INSTANT COLD BREW MACHINE

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Abstract

The following document details the design, development, and results of our project, the Instant Cold Brew Machine. This machine addresses the lengthy process of traditionally brewed cold brew, which requires 12-24 hours, by introducing a novel approach to brewing cold brew coffee. By utilizing an airtight aluminum chamber to significantly lower the boiling point of water, we are able to expedite the extraction of coffee with water at no more than room temperature. The paper will go over the methods used to verify the requirements outlined for the machine and its subsystems, examine cost, and conclude with the ethical considerations and future of this machine.

Contents

1. Introduction

1.1 Overview

In recent years, there has been a surge in demand [1] for cold coffee beverages as opposed to the traditionally served hot coffee. There are two main types of cold coffee: Iced coffee and cold brew. Iced coffee is simply hot-brewed coffee that has been cooled down using ice or refrigeration, whereas cold brew coffee is made by steeping coffee grounds in cold water for 12 to 24 hours. The prolonged low-temperature extraction of cold brew coffee results in a sweeter, less acidic, and less bitter coffee as compared to iced coffee made from the same grounds, without the need for milk or sugar.

1.2 Problem

The rapid nature of hot coffee brewing gives iced coffee many advantages over cold brew from a production standpoint. The short brew time allows coffee connoisseurs to finely control the temperature of the brewing water, the duration of the brew, and even the packing of the grounds they use. Cold brew, in comparison, takes 12 to 24 hours to brew and restricts consumers to the temperature of their fridge and a very wide window of brew times. While preparing cold brew in advance may not be a hindrance to some, it does not have the fine-tuned control seen in iced-coffee brewing, and does not allow a consumer to try new coffee grounds for their cold brew every morning.

1.3 Solution

Our solution to this problem is a machine that extracts cold brew coffee at the same rate as hot coffee brewing. By reducing the brew time for cold brew from 12 to 24 hours to less than 10 minutes, we enable consumers to exercise fine-tune control on their cold brew each morning, being able to change coffee grounds and brewing parameters like they can for hot coffee brewing.

The low temperature of the water used in cold brewing introduces two problems that lead to a large brew time. Firstly, the coffee grounds themselves take a long time to saturate with water, and secondly, the rate of extraction of coffee is extremely slow. Our machine leverages air pressure to effectively reduce the boiling point of water. Figure 1 below shows the boiling point of water as a function of air pressure.

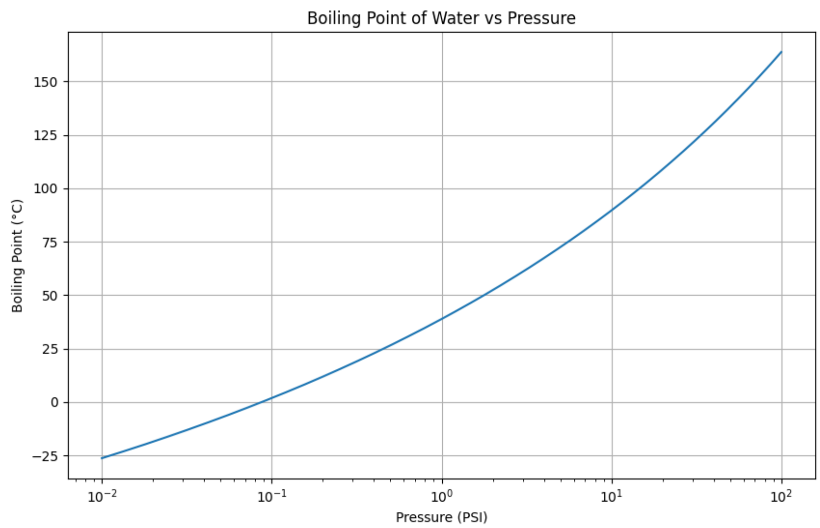

Figure 1: Boiling Point of Water vs. Pressure

As seen in Figure 1, by reducing the pressure in the brew chamber to 1 PSI, the boiling point of water reaches approximately 39 ℃. While this does not bring room temperature water to a roaring boil, it does saturate the grounds rapidly and greatly increases the rate of extraction.

1.4 Requirements

With the basic principle of our machine established in Section 1.3 above, the following high-level requirements were set for the machine:

1. The machine must be able to achieve the user-defined brew pressure between 1 and 7 PSI in the brew chamber within 2 minutes ±5 seconds of the brew starting. It must then maintain this brew pressure for the user-defined brew time between 0 and 20 minutes.
    a. The error tolerance for the vacuum time is ±5 seconds.
    b. The error tolerance for the brew pressure is ±0.5 PSI.
2. The machine must detect faults and reach a safe stop-state. It must convey this error through a human-readable error code and sound a buzzer if human intervention is needed. The primary failure modes are:
    a. Loss of Solenoid Control: Given the importance of the solenoids in this project, unresponsive solenoids (caused by solenoid or driver circuit burn out) must abort the brew cycle and display the appropriate error code.
    b. Loss of Pressure: A pressure loss rate that cannot be overcome by the vacuum pump must abort the brew cycle and display the appropriate error code.
3. The machine must be able to brew a cold brew coffee in under 10 minutes using water at no more than 25℃.
    a. The error tolerance for the starting water temperature is ±5℃.
    b. The error tolerance for the brew duration is ±3 minutes.
    c. Cold brew coffee is defined as coffee that does not have the acidic taste found in hot-brewed iced coffee made from the same coffee grounds.

2. Design

This section of the report will focus on the design decisions made when implementing the subsystems that make up the machine. Before a detailed description of each subsystem, Figure 2 below serves as a visual aid of the pneumatic and electrical connections in this machine at a high level.

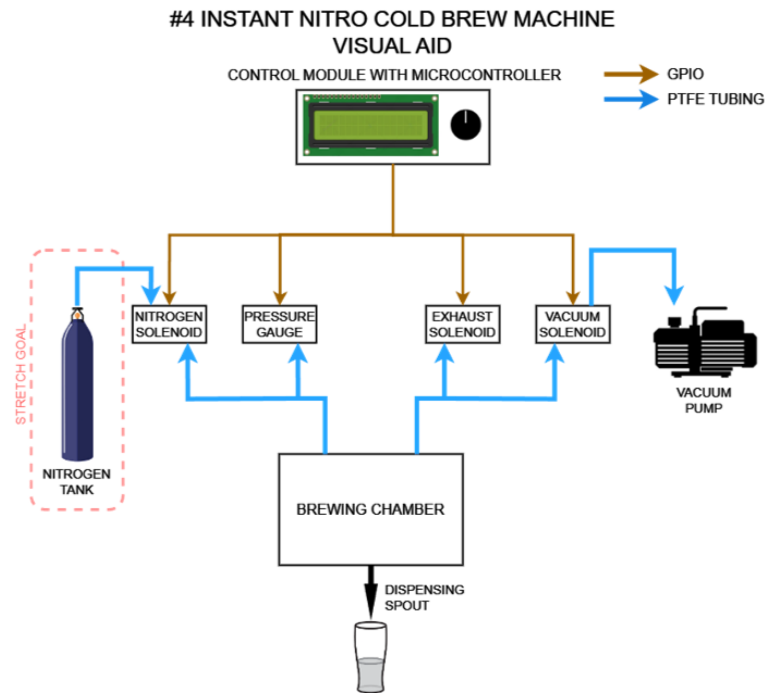

Figure 2: Visual Aid Showing the Pneumatic and Electrical Connections at a High level

The aluminum brewing chamber is connected to two essential solenoid valves. The vacuum solenoid connects and disconnects the chamber from the oil-free diaphragm vacuum pump. The exhaust solenoid is used to vent the chamber and bring it back to atmospheric pressure once a brew cycle is completed. It is also held open when dispensing coffee to allow air into the chamber as coffee leaves it. Connected to the chamber is also an analog pressure gauge used to verify the accuracy of our pressure sensor. Finally, the nitrogen solenoid was included, keeping our stretch goal of *nitro* cold brew in mind. However, this stretch goal was not implemented and the solenoid is unused in our current design.

With this background, Figure 3 below shows the block diagram of our machine. The following subsections detail the decisions made when designing each of these subsystems.

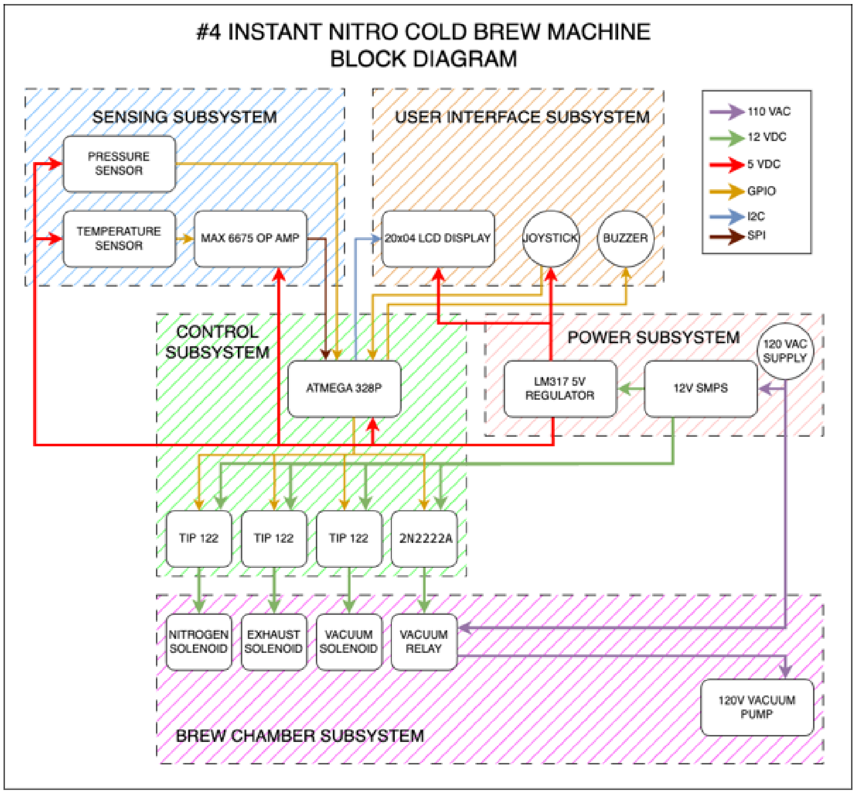

Figure 3: Block Diagram

2.1 User Interface Subsystem

The User Interface Subsystem consists of an LCD display, a 2-axis joystick, and a buzzer. Using the joystick, the user can navigate the submenus on the LCD display to view and adjust brew parameters, start and abort a brew, and view any errors the machine has detected. The buzzer provides distinct audible feedback when a brew has either completed or been aborted due to an error. The UI subsystem is connected to the Control subsystem through I2C for the LCD and GPIO for the buzzer and joystick.

While the LCD and joystick connect directly to the ATMEGA328P microcontroller in the control subsystem, the buzzer requires a transistor acting as a low-side switch to operate without overcurrenting the microcontroller's GPIO pins. Appendix A shows the connection of a 2N2222A transistor to the buzzer to act as this low-side switch.

For the best user experience, the LCD display shows essentially three main menu screens under normal conditions. The first is the "idle" menu shown when the machine boots up. Figure 4.1 below shows a graphical representation of this menu.

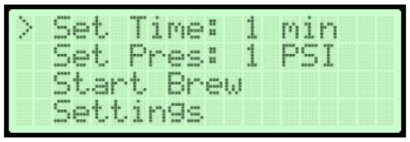

Figure 4.1: Idle Menu

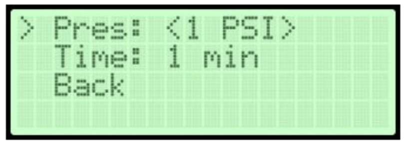

Figure 4.2 Settings Menu

Figure 4.3 Brewing Menu

To adjust brew parameters, the user can enter the settings menu shown in Figure 4.2 by scrolling down and selecting “Settings” on the Idle Menu. Using the joystick, the user can adjust brew time and brew pressure, selecting “Back” to save the brew parameters and return to the idle menu.

Finally, to start the brew, the user can select “Start Brew” on the Idle menu to enter the brewing menu shown in Figure 4.3. In this menu, the brew temperature, current chamber pressure, and time remaining are displayed. The user can only abort a brew once it has begun and can no longer adjust brewing parameters. Apart from the menus shown in Figures 4.1 to 4.3, the LCD also displays human-readable error codes on the detection of a fault. The two possible error codes are “Leak Detected” and “Solenoid Failure” as shown in Figure 5.1 and 5.2 below.

Figure 5.1: Leak Detected Error Screen

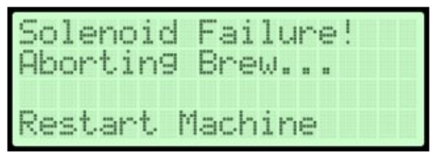

Figure 5.2: Solenoid Failure Error Screen

Fault detection is discussed in greater detail in Section 2.2.

2.2 Control Subsystem

The control subsystem houses the microcontroller used in this project, an ATMEGA328P. Using the set brew parameters from the user interface subsystem, the control subsystem actuates the solenoids and pumps in the project using data from the pressure sensor to perform the actual brew. Using TIP122 power transistors as low-side switches, the 5V microcontroller is able to switch on and off the 12V solenoids. Using a 2N2222A amplifier transistor as a low-side switch, it is also able to turn on and off a 5V relay used to power the vacuum pump. See Appendix A for a schematic of the switching circuits.

The control subsystem is responsible for maintaining accurate brew pressure in the brewing chamber, as per our first high-level requirement. It does this using our simple yet effective pressure maintenance algorithm. A flow chart of this algorithm is shown below in Figure 5.

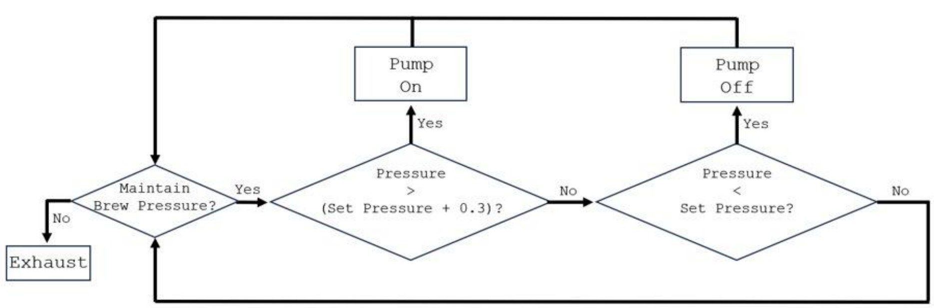

Figure 5: Pressure Maintenance Algorithm Used by the Control Subsystem

The pressure maintenance algorithm essentially turns on the pump when the chamber pressure is above the set pressure, and turns it off when the chamber pressure is at or below the set pressure. To prevent the vacuum pump and solenoid from oscillating between on and off when at the set pressure, an offset threshold of 0.3 PSI is set. Only when the chamber pressure is above the *set pressure + 0.3 PSI* does the pump turn on, and only once it's at or below the set pressure does the pump turn off. This simple algorithm was able to satisfy our requirement of the pressure not exceeding 0.5 PSI above or below the set pressure. This verification is detailed in Section 3.2

The final essential role of the control subsystem is the detection of faults. The two types of faults we check for are leaks, and unresponsive solenoids caused by burnout.

For leak detection, the control subsystem simply checks the chamber pressure at half-second intervals, and compares the last two measured values. If there is an increase in pressure, it compares the rate of increase to the maximum leak the vacuum pump can overcome. If the leak is greater than this threshold, it throws a leak detection error.

For solenoid failure, each of the driver circuits seen in Appendix A under the control subsystem includes a voltage test point that measures the voltage across each solenoid. When the solenoid is off, the voltage is 12 V, and when it is on, the voltage is 1.2 V (corresponding to the drop across the power transistor). Using a voltage divider, these voltages are stepped down to 4 V and 0.4 V for the microcontroller to read.

Finally, to save digital I/O pins on the microcontroller, a CD4051B 8:1 MUX configured as a 4:1 MUX is polled to read the voltage at the three solenoid test points, and the joystick button input.

2.3 Sensing Subsystem

To bring in the fine-tune control seen in hot coffee brewing to cold brew, the machine must be able to precisely measure and report the chamber pressure and temperature. The sensing subsystem is responsible for these measurements. Figure 6 below shows the mounting of the temperature probe and pressure sensor.

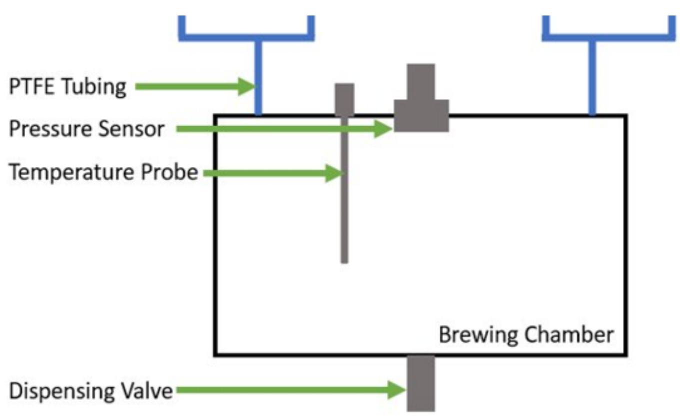

Figure 6: Temperature Probe and Pressure Sensor Mounting

The pressure sensor is a simple liquid/gas pressure transducer that threads into the chamber lid using ⅛" NPT threads. Powered by 5V, the sensor outputs an analog voltage signal that varies linearly with the measured pressure. The sensor outputs 0.5 V for a pressure of 0 PSI (perfect vacuum) and 4.5 V for 100 PSI (maximum pressure). The voltage readings scale linearly for pressure values between 0 PSI and 100 PSI. This analog voltage signal is measured using the ATMEGA328P's built-in ADC.

The temperature probe was not as simple as the pressure sensor. The probe itself is a K-type thermocouple which needs to be paired with an amplifier before the microcontroller can accurately use it to compute temperature. Our design uses the MAX6675 OpAmp to take in the voltage differential created by the thermocouple and send it to the microcontroller using the SPI protocol. An ADC on-board the MAX6675 module converts the temperature reading to a serial output of 12 bits, which can then be converted to temperature on the ATMEGA328P.

The verification of pressure and temperature sensors is detailed in Section 3.3.

2.4 Power Subsystem

The power subsystem is responsible for providing the different stable voltages needed by our design. The vacuum pump is a 120 VAC device, while the solenoids are 12 VDC and the microcontroller electronics are 5 VDC. Figure 7 below shows the components within the power subsystem that make these voltage conversions possible.

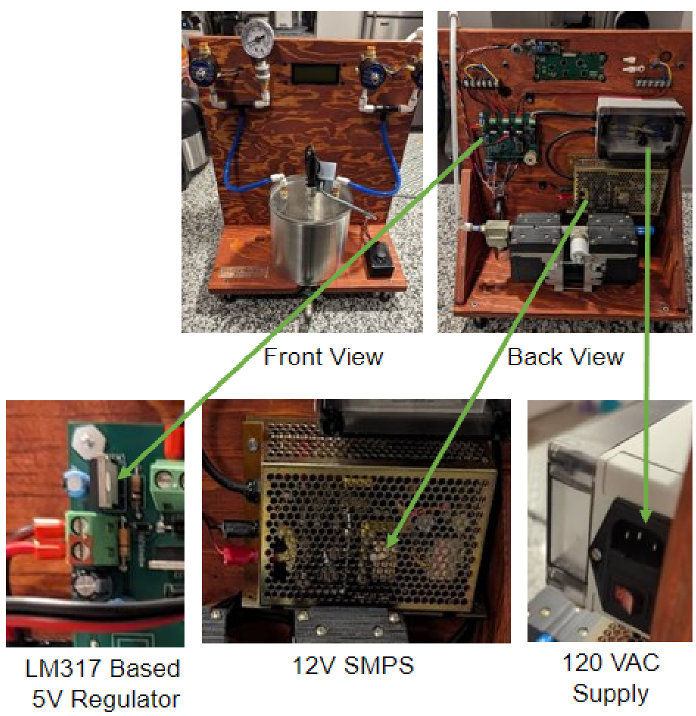

Figure 7: Power Subsystem Components

An IEC 60320 C14 connector with a 10A inline fuse is used to accept mains voltage to power the vacuum pump through the 5V relay. The 120 VAC also powers a 12 V, 7.5 A switched-mode power supply. This power supply is used to power the 12 V solenoids used in this project, along with the 5 V regulator built into the PCB. The LM317-based 5V regulator is used to provide 5V to the ATMEGA328P, LCD, joystick, and sensing subsystem. The requirements and verification of these components are detailed in Section 3.4.

2.5 Brew Chamber Subsystem

The brew chamber subsystem is the heart of this machine. The 6061 aluminum chamber holds the coffee grounds and water, along with the vacuum used to increase the extraction rate. The chamber lid is constructed from 1” thick polycarbonate sheet which threads onto the chamber. Food-safe o-rings are used on the chamber lid and bottom to maintain pressure. Keeping the stretch goal of nitrogenation in mind, the chamber was designed to hold a vacuum and positive nitrogen pressure, leading to the inclusion of threads on the chamber lid. If nitrogenation was not planned for, threads would not be needed on this lid as atmospheric pressure would be sufficient in holding the lid to the chamber.

Connected to the brew chamber are the three solenoids and analog pressure gauge. The vacuum solenoid connects to the vacuum pump and the exhaust solenoid vents into the atmosphere. The nitrogen solenoid is unused in the current design. The analog pressure gauge was used to verify the accuracy of the pressure sensor, detailed further in Section 3.3.

The biggest design consideration when designing this subsystem was the safety of the chamber in holding a vacuum of 1 PSI. Without unnecessarily oversizing the chamber, we needed a rough and empirical proof the chamber would be safe. Figure 8 below shows the mechanical drawing of our proposed chamber, and Section 3.5 details the integrity verification of this chamber.

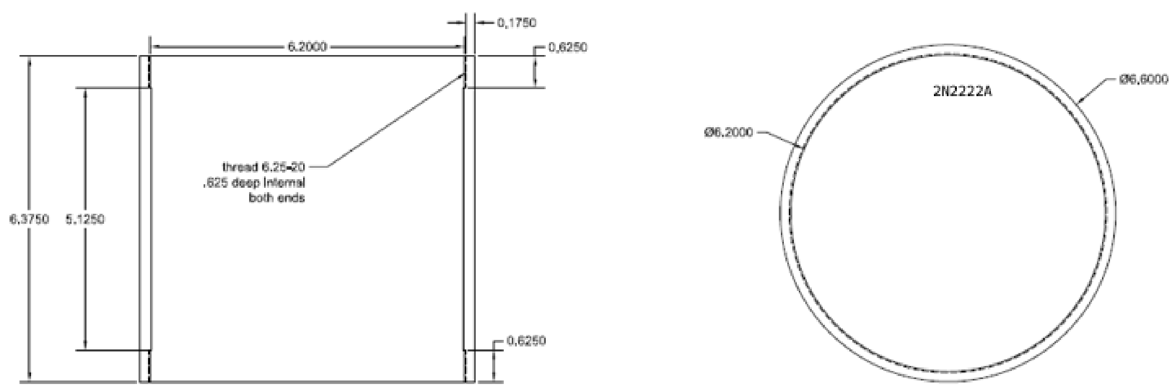

Figure 8: Mechanical Drawing of Aluminum Brew Chamber [2]

3. Design Verification

This section details the requirements for each of the subsystems mentioned in Section 2, along with the steps taken to verify that these requirements are met. The requirements and verifications mentioned here are at a higher level, only to ensure the basic functioning of the machine. Detailed requirements and verifications can be found in Appendix B.

3.1 User Interface Subsystem

3.1.1 Requirements

To provide intuitive control of the machine, the LCD shows three types of menus in normal operation, and two possible error screens when a fault is detected. The essential requirements of the UI Subsystem are thus:

1. Must allow intuitive navigation of all three normal operation menu screens and brew parameter adjustments using the 2-axis joystick and the built-in button to make selections
2. Must display error screens when a fault is detected. These screens must persist till the user acknowledges them by restarting the machine.
3. Must provide distinct audible feedback on the completion of a brew cycle or the detection of a fault.

3.1.2 Verification

These requirements were verified as follows:

1. The expected functioning of this machine ensures that this first requirement is met. To ensure validation, multiple users were requested to operate an entire brew cycle on the machine. All users were able to access all menu screens without having to restart the machine. They were also able to alter brew parameters using the X axis of the joystick.
2. To test this requirement, the artificial creation of a leak and solenoid failure was required. This is detailed in Section 3.2. On the injection of an artificial fault, the appropriate error screen was shown and this screen persisted until the machine was restarted.
3. On the injection of a fault, along with the appropriate error screen, a continuous beep 3 seconds long was produced by the buzzer. On the completion of a brew cycle, an intermittent beeping 3 seconds long was produced by the buzzer.

3.2 Control Subsystem

3.2.1 Requirements

Since the control subsystem consists of the microcontroller, it is responsible for controlling the actuators and detecting faults. Thus, the essential requirements for the control subsystem are:

1. Must be able to actuate the exhaust and vacuum solenoid along with measure the voltage test points used for solenoid failure detection (detailed in Section 3.2.2 Verification).
2. Must be able to actuate the vacuum pump using the 5V relay.

3. Must be able to compute pressure changes to detect leaks, and use voltage test point measurements to detect solenoid failures.

3.2.2 Verification

These requirements were verified as follows:

1. A test program was written to individually actuate each of the solenoids. The actuation of each solenoid was confirmed using audible feedback and through a multimeter measuring the voltage across each solenoid.
2. A test program was written to periodically actuate the vacuum pump. Initially, the switching of the relay was verified using a multimeter in continuity mode. Once the mains circuitry was complete, the actuation of the vacuum pump was verified using the analog pressure gauge on the brewing chamber
3. The verification of leak detection and solenoid failure were done as follows:
   a. Leak detection: A 1 PSI vacuum was pulled on an empty brewing chamber. The dispensing valve was then opened just enough to cause a minor leak and a leak detected error was immediately thrown.
   b. Solenoid failure: A fault injection single pole double throw switch (with center off) was included on the gate of each power transistor in the solenoid driver circuit (Appendix A, Control Subsystem). This switch can electrically override a solenoid to on or off, simulating a burnt out solenoid or power transistor. On injecting a fault, a solenoid failure error was immediately thrown.

3.3 Sensing Subsystem

3.3.1 Requirements

The sensing subsystem must accurately report the brew temperature and pressure to the control subsystem, and we set the following requirements:

1. The chamber pressure must be reported within ±0.5 PSI of the “true brew pressure.”
2. The brew temperature must be reported within ±0.5 °C of the “true brew temperature.”

3.3.2 Verification

These requirements were verified as follows:

1. The analog gauge was used to measure the “true brew pressure” and compared to the reading from the pressure sensor. The error measured at atmospheric pressure was 0.3 PSI above atmospheric pressure, and the error at a 1 PSI vacuum was 0.2 PSI above the “true brew pressure.”
2. An infrared temperature gun was used to measure the temperature of boiling water and room temperature water and compared to the readings from the temperature probe. With the boiling water, the infrared thermometer read 94.7 °C and our probe measured 94.5C. At room temperature, the infrared thermometer measured 24.3 °C and our probe measured 24.6 °C .

3.4 Power Subsystem

3.4.1 Requirements

Given that 120 VAC was supplied from a wall socket and the 12 V SMPS was a commercially purchased power supply, the only requirement in the power subsystem is that of the LM317 5V regulator.

1. The LM317 configured as a 5V regulator must be able to provide 5V from 12V at 500mA continuous current, with a voltage ripple no greater than ±0.3V.

3.4.2 Verification

This requirement was verified using an oscilloscope:

1. The voltage at the output of the LM317 with all peripherals on was measured to be 5.06 V with a ripple of 0.1 V. With the relay off, the voltage was measured to be 5.1 V with a ripple of 0.1 V.

3.5 Brew Chamber Subsystem

3.5.1 Requirements

The two requirements of the brew chamber subsystem are its structural integrity and ability to hold a vacuum of 1 PSI without leaks. The detailed requirements are:

1. The chamber must be able to hold a vacuum of 1 PSI without risk of implosion. The safety factor for fatigue stress must be five at the least.
2. The chamber must be able to hold a vacuum of 1 PSI with a leak no greater than 1.5L/min, or the flow rate of the vacuum pump at 1 PSI.

3.5.2 Verification

1. The structural integrity of the vacuum chamber was verified using a Finite Element Analysis (FEA) of a CAD model of the vacuum chamber. The material of the chamber and lid were set to 6061 Aluminum and Polycarbonate respectively. Figure 9 below shows the result of this FEA.

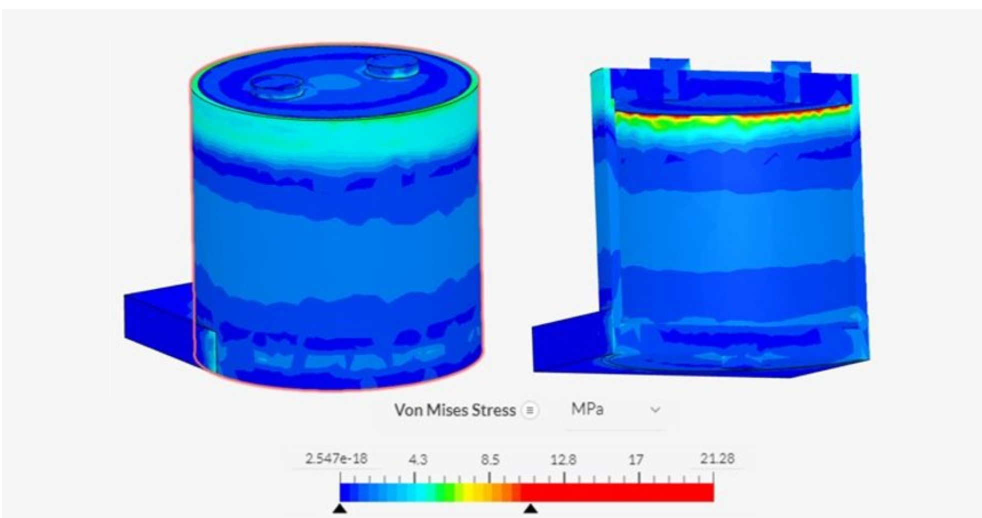

Figure 9: FEA of the 6061 Aluminum Brew Chamber with Polycarbonate Lid

The FEA indicated a peak stress of 10 MPa on the chamber. The yield stress of 6061 Aluminum is 276 Mpa and fatigue stress (after 500,000 cycles of loading and unloading) is 96.5 Mpa [3]. This gives us a minimum safety factor of 9.65, exceeding our initially proposed requirement. Additionally, this FEA assumes a 100% vacuum (0 PSI) in the chamber, while our machine only achieves a 93% vacuum (1 PSI).

2. The requirement for the maximum allowed chamber leak was set to match the flow rate of the pump at its lowest pressure, essentially eliminating a rise in pressure if the pump was kept on. However, thanks to the excellent machining from the machine shop, our chamber had a negligible leak and this requirement was easily satisfied.

4. Costs/Schedule

4.1 Components and Labor

Appendix C shows an itemized list of all costs for this project. The first section of the Appendix shows the cost of the components used by the Machine Shop, and the cost of their labor. The components used by the machine shop totalled to \$92.35, and their labor for this project was found to be \$1515.24 using Equation (1.1).

$$\$56.12/\text{hr} \times 27\text{ hrs} = \$1515.24 \tag{1.1}$$

The second section of the table shows the cost of all electronics components along with our labor costs. We found the labor cost for both of our team members to be \$18450 using Equation (1.2).

$$\$41/\text{hour} \times 2.5 \times 6\text{ hrs/wk} \times 15\text{ wk} \times 2\text{ group members} = \$18450 \tag{1.2}$$

The cost of the electrical components came out to a total of \$271.10. Given the abundance of parts in the ECE building, many of the parts for this project have been salvaged from previous projects or checked out from the Electronics Services Shop. The cost to the team for these components have been approximated. The total cost for this project is \$20328.69.

4.2 Schedule

This project, including thorough machine and user testing, was completed in a timely manner by following the detailed weekly schedule seen in Appendix D.

5. Conclusion

5.1 Accomplishments

We were able to satisfy all three of our high-level requirements along with each subsystem requirement. Most importantly, we met our requirement of being able to brew cold brew coffee in under 10 minutes using water at no more than 25 ℃. Our PCB and all of its components worked perfectly for what we had set out in our design, meaning our chamber was able to reach and maintain user-defined pressure settings for the specified time duration. On top of this, our machine is able to detect faults and reach a safe stop-state where an error code is shown that calls for human intervention. We were able to accomplish this because all of our individual subsystems were well thought out and verified to make sure they worked for the overall goal of the machine.

5.3 Ethical considerations

The main ethical matter when it comes to this project is with regard to the safety of the machine. This falls under the first section of the IEEE code of ethics, in which we must “hold paramount the safety, health, and welfare of the public” [4]. Specifically, the food safety of the machine was the biggest safety concern we dealt with when designing our project, since our final product is designed to be ingested. The chamber was constructed from 6061 aluminum with a polycarbonate lid; both of these materials are labeled as food-safe[5][6]. We also made sure to choose a dispensing spout that was labeled as food-safe[7]. All of these food-safe components that touch the coffee are cleaned using dish soap and warm water, like any other cooking utensil, between each brew. The final consideration we made for the food safety of our project was the use of an oil-free diaphragm pump. By using an oil-free pump, we eliminated the possibility of oil vapor backflow into the chamber.

Another possible safety hazard has to do with our project's use of mains AC. As we have learned from our lab training, it is of the utmost importance to make sure that there are no possible electrical hazards when operating at high voltages. To prevent any hazards, we made a waterproof distribution box in which mains voltage enters and exits through strain reliefs. All of the connections within this box were made on a terminal strip using fork thimbles. This box will prevent anyone from contacting mains voltage directly, as well as protect the high-voltage components from hazards such as spilled fluids.

5.4 Future work/Alternatives

1. **Nitrogenation:** An original stretch goal of ours was to implement nitrogenation into our Instant Cold Brew Machine. We currently have the necessary build to allow for nitrogenation, but we were unable to implement it due to budget. A nitrogen tank would connect to our brewing chamber through the nitrogen solenoid, and instead of bringing the pressure back to atmospheric we would introduce nitrogen into the chamber, further enhancing the sweet, smooth taste of cold brew coffee. A design that included nitrogenation was the main reason we used a threaded lid for our chamber. With just the current function of our design, the user experience would benefit from an easily removable lid that was pulled onto the top of the chamber by the pulling of the vacuum.

2. **Agitation:** Many current rapid cold brew machines use agitation as their primary method of brewing. These cold brew machines are just blenders in a way, but by adding this to our current design, it could result in an even more intense brew. This would be a useful fourth brewing variable, as our goal with this project was to give the user the freedom to fine-tune every aspect of the brew.
3. **Upscaling/Downscaling:** Our current design acts as a test bench for a smaller machine for the home user or a larger machine for coffee chains. By using a smaller vacuum pump that could still reach the same pressure levels, we could miniaturize this design for home use. The pump and all of the electronics would be contained in an enclosure to reduce the noise produced by the vacuum pump, making the machine more suitable for the home consumer. On the other hand, scaling up the project for coffee shops such as Dunkin’ is a real possibility. These coffee shops run out of cold brew late into the day and can no longer serve it, since they have to brew it overnight. An upscaled version of this test bench could be used by large coffee shops to continuously roll out cold brew coffee during all hours.

References

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Appendix A Circuit Schematic

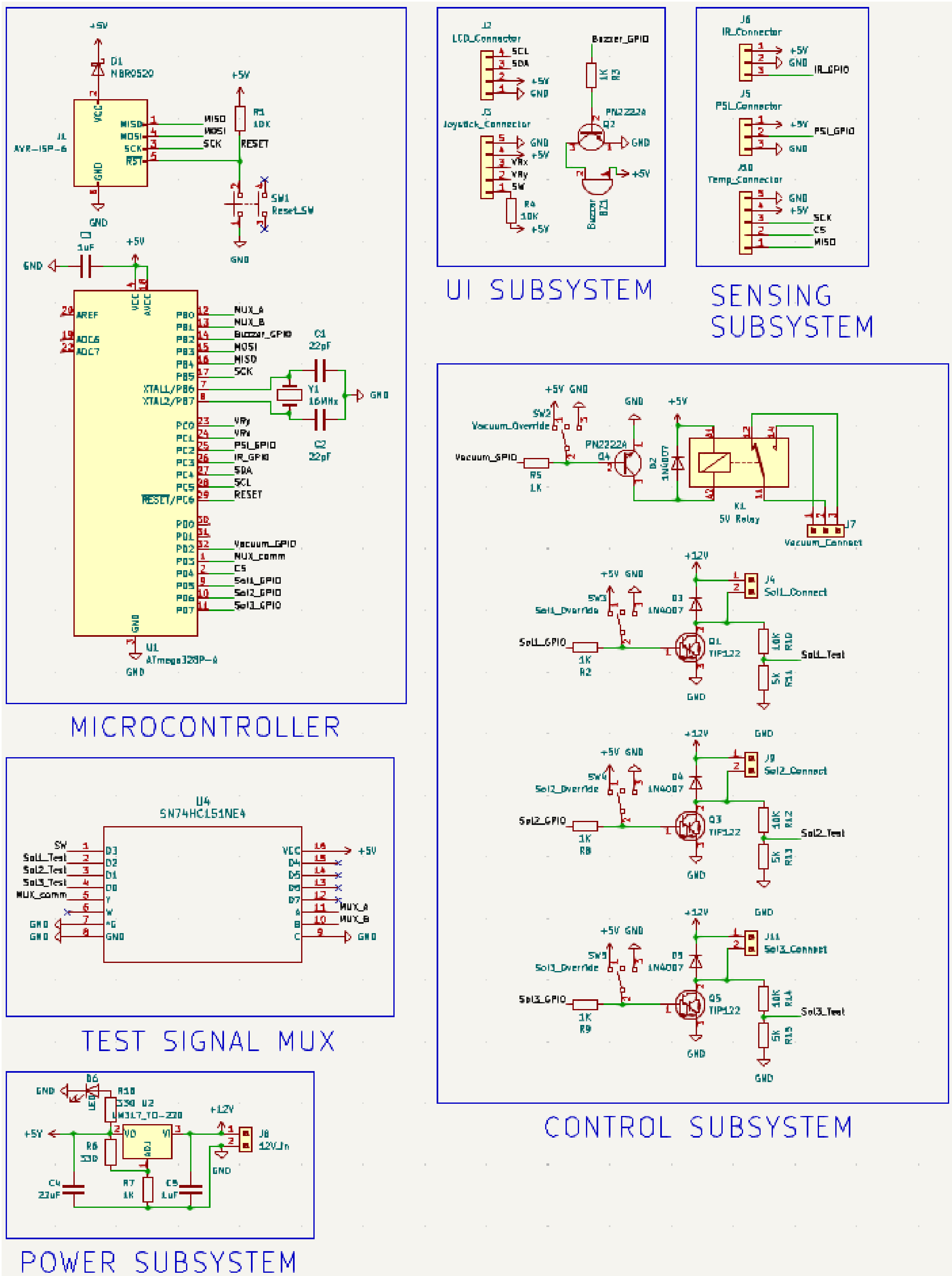

Figure 10: Circuit Schematic

Appendix B Requirement and Verification Table

Table 1 User Interface Subsystem Requirements and Verifications

Requirements	Verification	Verification status
1. The user must be able to navigate the UI using the joystick to set brew time and pressure.	1. After adjusting the brew time or pressure, the new user set time or pressure must be displayed on the “idle” screen of the UI.	Y
2. The user must be able to view the brew temperature, pressure, and time remaining on the “brewing” screen of the UI once a brew has started.	2. On starting the brew cycle, the UI must present the “brewing” screen with a constantly refreshing brew time remaining, pressure, and temperature provided by the control subsystem.	Y
3. Once a brew has started, the user must only be able to abort the brew, and not adjust brew parameters.	3. Once a brew has started, the only user selection available on the brew screen must be to abort that brew. Once aborted, the UI must return to the idle screen, where the user can adjust brew parameters.	Y
4. On detection of errors, the display must present an “error” screen with a human readable error code, with an option to acknowledge the error and restart the machine. Once restarted, the UI must present the “idle” screen.	4. Overriding the solenoids must trigger a loss of solenoid control error on the UI. Acknowledging this error through the restart button must restart the machine and present the “idle” screen.	Y

Table 2 Control Subsystem Requirements and Verifications

Requirements	Verification	Verification status
1. The Control Subsystem must be able to control the Vacuum Solenoid, Exhaust Solenoid, and Nitrogen Solenoid (if we have time for Nitrogenation)	1. Using a test program, the control subsystem will set the GPIO to the solenoid’s BJTs to HIGH sequentially. Verify that each of the solenoids is actuated as its corresponding GPIO is pulled HIGH.	Y
2. The Control Subsystem must be able to control the vacuum pump relay.	2. Using a test program, the control subsystem will set the GPIO to the relay’s BJT HIGH and then LOW after a fixed delay. When HIGH, the NO and COM pins of the relay must be connected. This will be verified	Y

	using continuity mode on a multimeter.	
3. The Control Subsystem must be able to detect unresponsive solenoids.	3. Each solenoid driver has a voltage divider to measure the voltage at the collector of the BJT. When ON, the voltage measured is logic LOW, and when OFF the voltage measured is logic HIGH. If the measured voltage does not match the expected state of the solenoid, the microcontroller must detect unresponsive solenoids. This will be verified using Serial Port debugging initially, and error handling once that is implemented.	Y
4. The Control Subsystem must be able to control the Vacuum Solenoid, Exhaust Solenoid, and Nitrogen Solenoid (if we have time for Nitrogenation)	4. Using a test program, the control subsystem will set the GPIO to the solenoid's BJTs to HIGH sequentially. Verify that each of the solenoids is actuated as its corresponding GPIO is pulled HIGH.	Y

Table 3 Sensing Subsystem Requirements and Verifications

Requirements	Verification	Verification status
1. The pressure sensor must be able to report chamber pressure within ±0.5 PSI of the "true chamber" pressure.	1. As a benchmark for accurate pressure, we will assume the pressure gauge to be "true pressure." The pressure computed by the microcontroller from the voltage signal given by the pressure sensor must be within ±0.5 PSI of the gauge pressure.	Y
2. The temperature sensor must be able to report the brew temperature within ±0.5℃ of the "true brew" temperature.	2. As a benchmark for accurate temperature, we will use an IR thermometer found in instructional labs to measure "true brew" temperature. The temperature computed by the microcontroller from the MAX6675 OpAmp must be within 0.5℃ of this reading.	Y

Table 4 Power Subsystem Requirements and Verifications

Requirements	Verification	Verification status

1. The LM317 configured as a 5V regulator must be able to provide 5V from 12V at 500mA continuous current, with a voltage tolerance no greater than ±0.3V.	1. When on the PCB, we will monitor the voltage output waveform of the 5V regulator with all peripherals ON using an oscilloscope. The nominal voltage must be 5V with a maximum ripple of 0.3V. The ripple must also be less than 0.3V as the relay is turned ON and OFF.	Y

Table 5 Brew Chamber Subsystem Requirements and Verifications

Requirements	Verification	Verification status
1. The brewing chamber can maintain a vacuum of 1 PSI without leakage above 1.5L/min.	1. A test program will turn on the vacuum pump till a pressure of 1 PSI ±0.5 PSI is detected by the pressure sensor. Once at this pressure, the vacuum solenoid will be closed and monitoring the increase in chamber pressure using the pressure sensor will indicate the leak in the chamber.	Y

Appendix C Cost Table

Table 6: Cost Table

	Machine Shop BOM				
#	**Item**	**Count**	**Unit Price ($)**	**Total Cost ($)**	**Source**
1	Threaded PTFE fittings	8	2.78	22.24	McMaster
4	PTFE Y connector/splitter	2	8.86	17.72	McMaster
5	O-ring to seal top lid	1	6.00	6.00	McMaster
6	Dispensing ball valve	1	11.14	11.14	McMaster
8	Pressure Gauge	1	14.12	14.12	McMaster
9	Female PTFE Fitting	1	4.20	4.20	McMaster
10	Aluminum Scrap Stock	4” length	*16.90	*16.90	Salvaged
11	27 Estimated Hours of Labor	27	56.12	1515.24	Labor - N/A
#	**Electronics BOM**	**Count**	**Unit Price ($)**	**Total Cost ($)**	**Source**
1	K-Type Thermocouple	1	8.29	8.29	Amazon
2	Analog Pressure Transducer	1	15.51	15.51	Amazon
3	MAX6675 OpAmp	1	3.99	3.99	Amazon
4	Oil-Free Vacuum Pump	1	132.99	132.99	Borrowed
5	12V Pneumatic Solenoids	3	*20.00	*60.00	Salvaged
6	12V SMPS	1	*9.89	*9.89	Salvaged
7	20x04 LCD Display	1	*12.24	*12.24	Salvaged
8	2-Axis Joystick	1	*2.99	*2.99	Salvaged
9	LM317 Voltage Regulator	1	*0.76	*0.76	ESS
10	TIP122 BJTs	3	*1.13	*3.39	ESS
11	2N2222A	2	*3.00	*3.00	ESS
12	ATMEGA328P	1	*2.15	*2.15	ESS
13	Buzzer	1	*0.78	*0.78	ESS
14	5V Relay	1	*1.10	*1.10	ESS
15	AVR ISP 6 Pin Connector	1	*0.10	*0.10	ESS
16	Phoenix Contacts	5	*0.76	*3.80	ESS

17	Molex Connectors	4	*0.27	*1.08	ESS
18	16MHz Crystal	1	*0.32	*0.32	ESS
19	22pF Capacitors	2	*0.37	*0.74	ESS
20	10uF Capacitors	1	*0.30	*0.30	ESS
21	1uF Capacitors	2	*0.10	*0.10	ESS
22	22uF Capacitors	2	*0.32	*0.64	ESS
23	1K Ohm Resistor	5	*0.10	*0.10	ESS
24	5K Ohm Resistor	3	*0.09	*0.27	ESS
25	10K Ohm Resistor	3	*0.10	*0.30	ESS
26	330 Ohm Resistor	3	*0.10	*0.30	ESS
27	SPDT Switches w/ Center Off	1	*2.45	*2.45	ESS
28	CD4051B	1	*0.52	*0.52	ESS
	Machine Shop Component Cost:	$92.35			
	Machine Shop Labor Cost:	$1515.24			
	Electronics Components Cost:	$271.10			
	Labor per Team Member ($41/hour*2.5*6*15):	$9225.00			
	Labor Cost for Two Teammates:	$18450.00			
	Total Project Cost:	$20328.69			

All costs labeled with a (*) are estimated prices since these parts were either salvaged, borrowed or checked out from ESS

Appendix D Schedule

9/25	Finish first draft of PCB and send it to ESS. Figure out I2C control of LCD Display and integrate with joystick readings.	Both
10/2	Identify errors in the PCB first draft. Resolve using wires and fix PCB for first round PCB ordering.	Mihir
	Get menu navigation working with dummy pages on the LCD Display.	Danis
10/9	Move off the development board and entirely onto the fixed PCB. Submit a new PCB order if there are significant fixes needed.	Both
10/16	Design closed loop control system for vacuum pump pressure maintenance.	Mihir
	Implement an entire state machine in C excluding closed loop control.	Danis
10/23	Integrate state machine with menu navigation.	Mihir
	Accurately display pressure, temperature, and time remaining on LCD.	Danis
10/30	Begin testing the entire machine without fault detection, brew coffee and finalize any mechanical changes with Gregg.	Both
11/6	Work with Danis on initial implementation of failure modes, move to validation as basic development is complete.	Mihir
	Implement detection of both failure modes.	Danis
11/13	Integrate failure mode detection into the state machine and develop failure code schema.	Both
11/20	Work on objective characterization of brew intensity. Work with regular cold brew drinkers to understand the nature of brew this machine is capable of.	Both
	Validation of failure modes in all possible machine states.	Both
11/27	Resolve any remaining bugs/final touch-ups/prepare and practice presentation.	Both
12/4	Final Demo.	Both