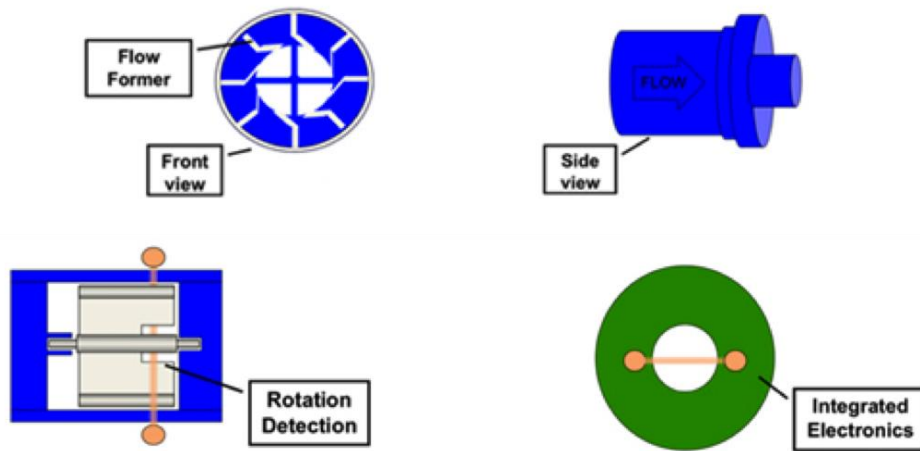


Figure 5.3.5 – Interior diagram of the infrared flow sensor used in the beer line

The flow sensor sends a frequency count to the PLC, which allows the PLC to identify how much beer has flowed through the sensor. The flow valve, shown in Figure 5.3.6 below, is a solenoid valve connected to the PLC.



Figure 5.3.6 – This is the ASCO subminiature solenoid valve used to control the dispensing of beer

When the user requests a beer and places the glass on the tilting mechanism, the PLC opens the flow valve when the motor has reached a 45° angle and starts receiving the pulse signal from the infrared sensor. Once the PLC establishes that the requested amount has flowed out of the system, it removes the power to the valve, causing it to close.

5.4 Electronic Component Subsystem

The PLC, temperature transmitters, electronic relays, terminal blocks, fuses, and power supplies have been mounted on the DIN rail in the electronic component enclosure. To prevent overheating of the components, multiple fans are mounted in the enclosure to dissipate the heat being emitted from the electronics. The power supplies are plugged into a 120 VAC terminal block, which is attached to one plug leaving the system. There is an additional plug for the router that allows the system to be accessed wirelessly. Each power supply connects power to the other electronics through a power strip, and the fuses are used to prevent surges to the system and to cut off power to any one component if it pulls too much current. The wires were organized using a cannon plug, and allow the TI team to set up the system within a matter of moments. Utilizing the cannon plug allows only one connection between the control panel and the water enclosures. The cannon plug does not carry the TEC wires, which require mounting onto a terminal strip, due to high current. Almost all electronic components are mounted on five DIN rails inside of the electronics housing unit of the system. These components are organized in terms of their necessary power supplies. The different terminal blocks are also color coordinated by the amount of voltage they are connected to; 12 volts is blue and 24 volts is gray. The system holds three custom temperature sensor circuits team 5348 developed, one industrial temperature transmitter, two 24 volt power supplies, two 12 volt power supplies, electrical relays, the PLC, a wireless switch for communication between the PLC and the iPad or computer and a circuit for the flow meter.

5.4.1 Temperature Sensor Layout and Wiring Subsystem

Each temperature sensor is made of three separate Texas Instruments integrated circuits, which interface with an RTD and the PLC. The ICs that are used are an ADS1220 (a 24-bit analog-to-digital converter), a MSP430 (an ultra-low power 16-bit microcontroller), and a DAC8760 (a 16-bit digital-to-analog converter). The three ICs are mounted on a printed circuit board, or PCB. These units are flashed with code through a JTAG connector the first time they are used.



Figure 5.4.1.1 – Above is one of the three populated PCB boards

Each RTD is connected to an ADS through a terminal connector on the PCB. The RTD connection to the ADS is shown below in Figure 5.4.2. The ADS1220 has two IDACS, or internal current sources that are suited to this application. One IDAC provides current across the RTD while the other is used to cancel out the resistance in the RTD leads. This leads to the input to the ADS solely being the voltage across the RTD:

$$V_{AIN0-AIN1} = I' R_{wire} + I' R_{RTD} - I' R_{wire} = V_{RTD} \quad (5.4.1.1)$$

To account for the current sources' temperature drift and their effect on the voltage across the RTD an external voltage reference that is in series with the RTD was used. This ensures that any change in the RTD voltage due to IDAC temperature drift is reflected in the reference to the ADS. This is considered a three-wire set up; this is middle of the road as far as accuracy goes for these set-ups. In order to optimize this set up, there are steps taken in the coding in order to cancel out the possible difference of current that the IDAC's may output. While coding, the IDAC's were switched and then averaged in order to get a near perfect estimation of the current.

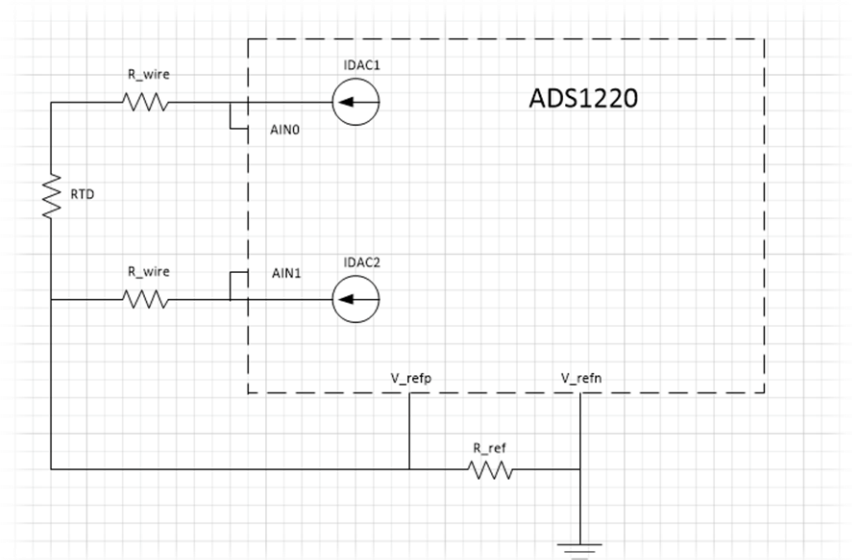


Figure 5.4.1.2 – The RTD and the ADS connection schematic

The MSP430 interfaces with both the DAC8760 and the ADS1220 via serial peripheral interface. A simplified diagram of the wiring between these three ICs is shown below in figure 5.4.2.

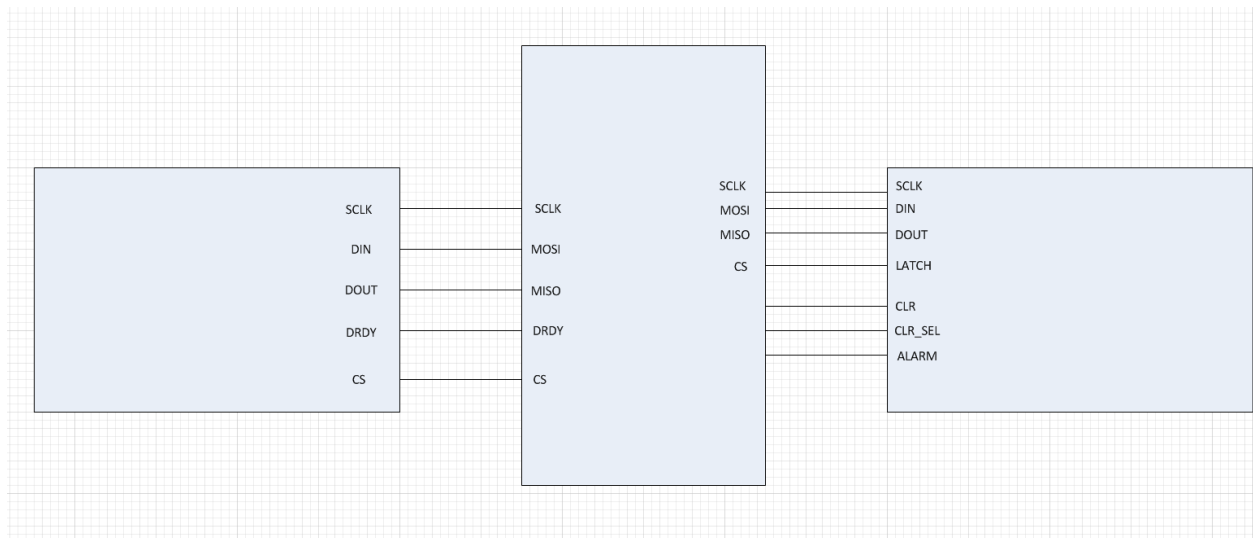


Figure 5.4.1.2 – ADS to MSP to DAC Wiring

Additionally, the PCB also contains a voltage regulator, various capacitors, and resistors.

5.4.2 Transmitter Design

The transmitter design is broken into different stages that consist of the MSP430, DAC8760 and the ADS1220 to sense input signals and converts the signal to a 4-20mA current loop output. The current loop is used as an interface that uses current instead of voltage for signaling over long distances with

little error due to resistance in the transmission line. The reduction of noise was important in designing the layout.

A schematic of prior evaluation module (EVM) designs were used to incorporate and determine many passive device values. In the datasheet there is a list of recommended operating condition parameters that were followed to reach optimum performance. Decoupling capacitors were used at each input to eliminate any inductance in the line. As the trace increases in length an increase in resistance begins to build up. This loss of voltage can be seen at input terminals through the integrated circuits and will cause a reduction in performance. Decoupling capacitors were used to act as a storage bin of energy to compensate any loss that is endured. The placement of the external capacitors is very important. The capacitors need to be placed as close to the power input pins of the ICs to be effective. If the capacitors were placed too far from the pin this would be least effective due to the built up of sagging current between the capacitor and input pin.

Noise coupling can be large in the input pin of any integrated circuit. To decouple the AC and DC signal, and to allow a smooth signal to be entered into the pin, a parallel pair of capacitors is needed. A large, mid, and small capacitance should be applied to eliminate different range of frequencies to eliminate the noise it creates, which can be seen by the following formula.

$$f = \frac{1}{2\pi ZC} \quad (5.4.2.1)$$

These parallel capacitors can be seen at the AVDD pins of the following figures. What also can be seen in the DAC analog voltage pin is a Zener diode, which passes current in the forward and reverse direction when a certain amount to positive and negative voltage is applied. This is to protect the IC in case of the input voltage changes polarity.

Most recommended values of capacitors and resistors needed for the design can be found through datasheets and are industry standard of values needed. Larger traces at the input and any sensor signal being monitored can be applied to help in the resistance in the transmission line.

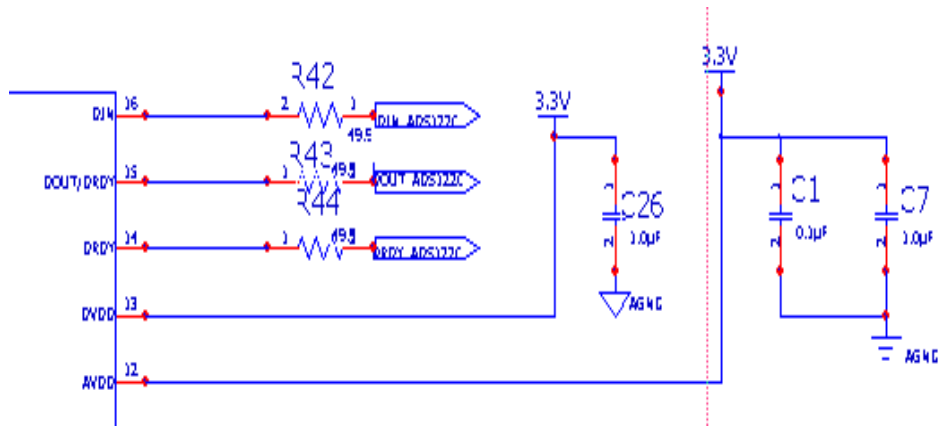


Figure 5.4.2.1 ADS1220 analog input voltage pin (AVDD)

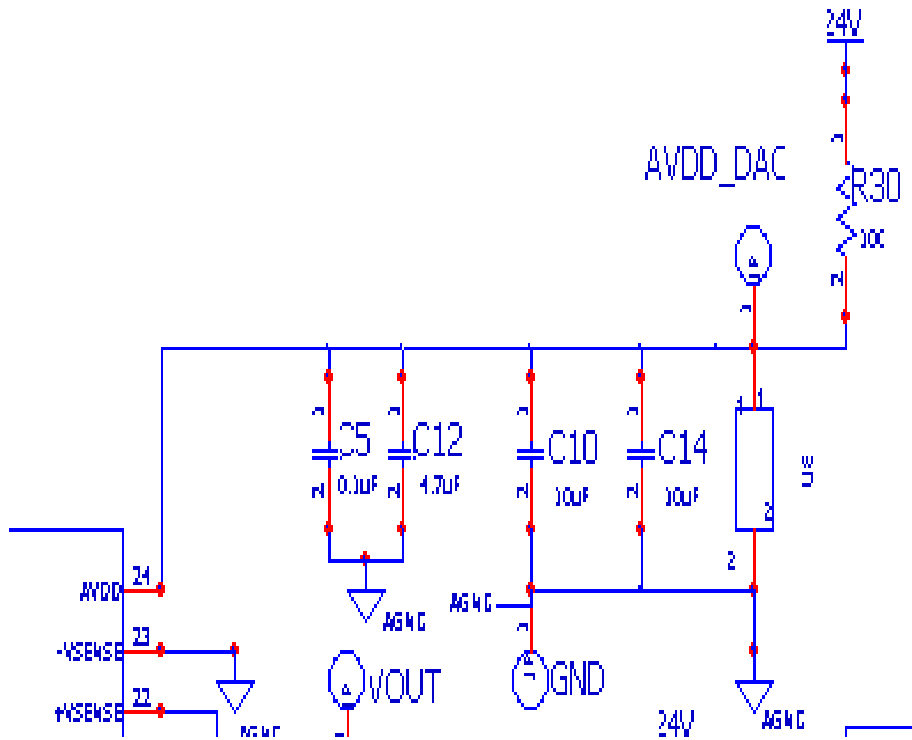


Figure 5.4.2.2 DAC analog input voltage pin (AVDD)

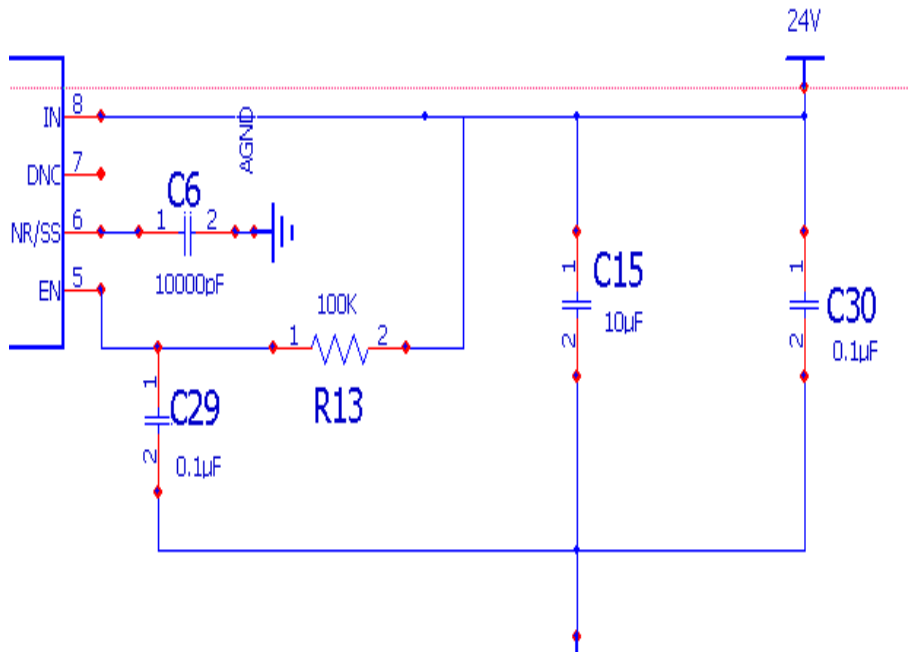


Figure 5.4.2.3 Voltage regulator analog input voltage pin (IN)

5.4.2.1 PCB Layout

In order to implement a resistance temperature detector (RTD) into our system, to detect the temperature of the beer flowing through the coils, Texas Instruments decided they wanted a printed circuit board design of a transmitter with all the necessary IC's to perform the temperature measurement. Texas Instruments wanted their DAC8760 (digital to analog converter), ADS1220 (analog to digital converter), MSP430 (microcontroller), and TPS7A49 (voltage regulator) to be incorporated into the PCB design. The team decided a three wire RTD would have sufficient accuracy to detect the temperature. The team decided to use PCB123, a free software from Sunstone Circuits to help in our circuit design.

The first step in the designing the circuit was to produce a schematic, which shows all connections between devices and any components needed to the ICs. Most of the software contained package detail for each component but occasionally a schematic symbol was needed and was produced through the symbol editor.

For each device a schematic and footprint symbol was created. If the library in the program did not contain the correct package for the device, a footprint was created using the new footprint design. In the figure below, an exact replica of the pads, where electricity will be flowing through the device, is needed to ensure proper operation of the device. The data sheet was used to look up the land pattern

of each device, paying close attention to the distances of the pads and outline of the device. Most data sheets for the devices give examples of proper layout and schematic design to ensure optimal performance for the device. Most value were industry standard.

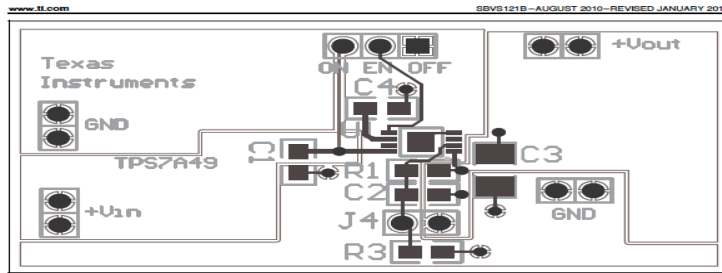


Figure 30. PCB Layout Example

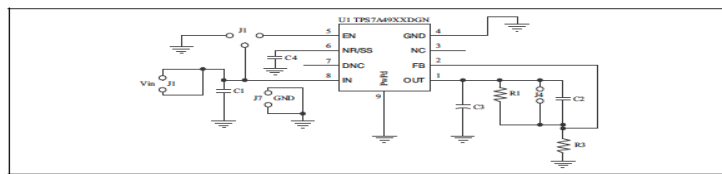


Figure 31. Schematic for PCB Layout Example

Figure 5.4.2.1.1 PCB and schematic example of the voltage regulator

The footprint is created using the layout folder and selecting new footprint. The grid was scaled to produce the correct dimensions of the device to the add pads.

Once all devices have their schematic and footprint symbols associated to them, the schematic design is produced. Again most of the data sheets were used to locate the proper connection of capacitors and resistors to gain optimum performance. Most capacitors where used as a store bin of energy for fluctuation of voltages created by resistance developed in the line. In communication with the software designers we determine which I/O pin will be needed to communicate to each device.

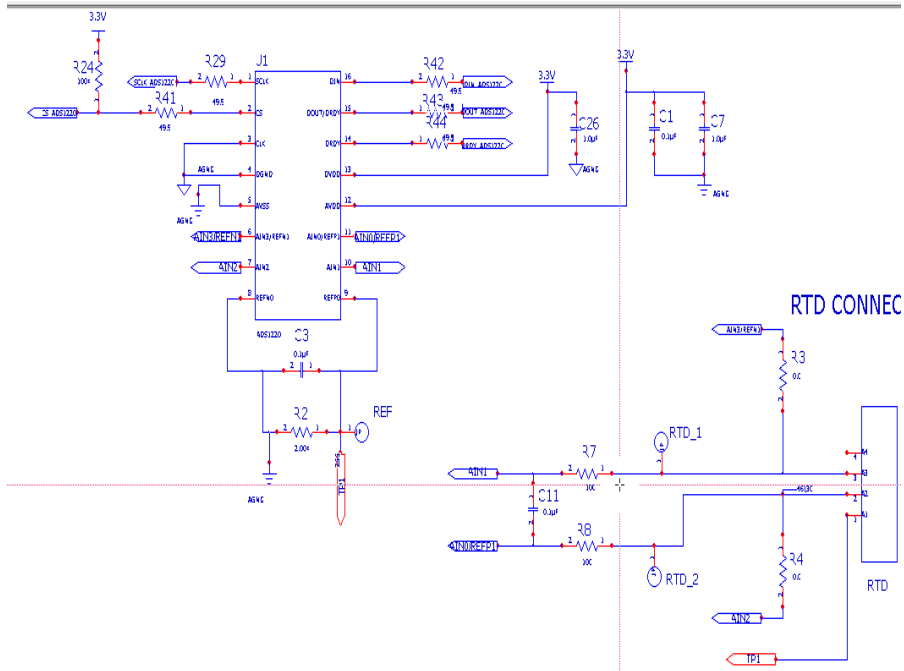


Figure 5.4.2.1.2 ADS schematic

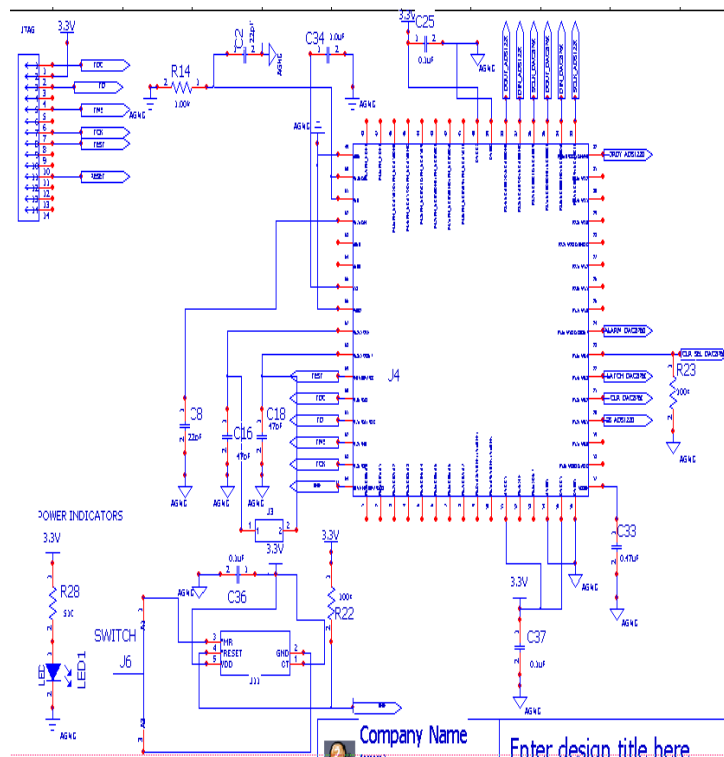


Figure 5.4.2.1.3 Microcontroller schematic

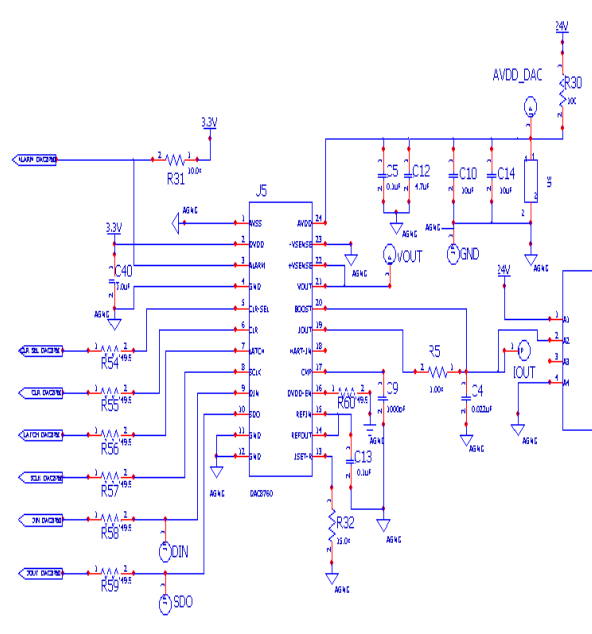


Figure 5.4.2.1.4 DAC schematic

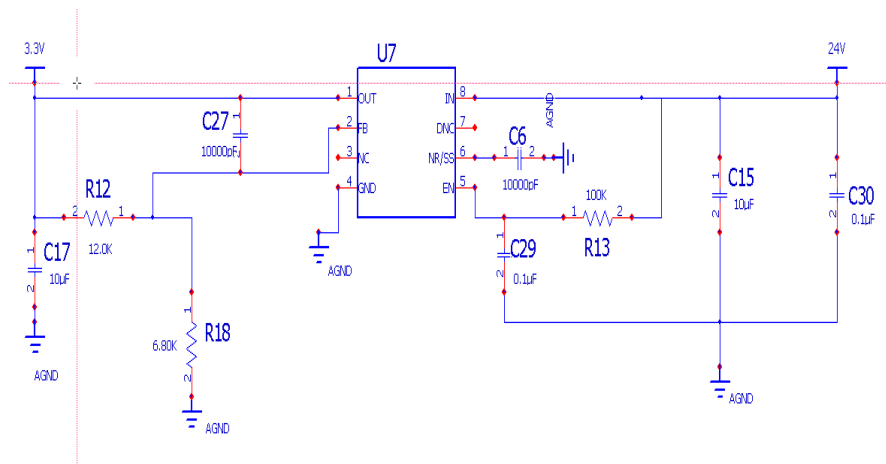


Figure 5.4.2.1.5 voltage regulator

The schematic was examined to ensure all proper connections were made. Once the transmitter schematic was finished, the layout of the actual printed circuit board was created. There were several design parameters, which needed to be followed. One was to keep the analog and digital signals from the ICs separated as much as possible. From figure 5.4.2.1.6 you can see the digital signals are flowing north whereas the analog signals are flowing south. The traces to power the board needs to be as large as possible so a 25mil trace was used for the input power.

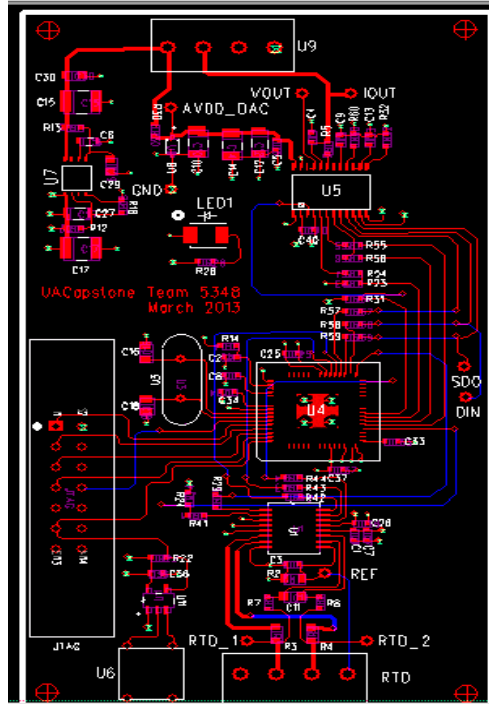


Figure 5.4.2.1.6 Transmitter Layout Design

Now that the layout is complete and all DRC errors were corrected, the team placed an order on the circuit boards and all the components. The first process was to populate the board and begin the debugging process. The debugging process included checking for the input power and making sure the voltage regulator was outputting a consistent 3.3 volts. The next step was to make sure all input voltages to the ICs were reading correctly. Following the readings, dummy code was flashed to the microcontroller to ensure each device was communicating and outputting the correct voltage, while checking the timing with the oscilloscope, to ensure the registers were outputting at the correct time.

5.5 Programmable Logic Controller Subsystem

Texas Instruments proposed the utilization of a Siemens brand programmable logic controller (PLC), because of TI's relationship with the Siemens Company. Since Siemens is the preferred brand, Texas Instruments funded the cost of the Siemens PLC and its components. The Siemens PLC suggested by Texas Instruments is the SIMATIC S7-1200. This PLC is made up of components that Team 5348 had to select to fit the need of this project.

The first component Team 5348 selected was the central processing unit: the CPU 1212C DC/DC/DC. The selection of this component was made due to its superior compact solution, the 14 integrated inputs and outputs (IO) built in, and its expansion capability. This CPU has the ability to expand by one

signal board or one communication board, by two signal modules, and by three communication modules. The integrated IO is made up of eight digital inputs, six digital outputs, and two analog inputs. What is especially unique about the integrated IO is that four of the digital inputs are able to become high speed counting (HSC) inputs, which the proposed flow meter uses for its potential accuracy rating of $\pm 1\%$.

The system requires an additional analog input signal module, SM 1231 AI (8 X 13 bit module). The selection of this module is due to its extremely short conversion times, along with the ability to connect analog sensors without additional amplifiers. This module is needed to enable the system to use more than two analog input signals, which are supplied with the PLC. This module enables the system to handle up to eight additional analog input signals. The analog signals in this system include the four RTDs.

To supply the PLC components and modules with power, a SIPLUS PM 1207 power supply was included. This power supply has the capability of taking in 120/230 VAC, which satisfies the power requirement for functionality around the world. The power supply is also able to output 24V/2.5A, providing enough power to drive the modules.

6.0 Algorithm Description and Interface Document

This system has been implemented using a Texas Instruments MSP430F5528 microcontroller interfaced with an ADS1220 and a DAC8760, and a programmable logic controller (PLC). The microcontroller is controlled by a while loop that is constantly pinging the ADC for a new temperature reading. The MSP430 then uses a look-up table to turn a 24 bit digital code corresponding to a temperature reading into a 16 bit code from which the DAC reads and then transmits as a 4-20 mA current to the PLC. This lookup table is a five-point table containing data for temperatures between -10 and 40 degrees Celsius. In order to determine the resulting codes between the five points of the lookup table, an equation is used which linearly scales the output code between the two closest lookup table points. The advantage of using this equation between two points on the lookup table, as opposed to over the entire range of the table, is that over the entire range the temperature-resistance curve may be non-linear. When the equation is used between a small distances, such as the 10 degree distance we use it for, the overall curve does not make quite an impact and the curve begins to look linear to this equation. The following modules make up the nearly 1000 lines of code that our program consists of.

6.1 Microcontroller Modules

The code put into the microcontroller is used to control the temperature sensor. There are three core files used: one for the main loop, and two separate sets of .c and .h files for both the ADC1220 and the DAC8760.

6.1.1 ADS1220 Code

The code used for the ADS1220 is contained under ADS1220.c. Its header file contains the function declarations as well as the definitions of commonly used hex values. These hex values allow the team to send the ADS1220 commands without looking in the data sheet and determine the exact hex value every time it reads through our code. Examples of these hex variables are seen throughout all code examples shown, and can be identified by their all-capital appearance. Although many functions contained in ADS1220.c are used, the two most important are the ADS1220WriteRegister() and the ADS1220ReadData(). ADS1220WriteRegister() is shown below in figure 6.1.1 and ADS1220ReadData() is shown in figure 6.1.2.1.

```

void ADS1220WriteRegister(int StartAddress, int NumRegs, unsigned * pData)
{
    int i;

    // assert CS to start transfer
    ADS1220AssertCS(1);

    // send the command byte
    ADS1220SendByte(ADS1220_CMD_WREG | (((StartAddress<<2) & 0x0c) | ((NumRegs-1)&0x03)));

    // send the data bytes
    for (i=0; i< NumRegs; i++)
    {
        ADS1220SendByte(*pData++);
    }

    // de-assert CS
    ADS1220AssertCS(0);

    return;
}

```

Figure 6.1.2.1 – The above picture shows a snapshot of the code for ADS1220ReadRegister()

The ADS1220WriteRegister() function uses another function, ADS1220SendByte(), that simply stores a byte in the microcontrollers' SPI transmit data buffer. Once the CS pin goes high, this byte allows the ADS1220WriteRegister() to send specific commands to the ADS. Bit addressing was used to write the correct register. After the chosen register has been written, the CS pin is pulled low.

```

long ADS1220ReadData(void)
{
    long Data;

    // assert CS to start transfer
    ADS1220AssertCS(1);

    // send the command byte
    ADS1220SendByte(ADS1220_CMD_RDATA);

    // get the conversion result
    Data = ADS1220ReceiveByte();
    Data = (Data << 8) | ADS1220ReceiveByte();
    Data = (Data << 8) | ADS1220ReceiveByte();

    // sign extend data
    if (Data & 0x800000)
        Data |= 0xff000000;

    _NOP();
    // de-assert CS
    ADS1220AssertCS(0);
    return Data;
}

```

Figure 6.1.2.2 – The above picture shows a snapshot of the code for ADS1220ReadData()

The `ADS1220ReadData()` function reads the data that has been converted from the ADS. It first sends the byte that signifies a data read, and then it receives the 24-bit result in three different segments of eight bits. Between each byte that is received, the result is shifted to the left eight bits, resulting in a 24-bit result. This function is the most integral portion of our code because it is used over and over again in the main while loop. It determines what the current temperature of the RTD is, and it is used twice for every reading because the IDAC currents need to be flipped and then averaged to allow calibration for each reading.

6.1.2 DAC8760 Code

The code that is used for the DAC8760 is stored under `DAC8760.c`. Similar to the ADS, the header file for the DAC contains function declarations and commonly used hex values. The lookup table that was previously mentioned is stored in the DAC8760 portion of the code because it is used to determine the output. Other important functions include `DAC8760Init()` and `DAC8760Config()`, which are simply setting up the DAC8760 to run and is only done once when the system is turned on.

6.2 Microcontroller Flow Diagram

Figure 6.2.1 below depicts the flow of the system. After the system starts up, the microcontroller continuously goes through a process of reading the voltage that the ADC is putting out. The voltage that the ADC is putting out is related to the RTDs' temperature; therefore, the microcontroller can use this voltage and translate it into a temperature reading. This temperature is then translated into the form of a 4-20mA loop, which is transmitted to the DAC, and finally to the PLC. The PLC finally translates this temperature back and sends this information to the GUI in the iPad.

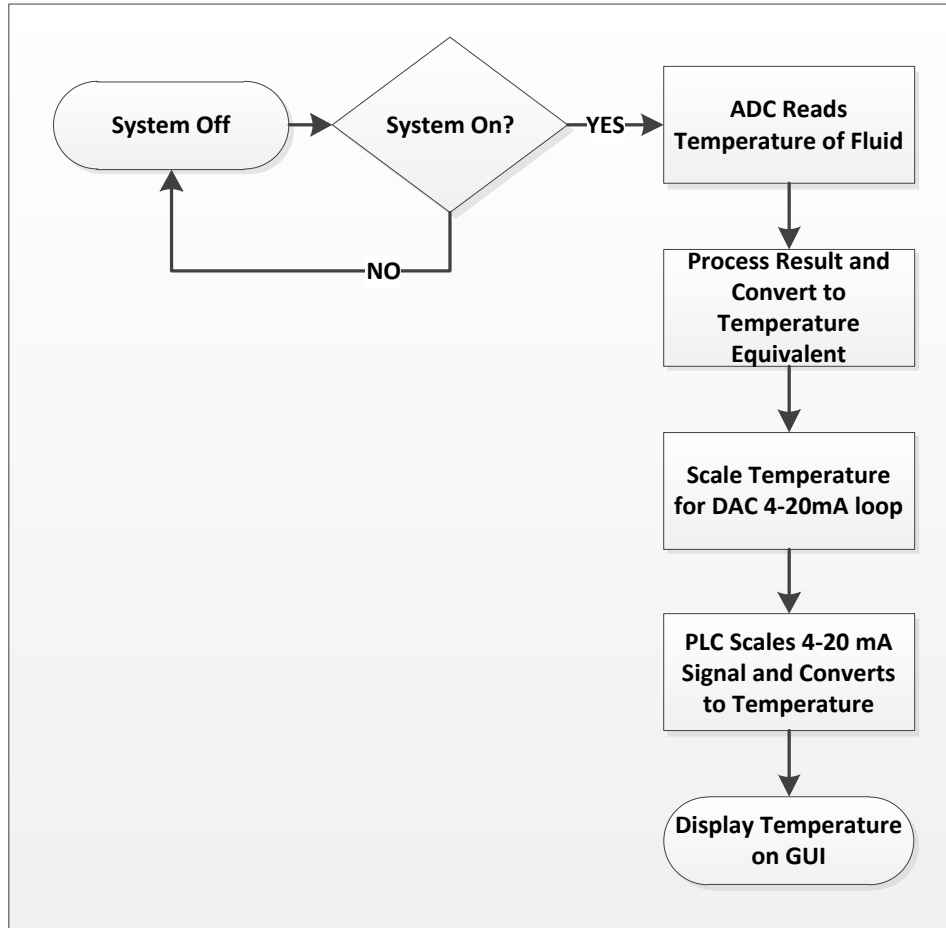


Figure 6.2.1 – This is the microcontroller flow diagram once the system is initiated

6.3 Microcontroller Trade Study

When choosing the microcontroller, team 5348 had to look at certain trade-offs that could affect the system’s performance down the road. The most simplistic trade-off is price. The selected microcontroller is more highly priced than other microcontrollers currently on the market. Since this microcontroller is a Texas Instruments product, and due to the trade-offs that were performed, the MSP430F5528 was selected. With regards to technology, the microcontroller may be superfluous for the task that it performs, but due to experience within the team’s sponsor group, it was decided that the MSP430F5528 would efficiently benefit Team 5348’s capstone design.

6.4 Programmable Logic Controller Flow Diagram

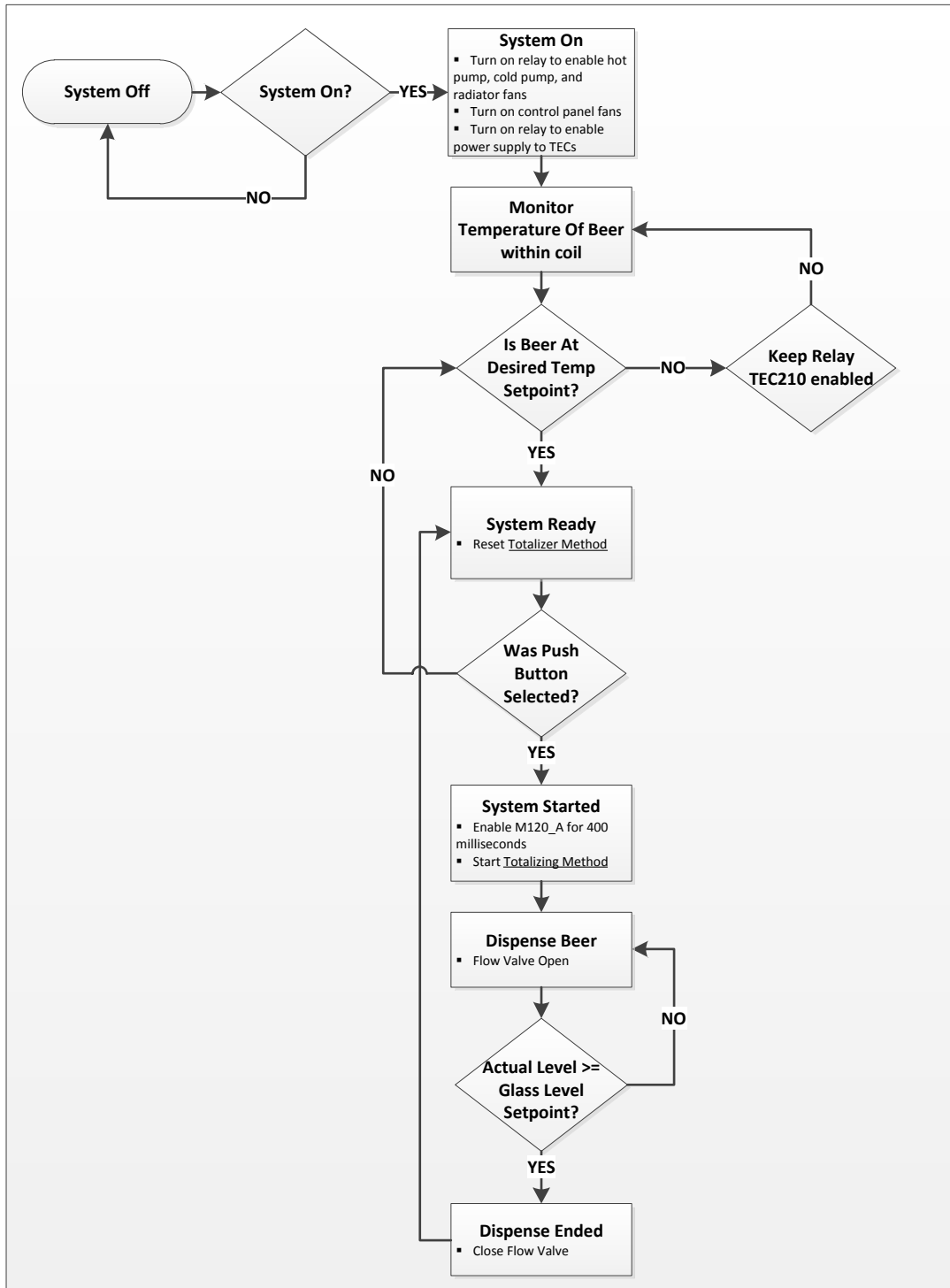


Figure 6.4.1 – This is the Programmable Logic Controller flow diagram once the system is initiated

The programmable logic controller (SIMATIC S7-1200) uses the STEP 7 Basic V11 engineering software. This software uses LAD (Ladder Diagram) programming language, which is the same language that this

project uses. Because of this, the number of rungs of code is less than 250. In Figure 6.4.1 above, the flow of the system is represented and is easily converted into LAD.

The system that Team 5348 developed remains off until the system is set up at a tradeshow or event. Once the system is plugged into an outlet, a number of actions take place within the PLC. First, two control relays are enabled by the PLC, which activate the cold and hot pumps, the radiator fan, and the control panel fans. The PLC then enables the control relay that turns on the power supply that is connected to the TECs. The PLC program initially provides a set-point value of 44°F, which can later be changed by the user through iPad. Once the system finishes its initializations, the temperature control begins. Due to the requirement that the beer temperature allowed to be dispensed is the set point $\pm 1^{\circ}\text{C}$ ($\pm 1.8^{\circ}\text{F}$), the system cools until the lower limit is reached. Once the system reaches that low limit, the control relay is disabled and the TECs stop cooling. The system resumes cooling again once the temperature of the beer within the coils reaches the desired temperature (or warms up 1.8°F). This ensures the power supply does not pulse continuously around a set point. The system continues to maintain the desired temperature while waiting for the user to dispense a beer.

Once the user pushes the dispense pushbutton, or enables the “Start Dispensing” bit on the iPad, the system waits until the beer within the coils is within the desired temperature set point $\pm 1.8^{\circ}\text{F}$. As soon as the beer reaches this window, the system checks to ensure there is a glass in the tilting mechanism. This is done by a mounted pressure switch that is triggered once a glass is placed on top of the switch. When the system receives the signal from the pressure switch, the PLC waits two seconds, then enables a control relay, which controls the forward movement of the motor. The motor stays on for the brief time of 400 milliseconds, and brings the glass to a 45° angle. The system waits for another second, and then starts the dispensing the beer by enabling another control relay to open the flow valve. As soon as the flow valve opens, the totalizer method is initialized.

The totalizer method is used to count the amount of pulses the flow meter is sending to the PLC. Once the amount of pulses reaches half the pulses of the set point fill level, the PLC enables the control relay that controls the reverse movement of the motor. As the beer is still filling the glass, the motor is enabled until the magnetic switch is sensed, which is mounted to the side of the tilting mechanism. This tells the PLC the glass has returned to the initial position, and disables the control relay that controls the reverse movement of the motor. The flow valve remains open until the fill level has been met, which is when the system displays the average temperature that has been dispensed into the glass, along with the percentage of beer that has been dispensed, to demonstrate the accuracy of the flow meter. This

ultimately displays the success the team has with dispensing beer at the perfect temperature and the perfect fill level.

6.5 Graphical User Interface

The graphical user interface (GUI) we were able to utilize was the S7-1200 iPad application available on the iTunes market. With this GUI, we the only communication module we needed was a wireless switch. This switch also allows computers to configure the PLC with no Ethernet cables needed. The GUI is comprised of various tags that allow the user to modify and monitor the system in real-time, with a refresh rate of two seconds. The following tags and descriptions that are available on the GUI are as follows:

- Start Dispensing - Start the dispensing of beer
 - 0 Off
 - 1 On
- Stop System - Turn the system completely off
 - 0 Off
 - 1 On
- Keg Temperature - The temperature of incoming beer from the keg
- Coil Temperature - The temperature of the beer in the middle of the beer line
- Dispensing Temperature - The temperature of the beer dispensing out of the system
- Water Bath Temperature - The temperature of the water bath
- Current Dispensed Fill Level - The percentage of beer that has been dispensed into the glass
- Fill Level Setpoint - The user can select 0.25, 0.5, or 1.0 pints
- Beer Type Number - The type of beer being dispensed out of the system; temperature set point
 - 1 Pale Lagers - 45°F
 - 2 Wheat Beers - 46°F
 - 3 Dark Lagers - 48°F
 - 4 British Ale, Stout - 55°F
 - 5 Strong Dark Ales, Barley Wine - 59.9°F
- Desired Beer Temperature - User defined beer temperature if not available in the Beer Type Number
- Average Dispensed Temperature - The temperature of the beer being dispensed averaged over a period of time

Figure 6.3.1 is four screenshots of the actual GUI in real-time, with how to monitor tags, modify tags, and the state of all the PLC modules.

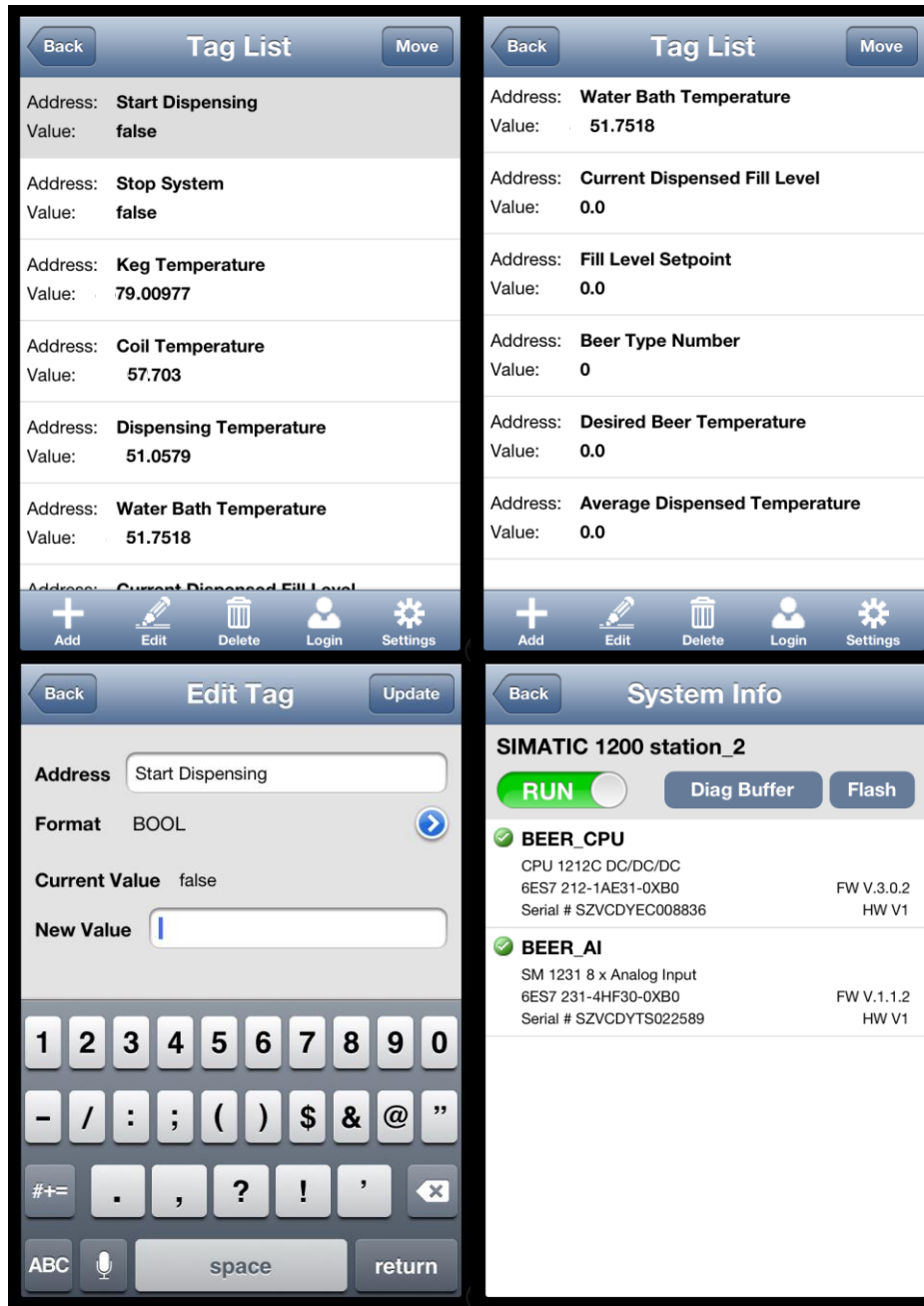


Figure 6.3.1 – S7-1200 GUI Application

7.0 Analysis

7.1 Heat Transfer Analysis

When considering external flow, as in the case of the water-cooling the beer inside the coil, it is necessary to consider the thermal analysis taking place to determine how temperature changes with time and position based on the heat dissipated from the fluids. Since the fluid through the tube is completely enclosed and pressurized, an energy balance is used to analyze the total convective heat transfer, q_{conv} , which relates the beer temperature at the inlet and outlet to the water temperature being cooled by the Thermo Electric Coolers (TEC). The water-cooling channel containing the TECs cools the recirculating water, and the heat generated by this system is from the heat transfer occurring at the surface of the coil. The water is mixed at a continuous rate by means of a pump. This mixing is assumed to be perfect and one that provides a uniform temperature throughout the cycle.

Based on the literature of the TEC, the cooler works best at temperatures close to ambient. These temperatures provide the maximum heat removal and thus improve the efficiency needed to cool the beer. The following figure shows the cooling performance of this device using water at a constant inlet temperature.

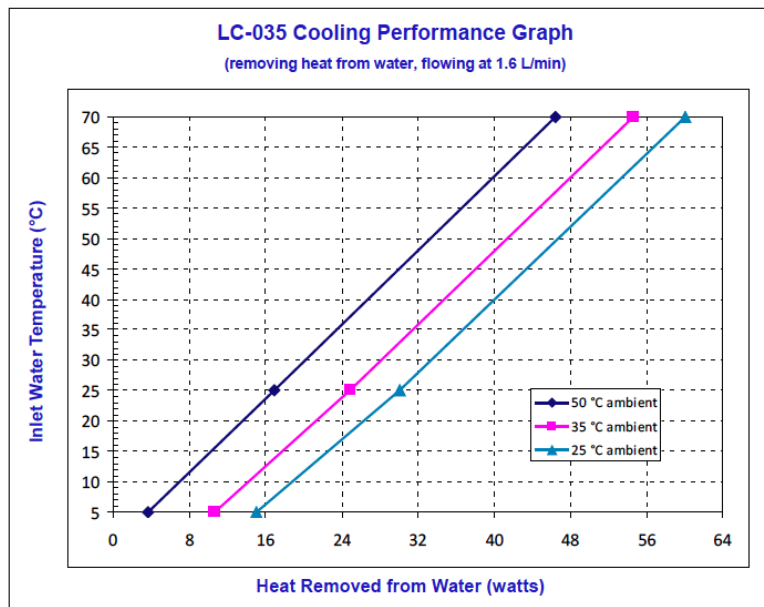


Figure 7.1.1 – The Heat Removal attributes are shown for three Constant Water Temperatures (TE Technology)

Assuming the mixing is perfect, the heat is directly removed from the water bath and it is given by solving the following differential equation:

$$m_{bath}c \frac{dT_{bath}}{dt} = -\dot{Q}_{TEC} \quad (7.1.1)$$

$$T_{bath} = T_{bath,o} - \frac{\dot{Q}_{TEC}}{m_{bath}c} \cdot t \quad (7.1.2)$$

Where:

- m : Mass of water (kg)
- c : Specific heat ($\frac{J}{kgK}$)
- \dot{Q} : Heat removed ($Watts$)
- t : Time ($seconds$)

Based on a mass flow rate of 1.6 L/m provided from the TEC website, and a water temperature of 6°C, the system removes about 20 watts of heat. If the water bath enclosure has a total volume of about 800 in³ (0.013 m³), cooling the water likely takes time, and it can be represented by the equation for temperature as a function of time:

$$T_{bath} = 6^{\circ}C - \frac{20 J/s}{(13.1 kg)(4181.4 J/kg \cdot K)} \cdot t \quad (7.1.3)$$

Due to steady state conditions, the temperature of the water bath becomes the temperature of the coil wall as it flows over the coil. This system becomes a coupled system; one that is dependent on each other to cool the end product of beer. This turns out to be the condition for internal flow in the coil heat exchanger since the coil thickness is assumed to be thin walled (0.79 mm thick); in other words, it is isothermal. Because heat is removed from the loosely wound coil and heat transfer occurs within the coil itself, centrifugal forces induce secondary flows that take place in the center of the coil which enhances the heat transfer altogether, but at a price of a pressure drop within the system. A visualization of such systems is shown in figures 7.1.2 and 7.1.3 below:

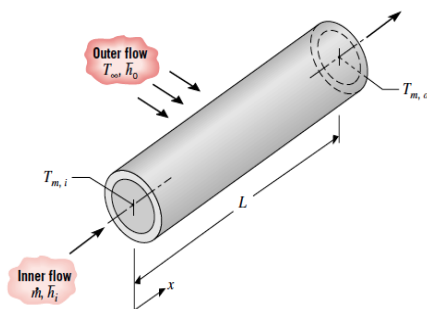


Figure 7.1.2 – The heat transfer between fluid flowing over and passing through the coil (Incropera)

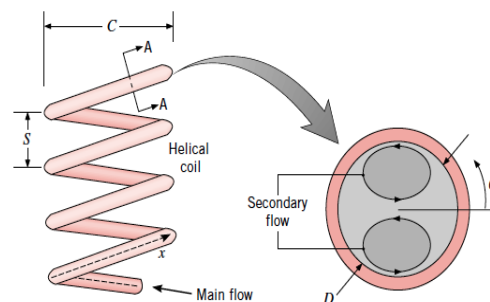


Figure 7.1.3 – The schematic of the helically coiled tube and the secondary flow (Incropera)

As the temperature of the coil wall reaches steady state, and the temperature of the beer decreases to the desired temperature set by the user, the temperature difference between the wall and the beer decreases exponentially with the distance along the tube axis and ultimately becomes the temperature of the water bath. The equation coupling both systems is shown below:

$$\frac{dT_{beer}(x)}{dx} = \frac{-Ph}{\dot{m}c} (T_{beer}(x) - T_{wall}) \quad (7.1.4)$$

$$\frac{\Delta T_o}{\Delta T_i} = \frac{T_{wall} - T_{beer,o}}{T_{wall} - T_{beer,i}} = e^{\left(\frac{-PL\bar{h}}{\dot{m}c}\right)} \quad (7.1.5)$$

Where:

- T_s : Surface Temperature (T_{wall})
- T_m : Mean Temperature (T_{beer})
- P : Perimeter of coil
- h : Heat transfer coefficient
- \dot{m} : Mass flow rate
- o : Outlet
- i : Inlet

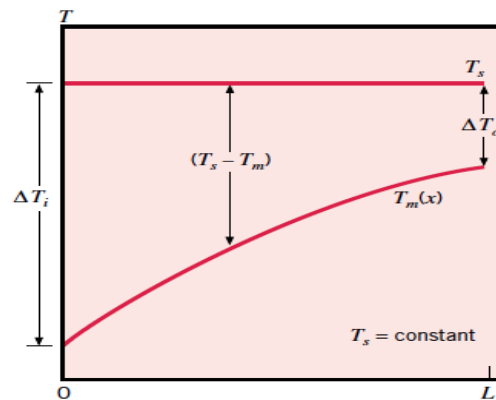


Figure 7.1.4 – The axial temperature variations for heat transfer on constant surface temperature (Incropera)

7.2 Pipe/Water Bath Analysis

An analysis was performed on the coil the beer runs through. The coil endures stresses from the pressure of the liquid, namely the cross-sectional stress. A force is exerted on the walls perpendicular to the axial length and radial of the cylinder (Cylinder Stresses). This stress causes the diameter of the

cylinder to increase before another change on the state of the material arises. This stress is known as Hoop stress.

$$\sigma = \frac{pr}{t} \quad (7.2.1)$$

Where:

- p : Pressure (*psi*)
- r : Radius (*inches*)
- t : Thickness (*inches*)

The pressure applied to the coils is between seven and 30psi, depending on the chosen rate of speed of the fluid. The coil purchased was a Micro Matic 304 Stainless Steel Cooling Coil with the dimensions of 5/16" outer diameter and 1/4" inner diameter. From the dimensions provided and the known pressures being applied to the coil, the hoop stress was determined to be between 35 and 150psi of applied cross-sectional stress. 304 Stainless Steel has a yield strength between 25 and 45ksi and is dependent on the outside diameter and wall thickness of the pipe (Mechanical Properties). There is a point where the material deforms elastically and returns to its original form; however beyond this point the material does not return to its original state and therefore deforms plastically (Mechanical Properties). When this point is attained, the material has reached its yield strength or yield point. The stress being applied in the coil is well below the allotted yield strength for the stainless steel material and therefore this does not cause severe deformation when pressure within the system is applied. Another stress that arises is the longitudinal stress, affecting the length of the coils. The following equation is the axial, or longitudinal, stress equation. As seen below, the longitudinal stress is half the Hoop stress equation, which can be ignored given that the hoop stress is almost negligible.

$$\sigma = \frac{pr}{2t} \quad (7.2.2)$$

The following analysis was done on the enclosure that holds the water in which the coils are placed inside. The enclosure must satisfy certain requirements, both physical and visual. Team 5348 has chosen to use an Igloo enclosure, which provides a better heat insulation from the whole system and the atmosphere. By picking the Igloo cylinder, the team has achieved the following requirements: insulation, durability and lightweight, shown in the following table.

Table 7.2.1 – Acrylic Properties

Material	Thermal Conductivity (4) $\left(\frac{W}{m \cdot K}\right)$	Weight (lb)	Flexural Strength (psi)
High Density Polyethylene (HDPE)	0.442	4.8	4550
Ultratherm™ (polyurethane foam)	0.018 - 0.023		56

The Igloo container must hold as much of the cold in and keep as much of the heat out as possible to decrease the power consumption from the thermo-electric coolers. As shown in the table above, both the HDPE and the Ultratherm™ have a low thermal conductivity value; therefore, the water bath is well insulated.

7.3 Tilting Mechanism Analysis

A tilting mechanism was designed to provide a perfect 45° pour. This mechanism was designed with cutout Plexiglas segments, a shaft, a motor and a pressure switch. Plexiglas has a weight of 2.88 lb/sqft. Therefore, based on the total weight of the Plexiglas for the bottom and the back holders, and the weight of the beer glass and the beer itself, the total tilting system weight is about 3.2lbs. The motor is rated for 38 in-lbs, therefore a quick calculation of the system’s torque requirements is done below in equation 7.3.1.

$$T = F \cdot D = m \cdot g \cdot \sin(\theta) \cdot R = (3.2lb)(\sin(45))(7in) = 15.84 \text{ in lb} \quad (7.3.1)$$

As seen above, the torque requirement for the mechanism is under the torque provided by the motor at full load. Based on the specifications of the motor, the RPM were high for this application. An adjustment was made to its voltage, 24VDC to 12 VDC, to slow it down in order to provide a better tilting speed.

8.0 Development Plan

To understand the components and subsystems that were created and tested, a development plan was implemented. There were four milestones the system followed towards the creation of this system. These milestones include the RTD structure milestone, the water bath enclosure milestone, the *totalizer method* milestone, and the graphical user interface milestone. To help have an understanding of the development and testing of the system, Figures D.1 and D.2 have been provided in Appendix D. This demonstrates the operational functionality at the highest level, all the way to the maintenance functionality at the RTD level.

8.1 First Build: RTD Structure

The construction of the RTD interface circuit was the first milestone. It involved wiring the RTD to the electronic ADS1220 to produce an analog to digital signal, which then communicates to the microcontroller. The waveform from the microcontroller is coupled with the DAC8760, producing a 4-20 mA signal. The data sheets for each device were studied to ensure the proper links were made to all the appropriate peripherals, and to optimize the resolution of each signal. After the completion of the RTD construction, Team 5348 tested different measurements of the RTD to achieve the accurate temperature. The test consists of taking a thermometer and the constructed RTD to ensure the temperatures of each read identically. All the electrical components are then stored in an angled iron enclosure surrounded by clear Plexiglas.

8.2 Second Build: Water Bath Enclosure

The development of the water bath enclosure, which houses the Igloo housing the beer coil, was the second milestone. The first step in constructing the enclosure was to use angled iron, Plexiglas acrylic panels and adhesive. The Plexiglas enables the Igloo container, the flow meter, the RTDs and the dispensing system to be seen to the outside viewers. The assembly of the external pipes and the coil is attached to the respective parts in the container. Once the water bath enclosure was built, testing was performed to ensure the beer within the system was cooled down to the desired temperature. The PLC was temporarily connected to the devices used in the water bath enclosure, and some temporary programming was implemented for testing. Water was forced through the coils, instead of beer, to test the cooling method. This enabled the verification of the efficiency and effectiveness of the cooling method within the system.

8.3 Third Build: Totalizer Method

The third milestone was to test the *Totalizer Method* with the complete system. To accomplish this, the water bath enclosure used the flow meter and flow valve. The system incorporated the PLC to test the proper flow through the use of the *Totalizer Method*. By testing this, there is verification that the fill level is within $\pm 2\%$.

Once the third milestone was reached, all wires were covered by a rubber shield to protect them from moisture along with giving them a clean look. The system is completed once it is supplied with power, ensuring the system runs without any issues.

8.4 Fourth Build: Graphical User Interface

Team 5348 created an interface using an iPad and a wireless switch. The fourth milestone was to set up the graphical user interface on the iPad application. To do this, the team had to add all variables pertinent to the system. This list includes a system dispense, system emergency stop, four temperature readings, a current dispense level percentage, a fill level set point, a beer type set point, a desired temperature set point, and an average temperature dispensed. To test this system, team 5348 allowed the system to solely run off of the iPad during an eight hour period to confirm there is no need for a computer for interfacing.

9.0 Budget and Suppliers

The budget for this project is \$3,000. Additionally, Texas Instruments donated various components for use in the circuits present within the system, along with the PLC and the iPad. Table 9.1 shows the materials involved in the project as well as the costs and delivery times.

Table 9.1 – The following table is a complete bill of materials for Team 5348

Date	Store	Description	Amount
12/4/12	FedEx	Report Printed	\$5.99
1/22/13	Micromatic	Coil	\$113.80
1/24/13	Ebay (sure-electronic)	TEC	\$45.98
2/8/13	Ebay (ussolarpumps)	Pump	\$68.00
2/8/13	Swissflow BV	Flow Meter	\$80.00
2/8/13	Ace Hardware	3Gal Water Cooler	\$37.30
2/15/13	Elliot Electronic	Heat Sink Silicone	\$13.00
2/15/13	Ace Hardware	Cooler Hardware	\$37.86
2/17/13	Jameco Electronics	12 V Power Supply	\$144.95
2/17/13	Lowe's	Wire	\$3.59
2/22/13	Elliot Electronic	Wire/Tape	\$16.40
2/24/13	Ace Hardware	Cooler Hardware	\$18.90
2/25/13	Ebay(sure-electronic)	TECs	\$88.96
2/25/13	Elliot Electronic	Terminal/Connectors	\$120.80
3/2/13	Ebay (koolertek)	Radiator	\$68.89
3/2/13	Ebay (koolertek)	Radiator hose fittings	\$5.89
3/2/13	Ebay (savebase)	Pump	\$29.39
3/2/13	Amazon	3 Fans	\$28.74
3/6/13	Ace Hardware	Cooler Hardware	\$5.36
3/6/13	Lowe's	Cooler Hardware	\$20.50
3/6/13	Elliot Electronic	Terminals/Wire	\$41.84
3/7/13	Ace Hardware	Cooler Hardware	\$7.50
3/7/13	O'Reilly Auto Parts	Cork Insulation	\$15.26

3/7/13	Ace Hardware	Cooler Hardware	\$3.81
3/8/13	Ace Hardware	Cooler Hardware	\$3.26
3/8/13	Ace Hardware	Cooler Hardware	\$10.08
3/8/13	Ace Hardware	Cooler Hardware	\$4.35
3/8/13	Elliot Electronic	Wire/Connectors	\$13.77
3/10/13	Cooler Master	Fans	\$27.57
3/17/13	Auberins	RTD	\$37.69
3/18/13	Calco	Terminal blocks	\$68.09
3/18/13	Control Resources	Jumpers	\$23.20
3/20/13	Elliot Electronic	Relays	\$100.31
3/21/13	Harbor Freight Tools	Clamps, meters, syphon	\$22.44
3/21/13	Creative Plastics	TEC Plexiglas	\$10.00
3/29/13	Industrial Metal Supply	Angled Steel	\$36.95
4/1/13	Creative Plastics	Tilting Mechanism Plexiglas	\$35.46
4/2/13	Ace Hardware	Painting material	\$26.10
4/2/13	Home Depot	Wood	\$14.11
4/2/13	Amazon	Cooling Fluid	\$12.95
4/2/13	Auberins	3 RTDs	\$90.24
4/2/13	Ace Hardware	Tilting Mechanism Hardware	\$4.41
4/3/13	Ace Hardware	Tilting Mechanism Hardware	\$8.29
4/4/13	Home Depot	Velcro, wood	\$16.89
4/5/13	Industrial Metal Supply	Angled Steel	\$24.84
4/6/13	Lowe's	Paint, Velcro	\$18.02
4/8/13	Creative Plastics	Plexiglas	\$182.94
3/28/13	Sunstone	PCB boards	\$546.57
4/3/13	Amazon	SSR	\$10.74
4/3/13	Amazon	SSR	\$21.48
4/4/13	Galco	Fuse, terminal, jumpers	\$73.70
3/27/13	Elliot Electronic	Push button, relays	\$53.96

	The Valve Shop	Valves	\$129.98
3/27/13	Beverage Equip. Co.	Tee for RTD	\$23.67
4/2/13	Digikey	Components for PCB	\$148.14
	Surplus Center	Tilting motor	\$21.00
4/11/13	Ace Hardware	Fasteners	\$3.08
4/12/13	Weekend Brewer	Beer line and connectors	\$86.02
4/16/13	Elliot Electronic	Flow meter circuit	\$11.51
4/15/13	Elliot Electronic	Flow meter circuit	\$13.57
4/12/13	Ace Hardware	Nuts and bolts for enclosure	\$3.77
4/22/13	Creative Plastics	Plexiglas	\$67.10
4/22/13	Ace Hardware	Term conn, wire, and glue	\$48.01
4/20/13	Amazon	SS fitting	\$32.89
4/20/13	Amazon	Pump, cleaner	\$28.45
4/19/13	Amazon	SS fitting	\$13.18
4/25/13	Brew your own	Sanitizer	\$13.46
4/20/13	Ace Hardware	Tube, glue, fittings	\$22.70
4/25/13	Elliot Electronic	Circuit	\$6.46
4/25/13	Ace Hardware	Velcro	\$20.61

Total: \$3,214.72

10.0 Requirements Review/Acceptance Test Plan

10.1 Requirements Review

The following is a list of our Functional, Technological and Performance requirements, and how they were met.

Table 10.1.1 – Below is the requirements and how they were met

Number	Type	Description	How it is Met
101	Functional	The system shall cool beer to a desired temperature based on beer type	The temperature of beer was taken
102	Functional	The system shall dispense beer at a specified flow rate based on beer type	The internal flow meter measures the beer flow
103	Functional	The system shall be limited to two power plugs (one per each compatibility)	The system only has two plugs
104	Functional	The system shall be controlled through a graphical user interface (GUI)	iPad GUI previously shown
105	Functional	The system shall disassemble and fit into, at most, three "Pelican 1690 Transport Cases" (30.01" x 25.02" x 15.00")	The system was planned to fit into the three cases
201	Technology	The system shall use a Siemens S7-1200 Series PLC to automate the system	This PLC is used
202	Technology	The system shall utilize an RTD probe, plus an ADS1220 and the DAC8760 to create an RTD	The RTDs were bought and the other TI components were given to the team
203	Technology	The system shall utilize Thermo-Electric Coolers (TECs) to cool the beer	The TEC water-cooling channel was implemented on the recirculation line
204	Technology	The system shall utilize a pushbutton to start the dispensing system	The pushbutton was connected to the PLC

205	Technology	The system shall use "see-through" tubes	The containers are see-through
206	Technology	The system shall utilize food-grade devices/equipment	Only food-grade equipment has been used
207	Technology	The system shall utilize an iPad GUI application to control the system	The iPad GUI controls the system without the use of a computer
208	Technology	The system shall be compatible with both 120V/60Hz and 220V/50Hz outlets	The system is able to switch between the two plugs
301	Performance	The temperature detector shall not consume more than 3.6mA each	PLC should not source more than 3.6 mA to temperature detector
302	Performance	The TEC device shall cool beer within $\pm 1^{\circ}\text{C}$	The temperature of the beer was taken by the PLC and the displayed on iPad
303	Performance	The TEC device shall cool beer utilizing the RTD	The RTD is the base for the team's temperature sensor
304	Performance	The flow meter shall determine a level with an error of less than $\pm 2\%$	The infrared flow meter has an accuracy of 1%
305	Performance	The system shall dispense beer into a $\frac{1}{4}$ pint, $\frac{1}{2}$ pint, and one pint glass	This is implemented through the flow valve and PLC logic
401	Utilization	The system shall not cost over \$3000	Current cost is well below \$3000
402	Utilization	The system shall be assembled in 30 minutes or less	The system ships mostly assembled
403	Utilization	The system shall require, at most, two individuals to set up	The system is not complicated to set up
404	Utilization	The system shall weigh light enough for two individuals to carry	The system is light for two people
405	Utilization	The system shall be reliable for at least 8 hour intervals	The system was tested for an eight hour period
406	Utilization	The system shall require one individual to operate the system	Only one operator is needed for the GUI
501	Trade-Off	The system shall use the following criteria for a trade-off analysis:	----

501.1	Trade-Off	Overall system performance is more important than Utilization of Resources	The system is very accurate
501.2	Trade-Off	Overall size of system is more important than cost in value	The system fits in the Pelican shipping boxes
501.3	Trade-Off	Technology within the system is more important than cost in value	Texas Instruments technology is being showcased
501.4	Trade-Off	Overall size of system is more important than aesthetics	The system fits in the pelican shipping boxes

10.2 Acceptance Test Plan

In order to verify that the system is working as anticipated, multiple tests were performed to ensure that all of the above requirements were met. The important criteria were the size of the system, the accuracy of the temperature sensor, the temperature of the beer, as well as testing the flow meter of the system.

The size of the system was tested by disassembling the products and packing them into the required shipping boxes. The test was expected to pass because Team 5348 designed the system with the specified size constraints in mind.

Testing of the temperature sensor transmitter and testing the temperature of the beer went hand in hand. The team tested the temperature of the beer by first buying a calibrated temperature sensor used to measure the temperature of the beer and ensuring that it was within 1 degree of the targeted temperature. The temperature sensor was then tested by comparing its reading for the same beer uncooled, with the calibrated external sensor.

In order to test the flow meter of the system, the team dispensed beer into each of the specified glass sizes, ensuring that the glass did not over- or under-fill with beer.

11.0 Summary of Risk Analysis and Mitigation Plan

In order to guarantee that the project was completed on time, Team 5348 had to perform a risk analysis and devise a mitigation plan in case something went wrong. The team quantified the possible risks by sorting them according to the frequency that they could happen and the severity of each possibility to the project. A risk score was calculated based on the determined frequency and severity score.

Team 5348 identified four major risks that could negatively affect the project (Table 11.1).

Table 11.1 – The four major risks identified for Team 5348

Risk#	Risk Description	Frequency	Severity	Risk Score
R1	Beer does not cool within desired time	.5	.9	.45
R2	Component failure	.3	.7	.21
R3	Excessive foaming	.4	.2	.08
R4	Cannot get iPad GUI implemented	.6	.5	.30

The first risk identified was the system not cooling the beer down to the desired temperature within the desired amount of time. This possibility could be due to the thermal electric coolers not cooling the water bath quickly enough. The team assigned a “moderate chance” rating to this risk because of the unfamiliarity with the thermal electric coolers and because the team is unsure of the specifics of how quickly the water is be cooled.

The next risk is component failure. This possibility could be cause by one of the various liquids that are used in the system shorting the circuitry, drawing too much power, or just a faulty component. Regardless, the team has assigned it a “low frequency” score because the team can control the liquids and power consumption and there is a low chance of having a faulty component. A solution to this problem is to procure extra components that may have a high chance of failure.

Another risk identified is excessive beer foaming. This can be due to an incorrect amount of CO₂ introduced into the system or the faucet being warmer than the rest of the system. The team has identified this risk as “very low severity” because in both cases there is a very simple fix: the CO₂ is easily adjustable and the faucet can be cooled down to a level that does not cause foaming within seconds.

The final risk that the team prepared for was the difficulty of getting the graphical user interface to work. This possibility could be due to either unfamiliarity with the code or simply running out of time. However, this problem can easily be worked around. Team 5348 looked at how to implement the GUI application ahead of time so that when the time came to implement it with the rest of the system, the team would be familiar with it. By getting a head start, the team effectively eliminated both causes of the risk. Additionally, the push button implemented in the system could serve as a start button, in case the GUI application is not working.

A graphical representation of the risk analysis is provided in Figure 11.1. The risks that have been explained above are labeled R1 to R4 in the figure below. The severity of the risk is on the x-axis and the likelihood of that risk happening is plotted on the y-axis. The dark red zone in the graph indicates high impact areas.

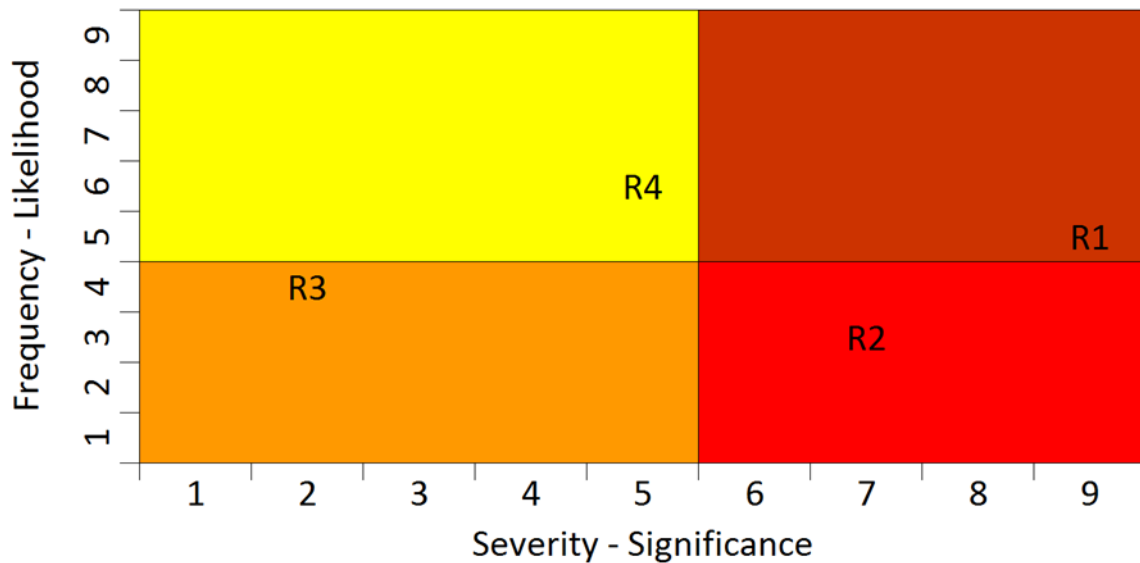


Figure 11.1 – This is the risk analysis of the system showing the severity against frequency of a problem actually occurring

As indicated in Figure 11.1, the only high impact risk that has been identified is R1; the risk consisting of the system not cooling down the beer quickly enough. The team has already taken the steps to speed the cooling of the water bath: the pipe that recirculates the water back into the system can go through the middle of the steel coil and disperse the water radially, ensuring there is a large enough heat transfer near the coils. Another part of the mitigation plan is to acquire another TEC cooling channel to cool more water at once. Table 11.2 shows a list of the risks and the solutions to each risk that have already been discussed.

Table 11.2 – The following table describes the four major risks’ solutions

Risk	Solution
Beer does not cool within desired time	System is designed to have maximum heat transfer; obtain another TEC water-cooling channel to lower the water bath temperature
Component failure	Acquire extra components; be careful with the current components
Excessive foaming	Adjust the amount of CO ₂ injected into the system; let beer flow out to cool the faucet
Cannot get iPad GUI working	Looking over code before use; backup push button is already implemented

12.0 Project Management Update

Team 5348 is currently on schedule with the given timeline. A preliminary implementation timeline and a Gantt chart are found in Appendix E. From the preliminary implementation timeline, it is shown that Team 5348 has completed all the events leading up to Design Day. The steps that the critical design review included are: placing orders for parts and receiving parts during the months leading up to April 30th. Once the parts were received, the construction of specified parts of the system was developed, per section 8 – *Development Plan*.

Once each individual build was completed, development testing was conducted in order to determine if each build was successful. These builds and tests occurred between the months of January and April. When the system was constructed and tested, the system test and acceptance test plan was performed to ensure the system meets all the requirements. This process took the team through the month of April, and allowed movement into the next step: operation and support. This was the step where the team trained the Texas Instruments employees in the operation of the system. They were trained to handle setup, operation, and maintenance of the system. Once this step was completed, the team was ready for design day.

Throughout this process, Team 5348 allocated a majority of its time to the construction of the system, since this was the most important factor for the final deliverable. The dates of the major builds of the system are included in the preliminary implementation timeline in Appendix E.

13.0 Closure

This University of Arizona senior design capstone report has covered all the systems and subsystems included in the Automated Beer Cooling and Dispensing System sponsored by Texas Instruments. The system requirements and changes since the critical design review presentation were presented in detail as well as a full description of the overall system assembly and top level design. Heat transfer analysis and piping stress analysis were performed for the heat exchanger subsystem and the results are in the analysis section and appendix section of this report.

Test plans and other planning data have also been covered in this report and the parts required for the construction of the dispensing system were ordered during the winter break and the beginning of the year for the complete fabrication of the cooling system by the end of the spring semester. After the parts arrived, the assembly and testing was conducted, including testing the cooling process of the TECs at a desired temperature set by the user. Moreover, every specification and requirement set by Texas Instruments was met beyond expectation and verified following all the proposed steps until the completion of the system.

The system was built to attract prospective clients and users around the world to events held by Texas Instruments, thereby increasing the potential of bringing in more sales and interest to the company's products. This project provides a fun experience for trade show attendees and allows viewers to see an electronic/mechanical system in action.

References

- "Amana Refrigerator Water Valve Solenoid." *Buy-it-now-store.com*. N.p., n.d. Web. 4 Dec. 2012. <<http://www.buy-it-now-store.com/12rewavafora.html>>.
- "Beer Drip Tray." *Micromatic.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.micromatic.com/draft-keg-beer/drip-trays-pid-DP-6X4.html>>.
- "Cylinder Stresses." *Wikipedia*. Wikimedia Foundation, 11 Dec. 2012. Web. 04 Dec. 2012. <http://en.wikipedia.org/wiki/Cylinder_stresses>.
- "D System - Keg Coupler - Tap W/ Black Lever Handle." *Micromatic.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.micromatic.com/draft-keg-beer/keg-taps-couplers-pid-7485E-S.html>>.
- "Double Gauge - CO2 Primary - Economy Series." *Micromatic.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.micromatic.com/draft-keg-beer/regulators-pid-842.html>>.
- "Flexural Strength." *Wikipedia*. Wikimedia Foundation, 11 May 2012. Web. 04 Dec. 2012. <http://en.wikipedia.org/wiki/Flexural_strength>.
- Incropera, Frank P. *Fundamentals of Heat and Mass Transfer*. New York [etc.: John Wiley & Sons, 2006. Print.
- "Infrared Flow Meter." *Swissflow.com*. N.p., n.d. Web. 4 Dec. 2012. <<http://www.swissflow.com/technology.html>>.
- "Liquid Tight RTD Sensor." *Auberins.com*. N.p., n.d. Web. 4 Dec. 2012. <http://www.auberins.com/index.php?main_page=product_info&products_id=249>.
- "Mechanical Properties, Stainless Steel, Annealed, Tensile Strength, Tempers - Tube Methods, Inc." *Tubemethods.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.tubemethods.com/mpss.htm>>.
- "Plexiglas - PLEXIGLAS SHEETS." *Professionalplastics.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.professionalplastics.com/PLEXIGLASS-ACRYLICSHHEET-EXTRUDED?gclid=CKL7ncrRq7MCFY6DQgodWFwAFw>>.
- "Plexiglas Weight Per Square Foot." *Eplastics.com*. N.p., n.d. Web. 04 Dec. 2012. <http://www.eplastics.com/Plastic/Plastics_Library/Plexiglass-Weight-Per-Square-Foot>.
- "Stainless Steel Cooling Coil, Right Hand, 50' X 5/16"" *Micromatic.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.micromatic.com/draft-keg-beer/jockey-boxes-pid-C050R.html>>.
- "Swissflow | SF 800 Low Pressure Infrared Flow Meter." *Swissflow.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.swissflow.com/sf800.html>>.
- "TEC Liquid Cooler." *Tetech.com*. N.p., n.d. Web. 4 Dec. 2012. <<http://www.tetech.com/Liquid-Coolers/LC-035.html>>.
- "Technical Center." *Plaskolite.com*. N.p., n.d. Web. 04 Dec. 2012. <<http://www.plaskolite.com/Resource/Search>>.
- "Thermal Conductivity of Some Common Materials and Gases." *Engineeringtoolbox.com*. N.p., n.d. Web. 04 Dec. 2012. <http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html>.

Appendix A

Individual Contributions

Nicole Rojas (Chief Executive Officer)

- Team leader
- 4.0 Top-Level Design of Final Design Concept
- 7.1 Heat Transfer Analysis
- 7.3 Tilting Mechanism Analysis
- 13.0 Closure
- Appendix A, B, C
- Entire final report editing
- Solidworks
- Tilting mechanism design and construction
- TEC water-cooling channel design and construction
- Design of TI logo onto Plexiglas
- Plexiglas window design enclosure
- Prototype construction
- System testing

Signature: _____

Ryan Kovalchick (Chief Operating Officer)

- Team leader
- 1.0 Introduction
- 2.0 System Requirements
- 3.0 Summary of Preliminary Design Review Results
- 5.4 Electronic Component Subsystem
- 5.5 Programmable Logic Controller Subsystem
- 6.4 Algorithm Description and Interface Document (Software)
- 6.5 Graphical User Interface
- 8.4 Fourth Build: Graphical User Interface
- 10.0 Requirements Review/Acceptance Test Plan
- 12.0 Project Management Update (Gantt Chart)
- Appendix D, E, F
- Final report editing
- Electronics purchasing and testing
- PLC coding
- System Integration
- Enclosure design and construction
- Prototype construction
- Final system construction
- Overall system wiring
- Commissioning of system
- Troubleshooting issues
- System testing

- iPad development and testing

Signature: _____

Tim May (Chief Financial Officer)

- 5.0 Subsystem/Sub-Assembly and Interface Design (Hardware)
- 9.0 Budget and Suppliers
- Research system components
- Purchasing/financing
- Cooling system design
- Enclosure design and construction
- Prototype construction
- Final system construction
- Troubleshooting issues
- System testing

Signature: _____

Danny Armenta (Chief Scheduling Officer)

- 7.2 Pipe Analysis
- 8.0 Development Plan
- PCB layout design and construction
- PCB debugging
- Assisted system wiring
- System testing

Signature: _____

Michael Sato (Chief Administrative Officer)

- 9.0 Budget and Suppliers
- 11.0 Summary of Risk Analysis and Mitigation Plan
- Microcontroller code and debugging
- PCB debugging
- Assisted system wiring
- System testing

Signature: _____

Kyle Burke (Chief Marketing Officer)

- 6.0 Algorithm Description and Interface Document (Software)
- Microcontroller code and debugging
- PCB debugging
- Assisted system wiring
- Wireless switch set up

Signature: _____

Appendix B

Hardware Drawings for Assemblies

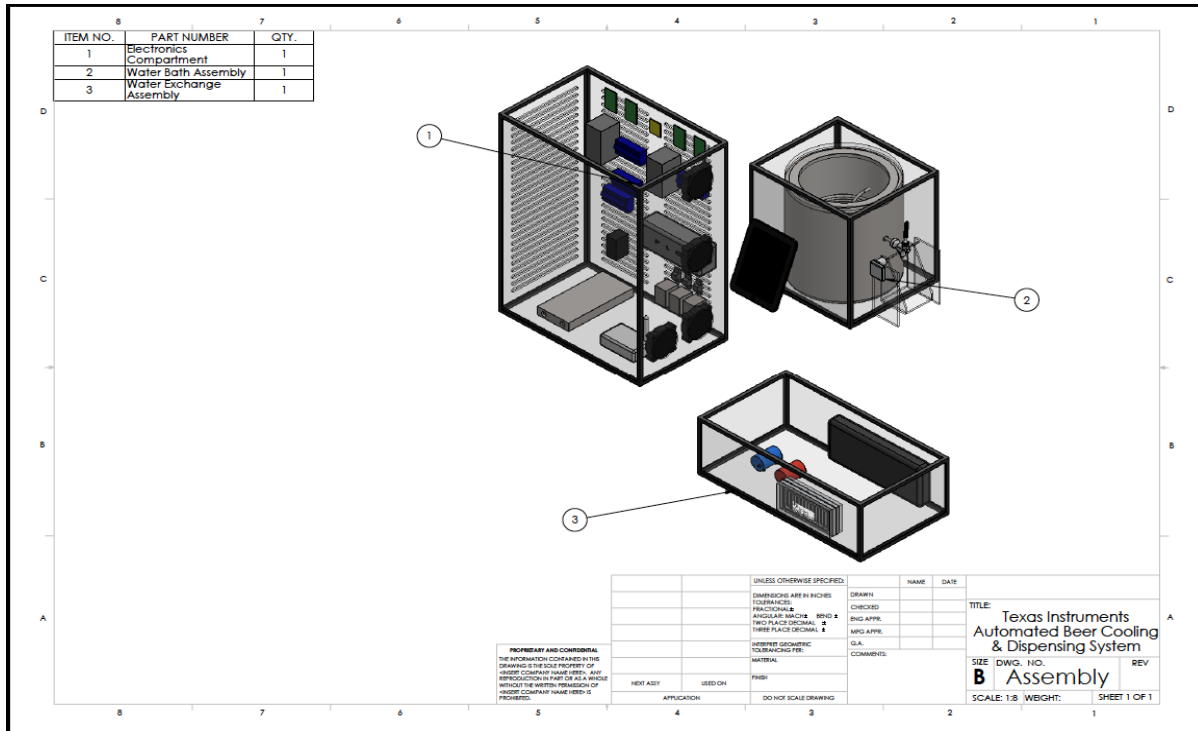


Figure B.1 – SolidWorks Drawing of Entire System

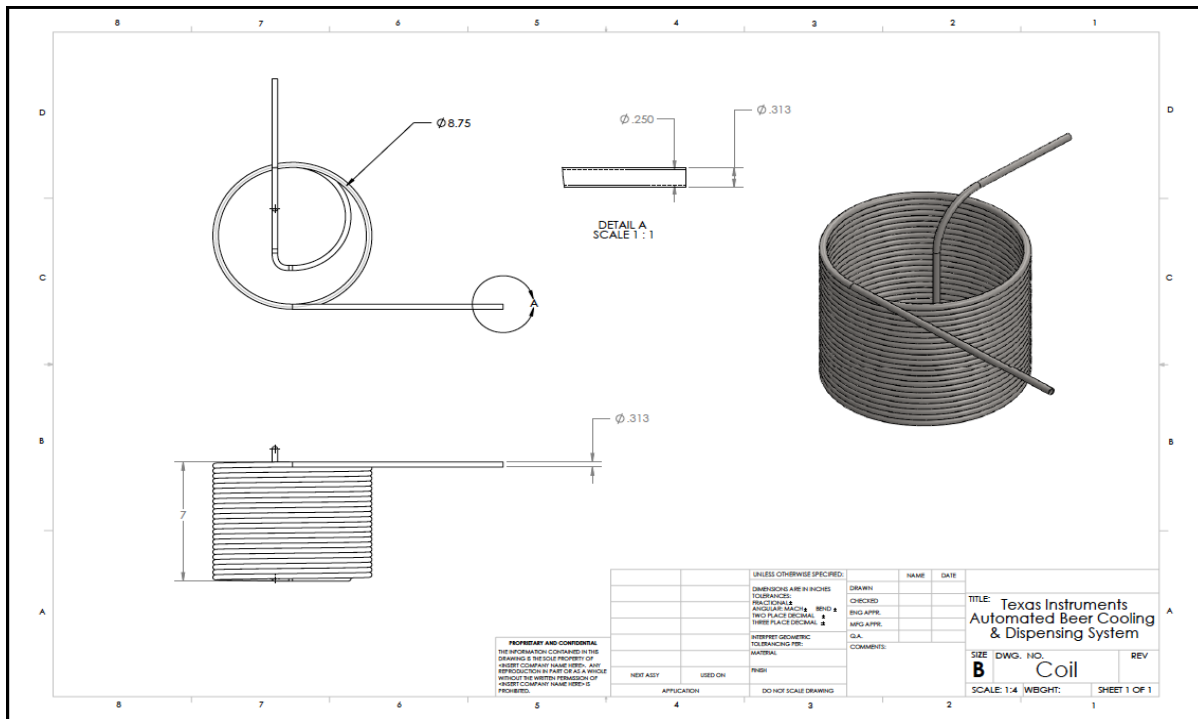


Figure B.2 – SolidWorks Drawing of Beer Coil

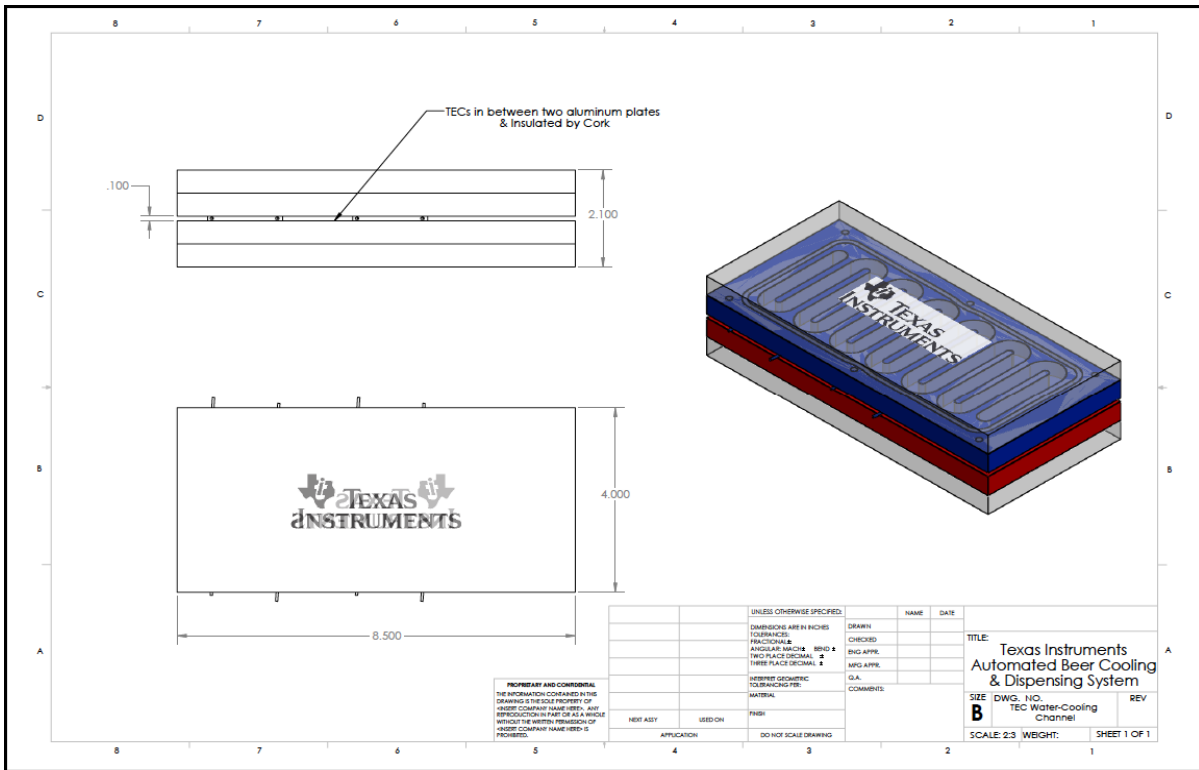


Figure B.5 – SolidWorks Drawing of the Machined Thermo-Electric Water-Cooling Channel

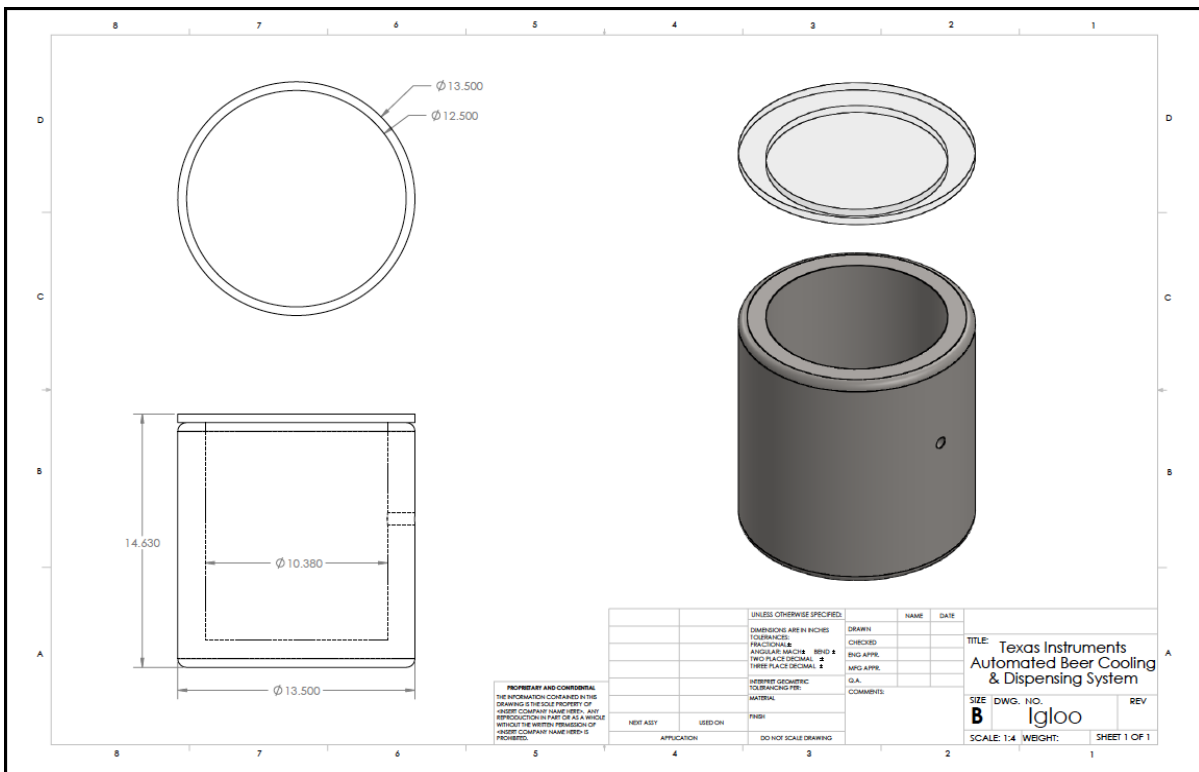


Figure B.6 – SolidWorks Drawing of Water Bath Container

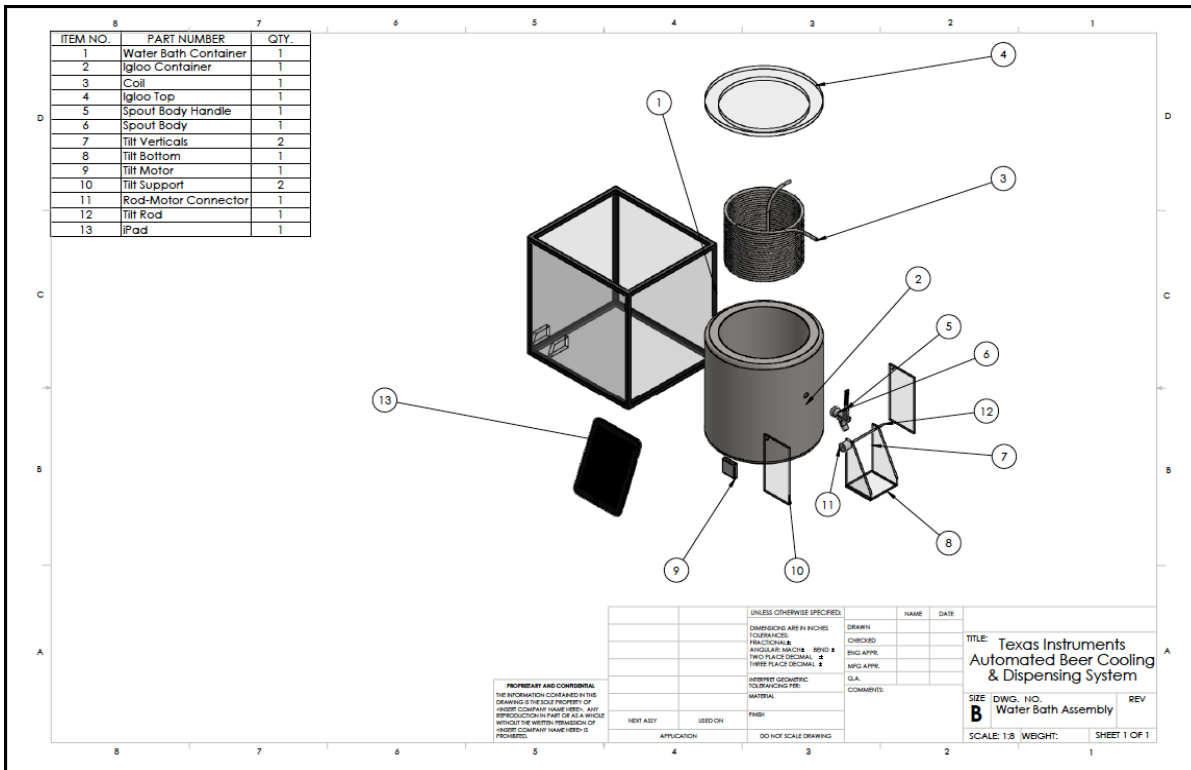


Figure B.7 – SolidWorks Drawing of Water Bath and Tilting Mechanism Assembly

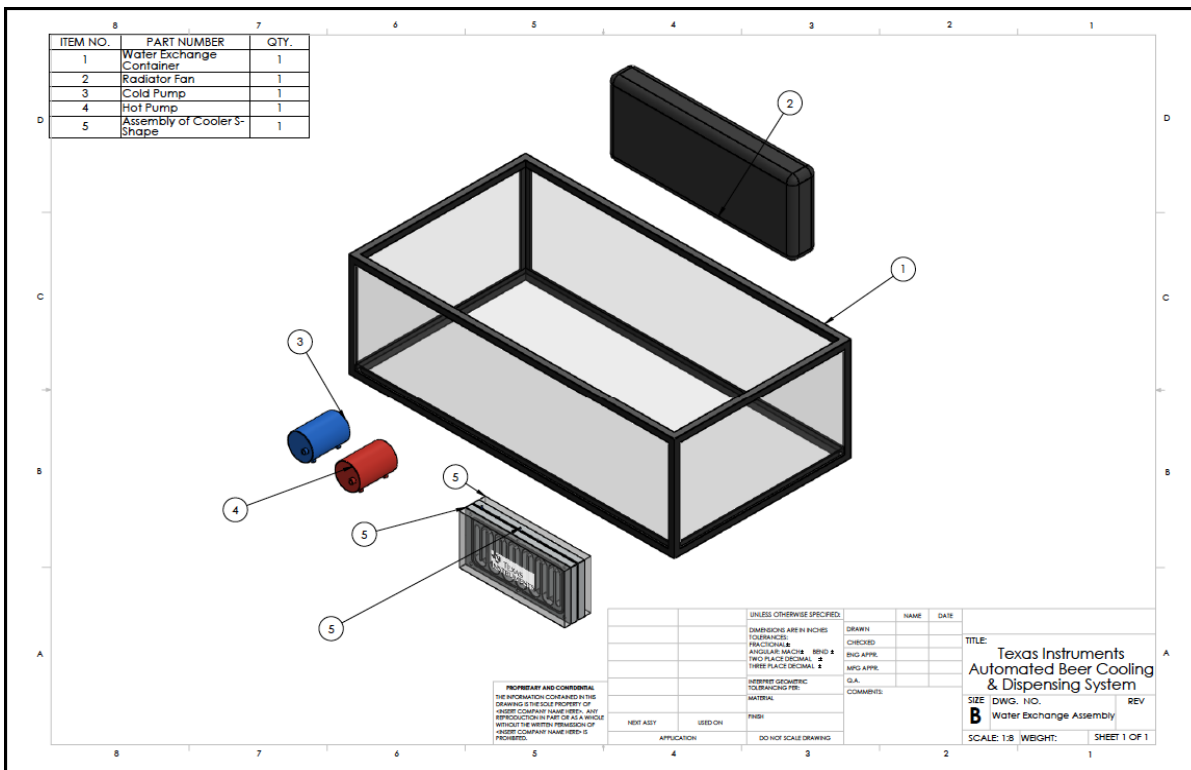


Figure B.8 – SolidWorks Drawing of Water Exchange Assembly

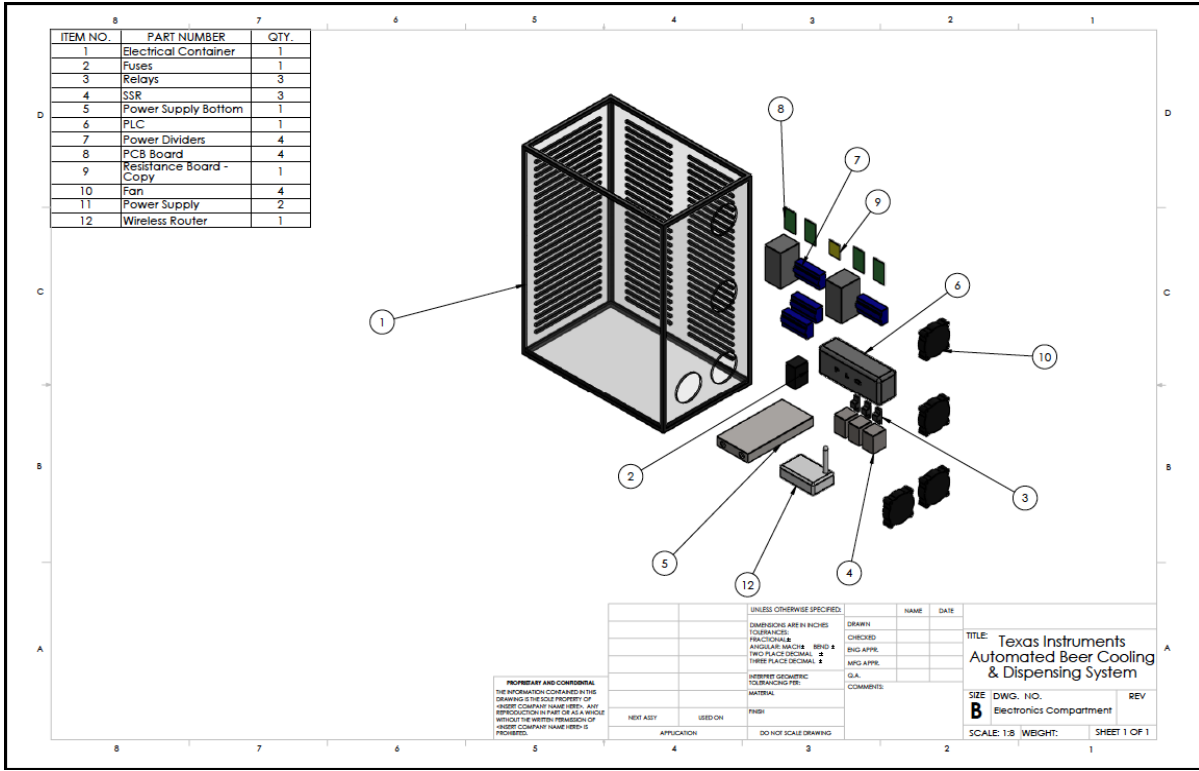


Figure B.9 – SolidWorks Drawing of Electronics/Control Panel Compartment Assembly

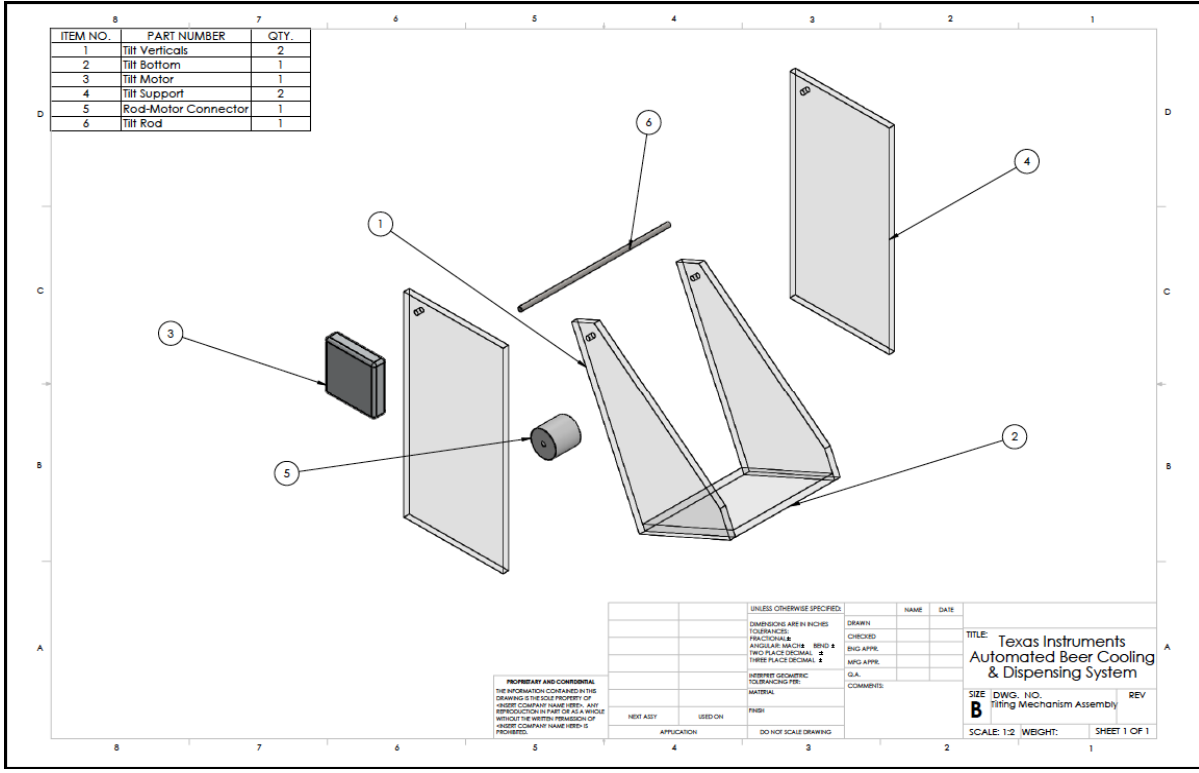


Figure B.10 – SolidWorks Drawing of Tilting Mechanism Assembly

Appendix C

Calculations

Heat transfer Calculations:

Room temp water = 25°C
 $\rho_{\text{water}} = 1000 \text{ kg/m}^3 = 1 \text{ kg/L}$
 Heat removed = 30 watts.
 $C_{\text{water}} = 4.1814 \text{ kJ/kg}\cdot\text{K}$
 $T_{\text{in}} = 25^\circ\text{C}$

Steady flow thermal energy equation
 $q = \dot{m} c_p (T_{\text{out}} - T_{\text{in}})$

$\frac{30 \text{ J}}{\text{s}} = \left(16 \frac{\text{L}}{\text{min}}\right) \left(1 \frac{\text{kg}}{\text{L}}\right) \left(\frac{1 \text{ min}}{60 \text{ sec}}\right) (4.1814 \frac{\text{J}}{\text{kg}}) \frac{1 \text{ kg}}{\text{kg}} (25 - T_{\text{out}})$
 $\rightarrow T_{\text{out}} = 24.73^\circ\text{F}$

for this flow rate

Reynolds Number:
 Turbulance in a helical tube
 $Re_{\text{sch}} = Re_{\text{pc}} [1 + 12(D/c)^{0.5}]$
 $= 2200 [1 + 12(1/4/5/16)^{0.5}]$
 $= 2692.62$

$U =$ overall heat transfer coefficient.
 $= \frac{1}{h A_{\text{outside}}} + \frac{t}{k D} + \frac{1}{h A_{\text{inside}}}$

$Q_{\text{out}} = \dot{m} c_p (T_{\text{in}} - T_{\text{out}})$

$Q = \frac{m c \Delta T}{dt} = \dot{Q}_{\text{rec}}$
 $\frac{dQ}{dt} = \frac{\dot{Q}_{\text{rec}}}{m \cdot 4.1814}$
 $T_{\text{out}} = \dots - t$

$h_{\text{water}} = 50 \text{ W/m}^2\cdot\text{K}$
 $h_{\text{beer}} = 100 \text{ W/m}^2\cdot\text{K}$
 $Area = \pi D L$

$Q = \frac{\Delta T_{\text{in}}}{R_{\text{tot}}}$

constant wall temperature:
 $q = \dot{m} c \frac{dT}{dt} = h A (T_{\text{in}} - T_{\text{act}})$

Assume TEC mixing is perfect & the temp is uniform.
 Heat removed directly from water bath.

1st order differential equation to determine $T_{\text{bath}}(t)$.

$m_{\text{bath}} c \frac{dT}{dt} = -\dot{Q}_{\text{rec}} \Rightarrow T_{\text{bath}}(t) = T_{\text{b0}} - \frac{\dot{Q}_{\text{rec}}}{m_{\text{bath}} c} t$

The wall boundary condition for the internal flow in the coil heat exchanger will then be $T_{\text{bath}} = T_{\text{wall}}$ as a function of time.

$\frac{dT_{\text{in}}(x)}{dx} = -h A (T_{\text{in}}(x) - T_{\text{w}}(t))$
 $T_{\text{in}} = T_{\text{c}}$

$V = 10 \times 10 \times 2000 \text{ in}^3 = 0.0131 \text{ m}^3$
 $m = \rho_{\text{water}} \cdot V = \frac{1 \text{ kg}}{\text{L}} \cdot \frac{1000 \text{ L}}{\text{m}^3} \cdot 0.0131 \text{ m}^3 \approx 13.1 \text{ kg of water}$ or 5.95 lbm

$C = 4.1814 \text{ kJ/kg}\cdot\text{K}$

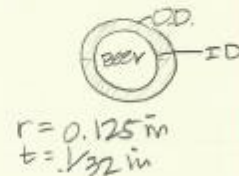
Figure C.1 – Heat Transfer/Pipe Analysis Calculations Page 1

$$T_b = 25^\circ\text{C} - \frac{30\text{J/s}}{13 \cdot (19.4 \cdot 10^3 \text{ kg/m}^3) \cdot (1000 \text{ kg/m}^3) \cdot t} = 25^\circ\text{C} - 55 \times 10^{-4} (t)$$

$$\frac{dT_m(x)}{dx} = \frac{-P}{m \cdot c_p} (T_m(x) - T_w(x)) \quad \text{values plugged into excel}$$

Pipe/Stress Analysis:

$$\text{Axial: } \sigma_2 = \frac{P_o \cdot r}{2t} \Rightarrow P_o = \frac{2\sigma_2 t}{r}$$



$$\text{Hoop: } \sigma_1 = \frac{P_o \cdot r}{t} \Rightarrow P_o = \frac{\sigma_1 \cdot t}{r}$$

Pressure: 14-20 psi
304 stainless steel

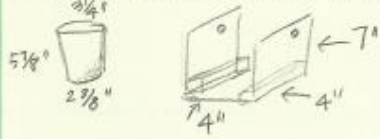
Hoop:
 σ (1 psi) = 20 psi
 σ (20 psi) = 120 psi
Yield strength

Hydrostatic Pressure:

$$P = \rho \cdot g \cdot h = 1000 \frac{\text{kg}}{\text{m}^3} \cdot 9.81 \frac{\text{m}}{\text{s}^2} \cdot 3 \text{ in} \cdot \frac{254 \times 10^{-2} \text{ m}}{1 \text{ in}} \cdot \frac{\text{N}}{\text{kg} \cdot \text{m/s}^2} = 2 \text{ kPa}$$

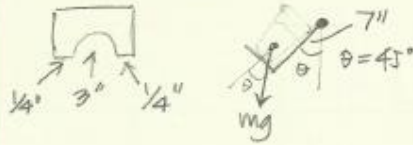
Figure C.2 – Heat Transfer/Pipe Analysis Calculations Page 2

Tilt Mechanism Calculations:



Plexiglas: $0.472'' \rightarrow 2.88 \text{ lb/sq.ft. glass}$

About 6" height, Diameter = 2.5"



Bottom Holder: $4.4 \text{ in}^2 \cdot 2.88 \text{ lb/sq.ft.} = 0.32 \text{ lbs}$

Back: $4.7/12^2 \cdot 2.88 = 0.56 \text{ lbs}$

Beer glass: 12oz = 1 lb

Beer: 1 lb

Total weight $\approx 3.2 \text{ lbf.}$

Torque required for the motor: $T = F \times D$

$$T = mg \sin \theta R = 32.174 \text{ lbf} \cdot \sin(45^\circ) \cdot (7 \text{ in}) = 15.84 \text{ in-lb}$$

Degrees per second:

$$\frac{3 \text{ rev}}{\text{min}} \cdot \frac{360^\circ}{1 \text{ rev}} \cdot \frac{1 \text{ min}}{60 \text{ s}} = 18^\circ/\text{sec} \quad \text{or} \quad 3.5 \frac{\text{rev}}{\text{min}} \cdot \frac{360^\circ}{\text{rev}} \cdot \frac{1 \text{ min}}{60 \text{ s}} = 21^\circ/\text{sec}$$

Figure C.3 – Tilting Mechanism Analysis Calculation Page 1

Appendix D

Functional Diagrams

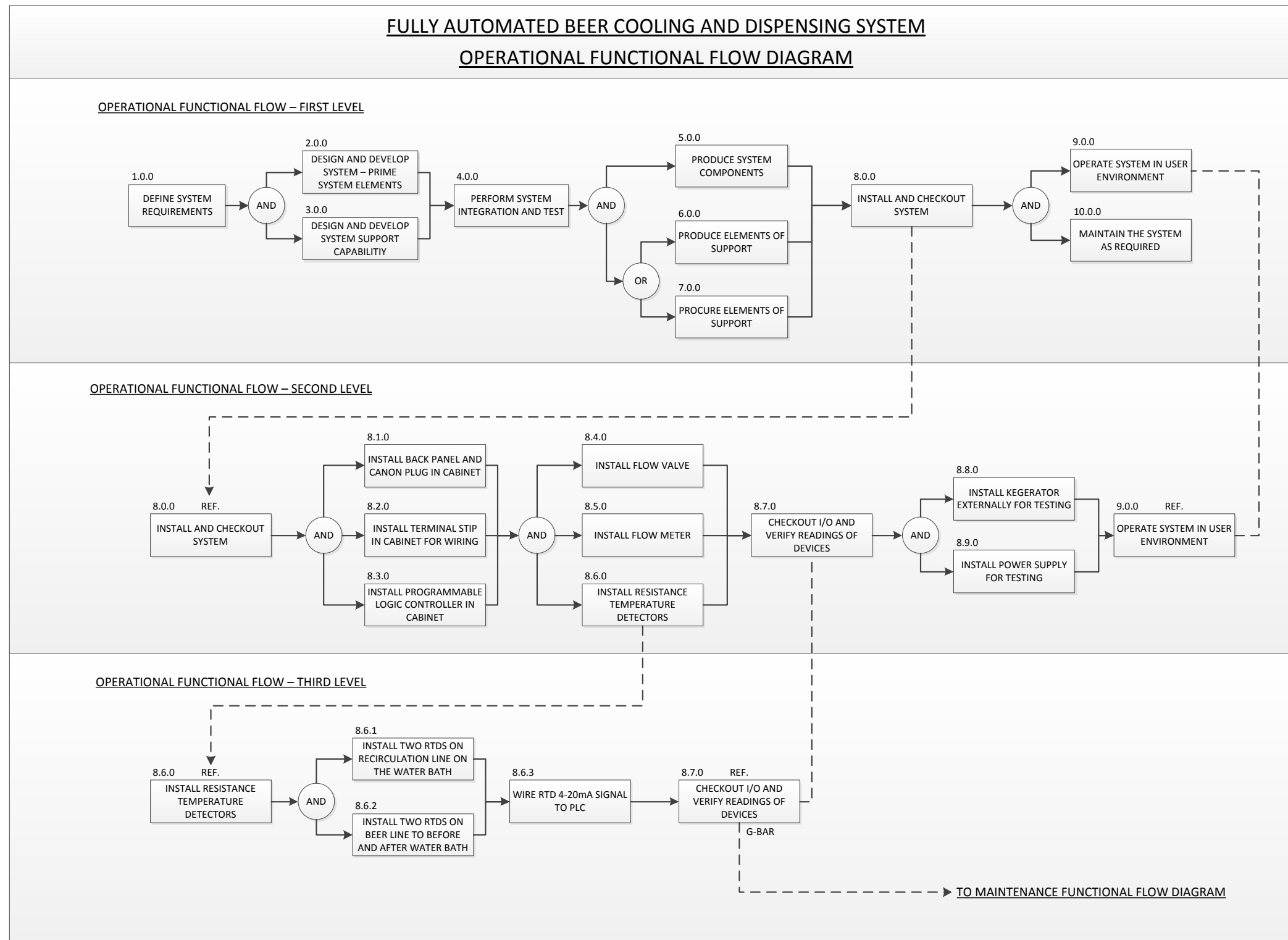


Figure D.1 – Operational Functional Flow Diagram Representation of the System

FULLY AUTOMATED BEER COOLING AND DISPENSING SYSTEM

MAINTENANCE FUNCTIONAL FLOW DIAGRAM

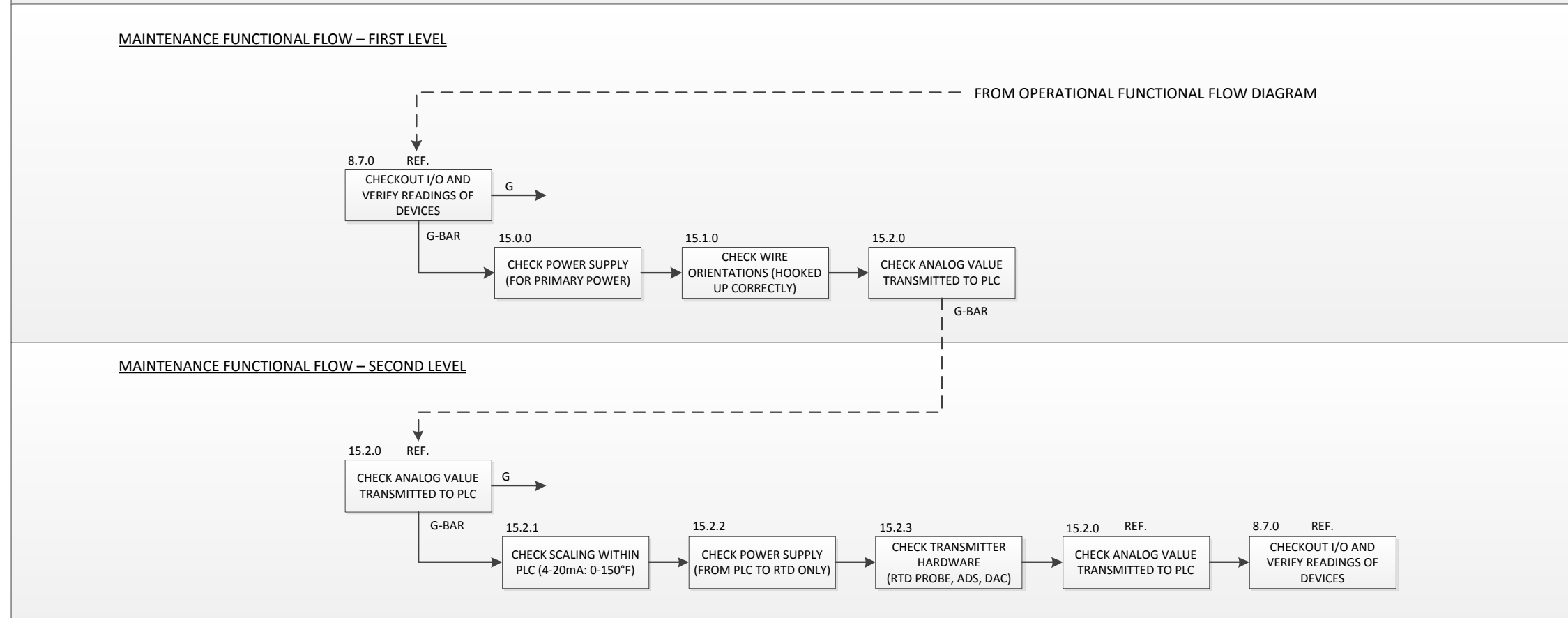


Figure D.2 – Maintenance Functional Flow Diagram Representation of the System

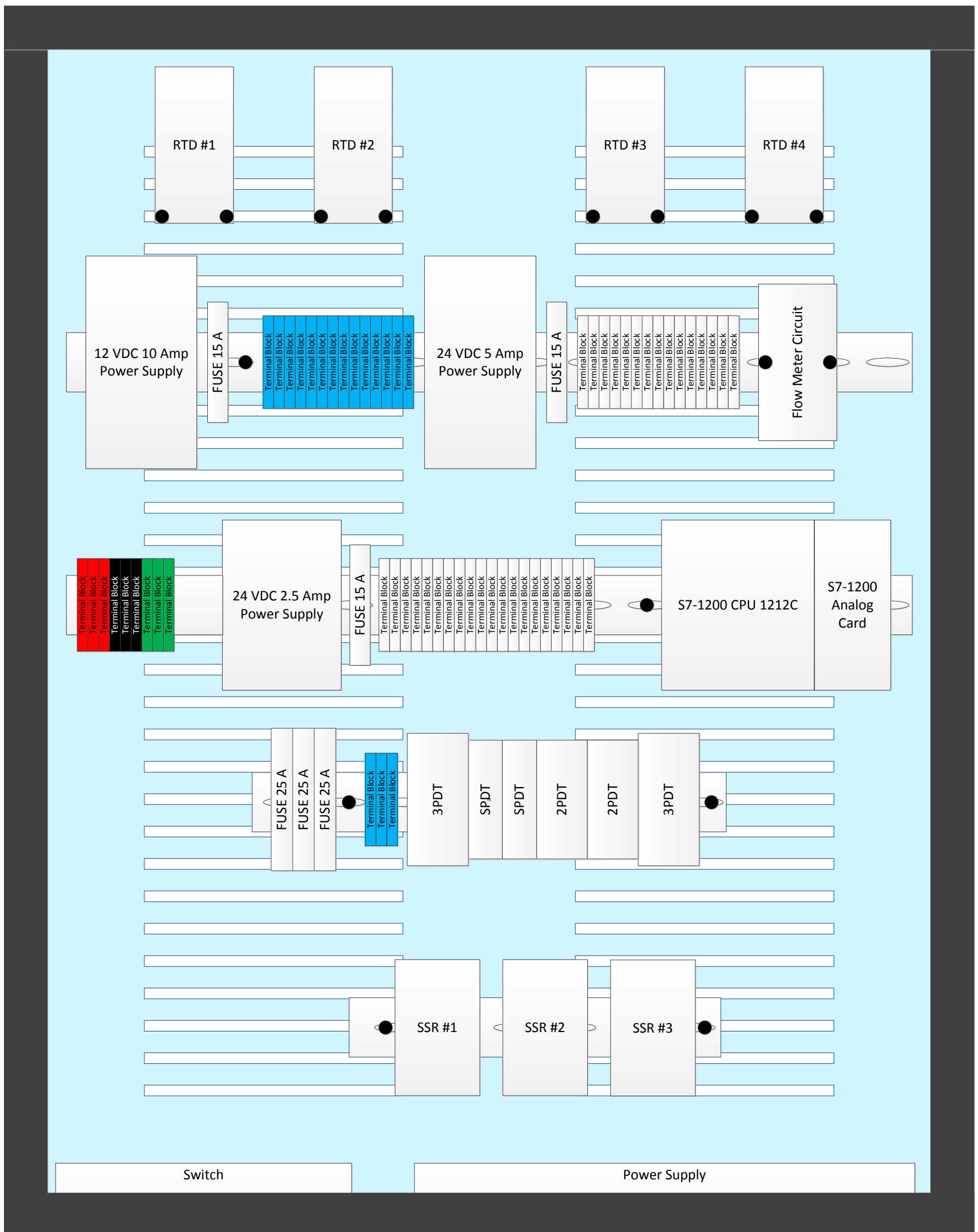


Figure E.1—Control Panel Layout Diagram to Scale

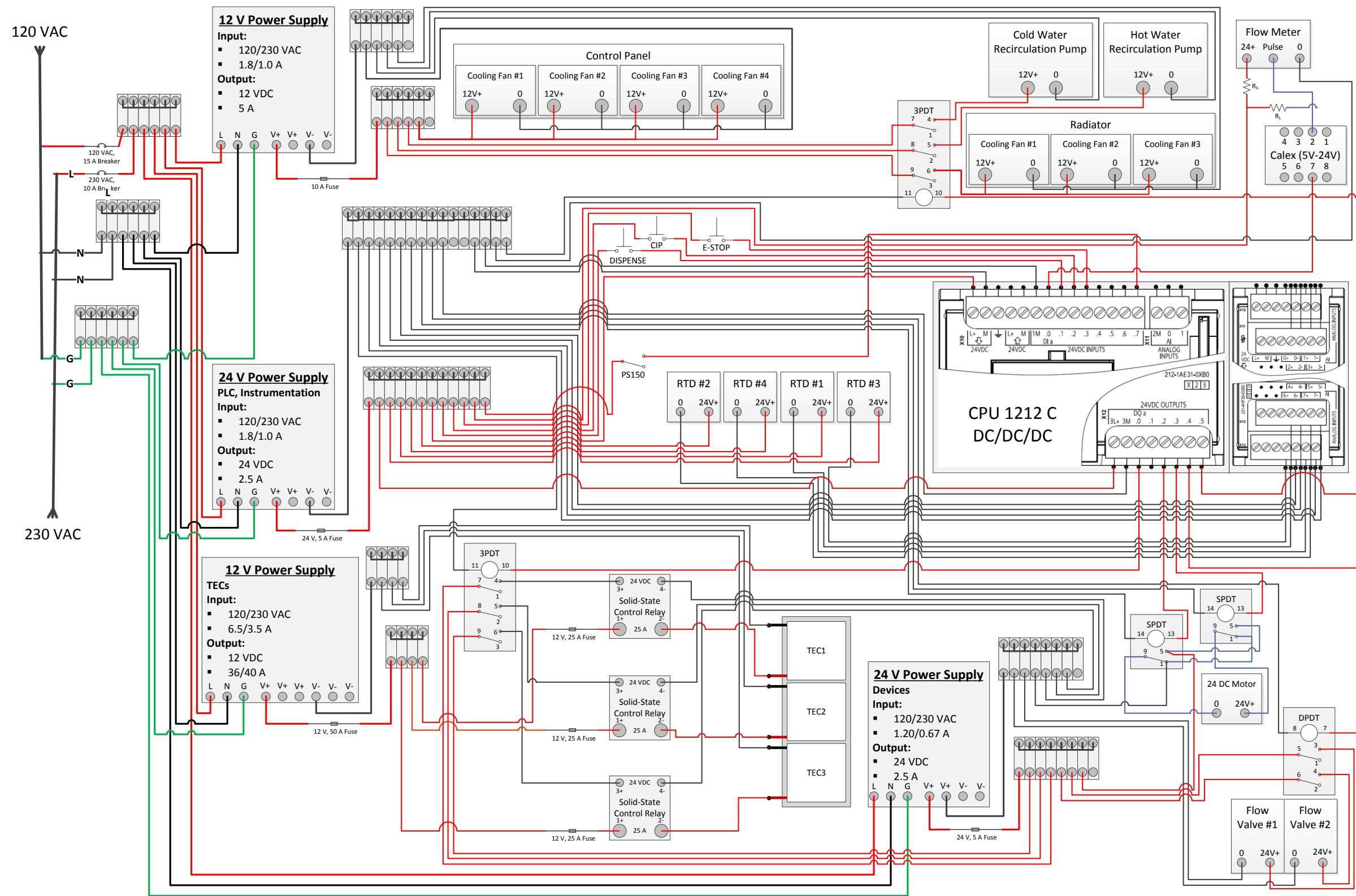


Figure E.2 – High Level System Components Diagram

Appendix F

Preliminary Implementation Timeline

Table F.1 – Preliminary Implementation Timeline for all of Fall 2012 – Spring 2013

WBS	Task Name	Duration	Start	Finish	% Complete
1	Project Management	1 day	Tue 8/28/12	Tue 8/28/12	100%
1.1	Formulate Project Management Plan	1 day	Tue 8/28/12	Tue 8/28/12	100%
1.2	Progress Reports	1 day?	Tue 8/28/12	Tue 8/28/12	100%
1.4		1 day	Tue 8/28/12	Tue 8/28/12	100%
9	Deliverables	11 days	Thu 9/13/12	Thu 9/27/12	100%
9.1	Concept of Operations	1 day	Thu 9/27/12	Thu 9/27/12	100%
9.3	System Requirements Review	13 days	Tue 9/11/12	Thu 9/27/12	100%
9.4	Peer Review Memo	2 days	Wed 9/26/12	Thu 9/27/12	100%
2	Requirements Development	96 days	Thu 9/27/12	Thu 2/7/13	100%
2.9	Draft Concept of Operations	6 days	Thu 9/13/12	Thu 9/20/12	100%
2.1	Develop Concept of Operations	2 days	Tue 9/25/12	Wed 9/26/12	100%
2.2	Draft Requirements	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.2.1	I/O Functional Requirements	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.2.2	Technology Requirements	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.2.3	I/O Performance	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.2.4	Utilization of Resources	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.2.5	Trade-Off	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.2.6	System Test (ATP)	5 days	Thu 9/20/12	Wed 9/26/12	100%
2.3	Submit Draft Requirements for Review	1 day	Thu 9/27/12	Thu 9/27/12	100%
2.3.1	Submit Draft Requirements	1 day	Thu 9/27/12	Thu 9/27/12	100%
2.3.2	Requirements Review Meeting	1 day	Thu 9/27/12	Thu 9/27/12	100%
2.4	Revised Requirements	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.4.1	I/O Functional Requirements	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.4.2	Technology Requirements	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.4.3	I/O Performance	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.4.4	Utilization of Resources	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.4.5	Trade-Off	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.4.6	System Test (ATP)	2 days	Tue 10/9/12	Wed 10/10/12	100%
2.5	Submit Revised Requirements	1 day?	Thu 10/11/12	Thu 10/11/12	100%
2.6	Respond to Comments	3 days	Thu 10/11/12	Mon 10/15/12	100%
2.7	Freeze Requirements	1 day	Fri 10/12/12	Fri 10/12/12	100%
2.8	Final ATP Acceptance	5 days	Mon 10/15/12	Fri 10/19/12	100%
3	System Design	109 days	Mon 10/1/12	Thu 2/28/13	62%
3.1	High Level Design	0 days	Thu 10/18/12	Thu 10/18/12	100%
3.1.1	Design Concept #1	3 days	Tue 10/9/12	Thu 10/11/12	100%

3.1.1.1	Identify Derived Requirements	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.1.2	High Level Functional Design	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.1.3	High Level Physical Design	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.1.4	Submit High Level Design for Review	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.2	Design Concept #2	3 days	Tue 10/9/12	Thu 10/11/12	100%
3.1.2.1	Identify Derived Requirements	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.2.2	High Level Functional Design	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.2.3	High Level Physical Design	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.2.4	Submit High Level Design for Review	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.3	Design Concept #3	3 days	Tue 10/9/12	Thu 10/11/12	100%
3.1.3.1	Identify Derived Requirements	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.3.2	High Level Functional Design	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.3.3	High Level Physical Design	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.1.3.4	Submit High Level Design for Review	2 days	Tue 10/9/12	Wed 10/10/12	100%
3.2	Modeling and Simulation	11 days	Fri 10/19/12	Fri 11/2/12	100%
3.2.1	Simulation Model Development	10 days	Fri 10/19/12	Thu 11/1/12	100%
3.2.2	System Experimentation	5 days	Fri 10/19/12	Thu 10/25/12	100%
3.3	Preliminary Design Review (PDR)	5 days	Thu 10/4/12	Thu 10/18/12	100%
3.4	Revise High Level Design	4 days	Fri 10/19/12	Wed 10/24/12	75%
3.5	Detail Design	31 days	Wed 10/24/12	Wed 12/5/12	100%
3.5.1	Component 1 - RTD Structure	10 days	Wed 10/24/12	Tue 11/6/12	100%
3.5.2	Component 2 - Water Bath Enclosure	31 days	Wed 10/24/12	Wed 12/5/12	100%
3.5.3	Component 3 - Totalizer Method	10 days	Wed 10/24/12	Tue 11/6/12	100%
3.5.4	Component Interface Definition	5 days	Wed 10/24/12	Tue 10/30/12	100%
3.6	Formulate Development Plan	8 days	Thu 10/11/12	Mon 10/22/12	100%
3.7	Critical Design Review	13 days	Thu 11/15/12	Mon 12/3/12	100%
3.8	Revise Detailed Design	5 days	Fri 11/9/12	Thu 11/15/12	100%
3.9	Place Order for Parts	16 days	Tue 12/4/12	Tue 12/25/12	0%
3.11	Receive Parts	63 days	Tue 12/4/12	Thu 2/28/13	0%
4	System Construction	56 days	Tue 1/1/13	Tue 3/19/13	0%
4.1	Construction Builds	37 days	Tue 1/1/13	Wed 2/20/13	0%
4.1.1	Build 1 - RTD Structure	7 days	Tue 1/1/13	Wed 1/9/13	0%
4.1.2	Build 2 - Water Bath Enclosure	12 days	Tue 1/15/13	Wed 1/30/13	0%
4.1.4	Build 3 - Totalizer Method	13 days	Mon 2/4/13	Wed 2/20/13	0%
4.2	Development Testing	32 days	Thu 1/10/13	Fri 2/22/13	0%
4.2.1	Test Build 1	3 days	Thu 1/10/13	Mon 1/14/13	0%
4.2.2	Test Build 2	2 days	Thu 1/31/13	Fri 2/1/13	0%
4.2.4	Test Build 3	2 days	Thu 2/21/13	Fri 2/22/13	0%
4.3	System Integration	35 days	Thu 1/10/13	Wed 2/27/13	0%
4.4	Error Resolution	39 days	Thu 1/24/13	Tue 3/19/13	0%
4.4.1	ATP Issues	10 days	Thu 2/28/13	Wed 3/13/13	0%

4.4.2	Operational Support	4 days	Thu 3/14/13	Tue 3/19/13	0%
5 System Delivery & Installation		64 days	Tue 1/1/13	Fri 3/29/13	0%
5.1	Equipment Delivery	43 days	Tue 1/1/13	Thu 2/28/13	0%
5.2	Hardware Installation	42 days	Tue 1/1/13	Wed 2/27/13	0%
5.3	Software Installation	33 days	Mon 1/14/13	Wed 2/27/13	0%
5.4	Installation Test and Verification	23 days	Wed 2/27/13	Fri 3/29/13	0%
6 System Test and Acceptance		19 days	Mon 4/1/13	Thu 4/25/13	0%
6.1	Execute ATP	15 days	Mon 4/1/13	Fri 4/19/13	0%
6.2	Problem Resolution	10 days	Mon 4/8/13	Fri 4/19/13	0%
6.3	Re-Test ATP	10 days	Mon 4/8/13	Fri 4/19/13	0%
6.4	Burn-in test	5 days	Fri 4/19/13	Thu 4/25/13	0%
7 Operation and Support		5 days	Mon 4/22/13	Fri 4/26/13	0%
7.1	System Training (Users)	5 days?	Mon 4/22/13	Fri 4/26/13	0%
7.2	System Training (Technical)	5 days?	Mon 4/22/13	Fri 4/26/13	0%
7.3	Operational Support	5 days?	Mon 4/22/13	Fri 4/26/13	0%
8 Customer Action		93 days	Fri 9/7/12	Tue 1/15/13	4%
8.1	Review Draft Requirements	1 day	Fri 9/7/12	Fri 9/7/12	100%
8.2	Review Revised Requirements	1 day	Fri 10/12/12	Fri 10/12/12	100%
8.3	ATP Review & Acceptance	39 days	Fri 10/12/12	Wed 12/5/12	1%
8.4	Review High Level Design	30 days	Wed 12/5/12	Tue 1/15/13	0%

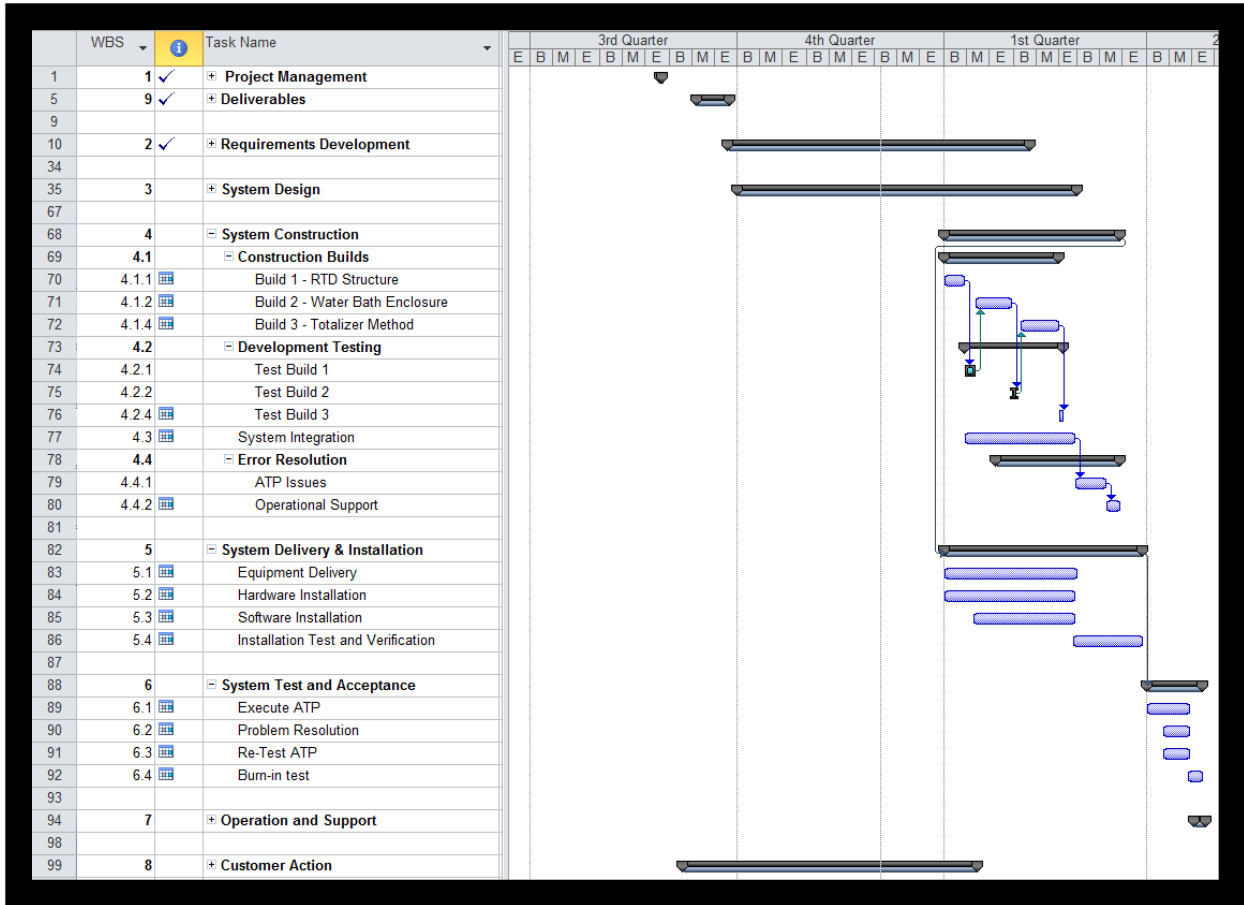


Figure F.1 – Gantt Chart Representation of the Timeline