ECE 445 Senior Design

Fall 2023

# Instant Cold Brew Machine

## Design Document

Project #4
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# Contents:

# 1. Introduction

## 1.1. Problem

Cold brew is made by steeping coffee grounds in cold water for 12-18 hours. This low-temperature steeping extracts fewer bitter compounds than traditional hot brewing, leading to a more balanced and sweeter flavor. While cold brew can be prepared in big batches ahead of time and stored for consumption throughout the week, this solution would make it impossible for someone to choose the specific coffee beans and brew they desire for that very morning. The proposed machine will be able to brew coffee in cold water in minutes by leveraging air pressure. The machine will also bring the fine-tuning and control of brewing parameters currently seen in hot brewing to cold brewing.

## 1.2. Solution

The brew will take place in an airtight aluminum chamber with a removable lid. The user can drop a tea-bag like pouch of coffee grounds into the chamber along with cold water. By pulling a vacuum in this chamber, the boiling point of water will reduce significantly and allow the coffee extraction to happen at the same rate as hot brewing, but using cold water. Next, instead of bringing the chamber pressure back to atmospheric with ambient air, nitrogen can be introduced from an attached tank, allowing the gas to dissolve in the coffee rapidly. The introduction of nitrogen will prevent the coffee from oxidizing, and allow it to remain fresh indefinitely. When the user is ready to dispense, the nitrogen pressure will be raised to 30 PSI and the instant nitro cold brew can now be poured from a spout at the bottom of the chamber.

The coffee bag prevents the coffee grounds from making it into the drink and allows the user to remove and replace it with a bag full of different grounds for the next round of brewing, just like a Keurig for hot coffee.

To keep this project feasible and achievable in one semester, the nitrogenation process is a reach goal that we will only implement if time allows. This design document will not include specific details of the nitrogenation process.

### 1.3. Visual Aid

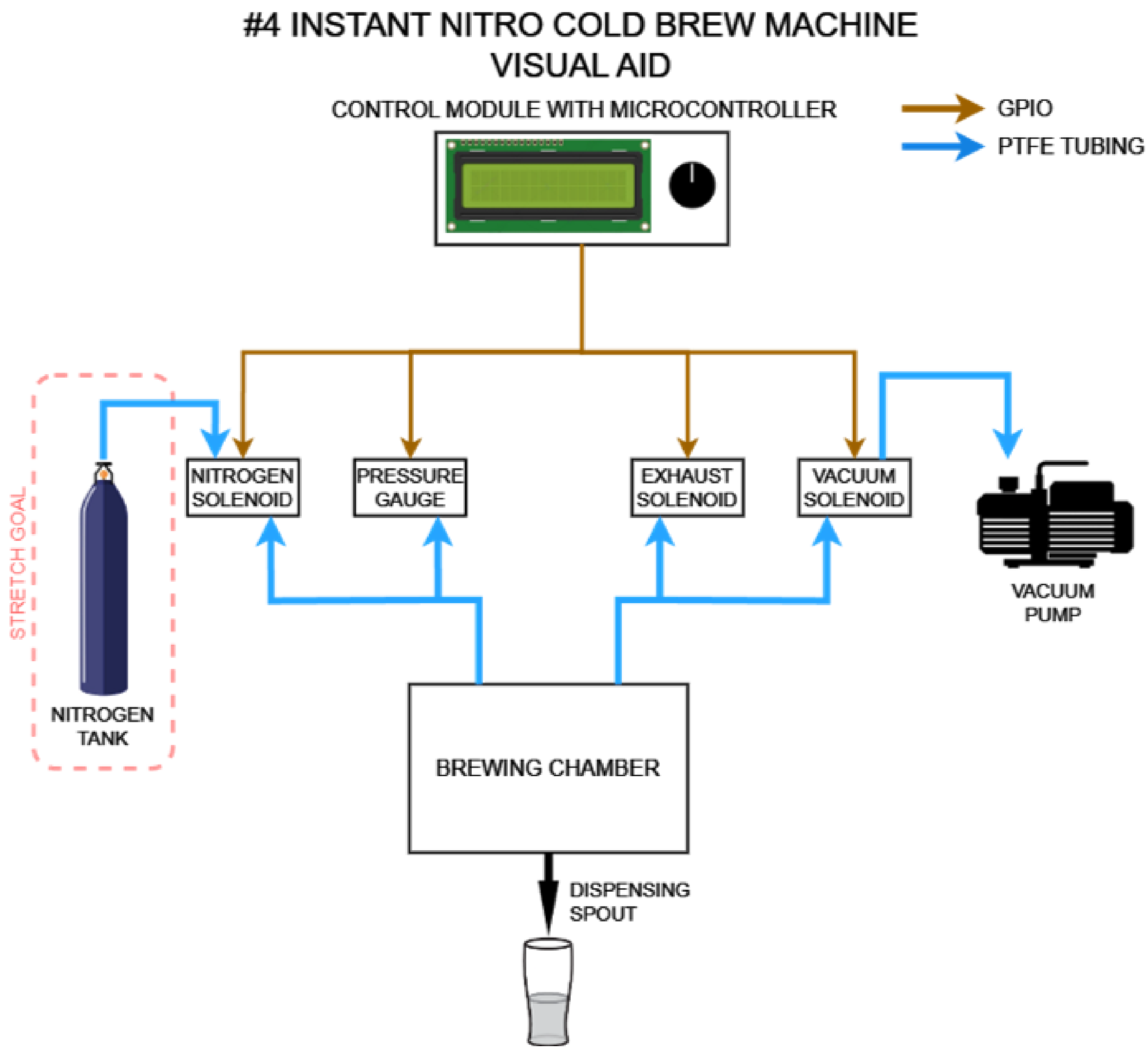


Figure 1: Visual Aid

### 1.4. High-Level Requirements

The main goal of this machine is to brew a cup of cold brew in a similar time frame as hot coffee brewing. This is accomplished by reducing the pressure at which the brewing occurs, allowing the water to start boiling at lower temperatures. Figure 2 below shows the boiling point of water (in ℃) as a function of pressure (in PSI).

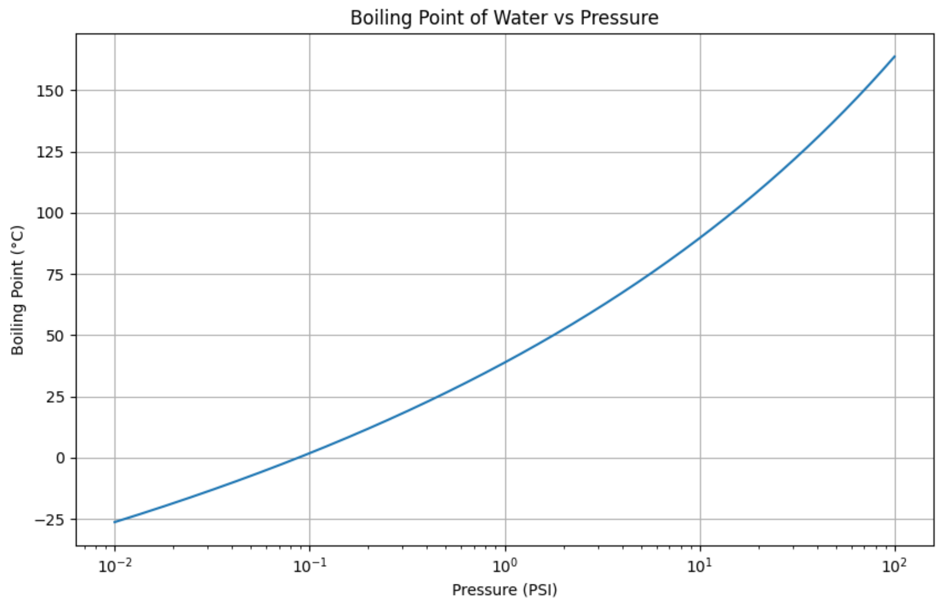


Figure 2: Boiling Point of Water Vs. Pressure

To match the brewing rate for hot coffee, the vacuum pump would need to achieve a complete boil of water at room temperature. From the plot above, the pressure required to do so is 0.44 PSI. While this would be ideal, the sourced oil-free vacuum pump is not capable of reaching such a low pressure, and can achieve vacuum of 1.4 PSI. While water boils at ~40℃ at 1.4 PSI, the rate of coffee extraction is still greatly increased. An initial test conducted with this vacuum pump confirmed that it is capable of brewing cold brew using water at 30℃ in ~3 minutes. Additionally, while the fastest brew will occur at the lowest pressure, the machine must allow the user to brew at pressures up to 7 PSI. This control of the brew pressure would allow a coffee enthusiast to precisely control the rate of extraction, and compare the flavors produced.

With this background, our **High-Level Requirements are:**

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 brew time is ±5 seconds.
    b. The error tolerance for the brew pressure is ±0.5 PSI.
2. A successful instant cold brew 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.
3. 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 must trigger the buzzer and call for human intervention to shut down the machine.
    b. Loss of Pressure: Once the chamber is constructed, a nominal leak rate will be established. A pressure loss rate 20% above the nominal leak rate must abort the brew cycle and display the appropriate error code.

# 2. Design

## 2.1. Functional Overview and Block Diagram

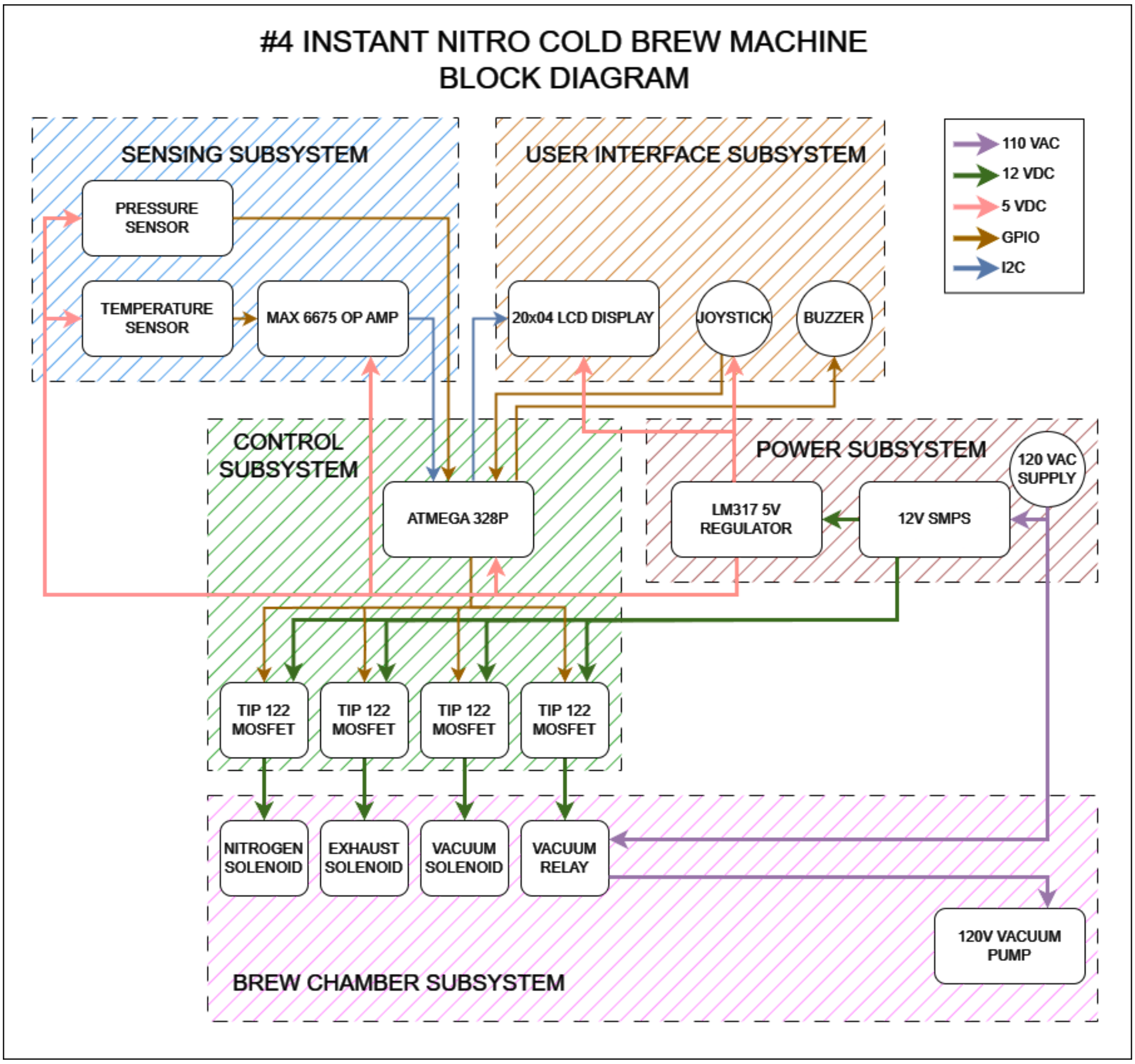


Figure 3: Block Diagram

### 2.1.1. Control Subsystem

This subsystem contains the microcontroller for this machine. It stores the brew parameters input given by the user through the UI, and runs through the different states of the machine. Using the TIP122 MOSFETs, the control subsystem can control the vacuum solenoid, exhaust solenoid, and nitrogen solenoid. Similarly, using the 2N2222A BJT, the control subsystem can control the vacuum pump relay. It uses measurements from the sensing subsystem to compute the brew temperature, and maintain the correct chamber pressure using the vacuum pump. The control subsystem also exits the brewing phase once the user set brew time has elapsed.

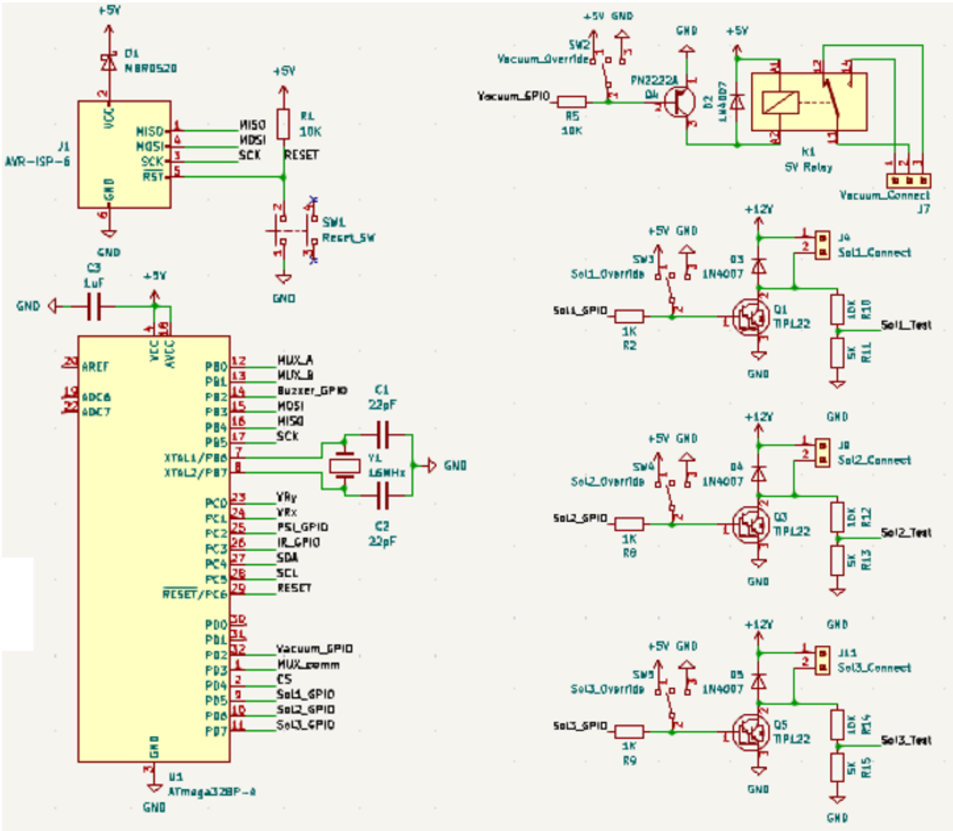


Figure 4: Control Subsystem Schematic

| **Requirements** | **Verification** |
|---|---|
| The Control Subsystem must be able to control the Vacuum Solenoid, Exhaust Solenoid, and Nitrogen Solenoid (if we have time for Nitrogenation) | 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. |
| The Control Subsystem must be able to control the vacuum pump relay. | 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 using continuity mode on a multimeter. |
| The Control Subsystem must be able to | Each solenoid driver has a voltage divider to |

| | |
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| detect unresponsive solenoids. | 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. |

### 2.1.2. Brew Chamber Subsystem

The brewing subsystem consists of the valves and vacuum pump. When the vacuum pump is powered off, air can leak into the chamber through the pump's exhaust port. The vacuum solenoid valve is used to cut off the connection to the vacuum pump when it is not on to prevent such a leak. The relay used to control the vacuum pump is a 5V relay capable of switching up to 5A at 250V. Finally, the exhaust solenoid is a safety mechanism used to release any pressure in the chamber in the case that an error is detected. By opening this solenoid, any vacuum in the chamber can be released. The exhaust solenoid will also need to be opened when dispensing the coffee. See 2.2 Physical Design for a mechanical drawing of this subsystem.

| **Requirements** | **Verification** |
|---|---|
| The brewing chamber can maintain a vacuum of 1 PSI without leakage above 5L/min. | 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. |

### 2.1.3. Sensing Subsystem

The sensing subsystem is responsible for measuring the pressure and temperature in the brewing chamber. The pressure sensor selected has a linear analog output and can be connected directly to the Control subsystem. The selected temperature sensor is a K-type thermocouple and will communicate to the Control subsystem using SPI through the MAX6675 OpAmp.

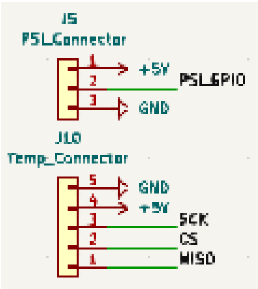


Figure 5: Sensing Subsystem Schematic Showing Molex Connectors for Pressure Sensor and MAX6675 OpAmp Module.

| **Requirements** | **Verification** |
|---|---|
| The pressure sensor must be able to report chamber pressure within ±0.5 PSI of the "true chamber" pressure. | 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. |
| The temperature sensor must be able to report the brew temperature within ±0.5℃ of the "true brew" temperature. | 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. |

### 2.1.4. User Interface Subsystem

This subsystem allows the user to interact with the brew settings of the machine. Using a 2-axis joystick with a built-in push-button, the user can navigate a menu to set their desired brew pressure, brew time and view the brew temperature and time remaining.

The UI also displays the human readable error codes when the machine detects a fault. The buzzer is used to notify the user when the brew is complete, or when there is an error that needs user intervention.

The UI subsystem is connected to the Control subsystem through I2C for the LCD Display and GPIO for the buzzer and joystick.

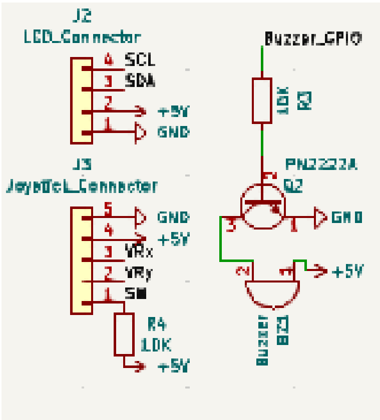


Figure 6: UI Subsystem Schematic

| Requirements | Verification |
|---|---|
| The user must be able to navigate the UI using the joystick to set brew time and pressure. | After adjusting the brew time or pressure, the new user set time or pressure must be displayed on the “idle” screen of the UI. |
| 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. | 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. |
| Once a brew has started, the user must only be able to abort the brew, and not adjust brew parameters. | 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. |
| On detection of errors, the display must present an “error” screen with a human | Overriding the solenoids must trigger a loss of solenoid control error on the UI. |

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|---|---|
| readable error code, with an option to acknowledge the error and restart the machine. Once restarted, the UI must present the "idle" screen. | Acknowledging this error through the restart button must restart the machine and present the "idle" screen. |

### 2.1.5. Power Subsystem

The power subsystem is responsible for providing the 12VDC for the solenoids and the 5VDC for the Control and Sensing subsystems. A 70W 12V SMPS is used to bring 110AC down to 12VDC to power the solenoids. An LM317 configured as a 5V regulator is used to bring the 12VDC down to 5VDC to power the Control and Sensing subsystems.

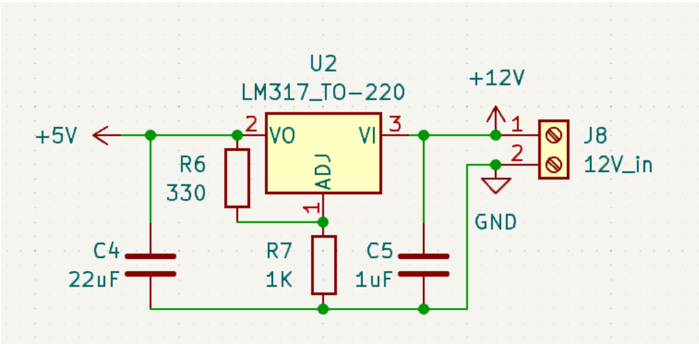


Figure 7: Power Subsystem Schematic. Not pictured here is the 12V SMPS.

| **Requirements** | **Verification** |
|---|---|
| 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. | 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. |

### 2.2. Physical Design

The physical design of the vacuum chamber and its solenoid connections plays a pivotal role in the success of this project. Figure 1: Visual Aid provides a complete depiction of the pneumatic connections to and from the chamber, and how the solenoid valves isolate the chamber throughout different phases of the brewing process.

a. The chamber walls and base are machined from 6061 aluminum, and the top is made from 1” polycarbonate sheet to look into the chamber.
b. The top and bottom are threaded onto the cylindrical chamber and sealed using a vacuum rated o-ring.
c. Pneumatic PTFE connectors are threaded into the polycarbonate top using NPT threads to prevent leaks, and will be wrapped with teflon tape. All fittings are rated for a vacuum environment.
d. The temperature and pressure sensors are also threaded into the polycarbonate top, and are rated for a vacuum environment.
e. Thick walled 5/16” PTFE tubing is used to connect to the chamber and is rated to carry a vacuum.

Figure 8 below shows the mechanical drawings for the vacuum chamber. The final thickness of the aluminum chamber will be determined by the Machine Shop after they complete their roughing passes. The minimum thickness is 6mm, and will be used for the FEA simulation in 2.3 Tolerance Analysis.

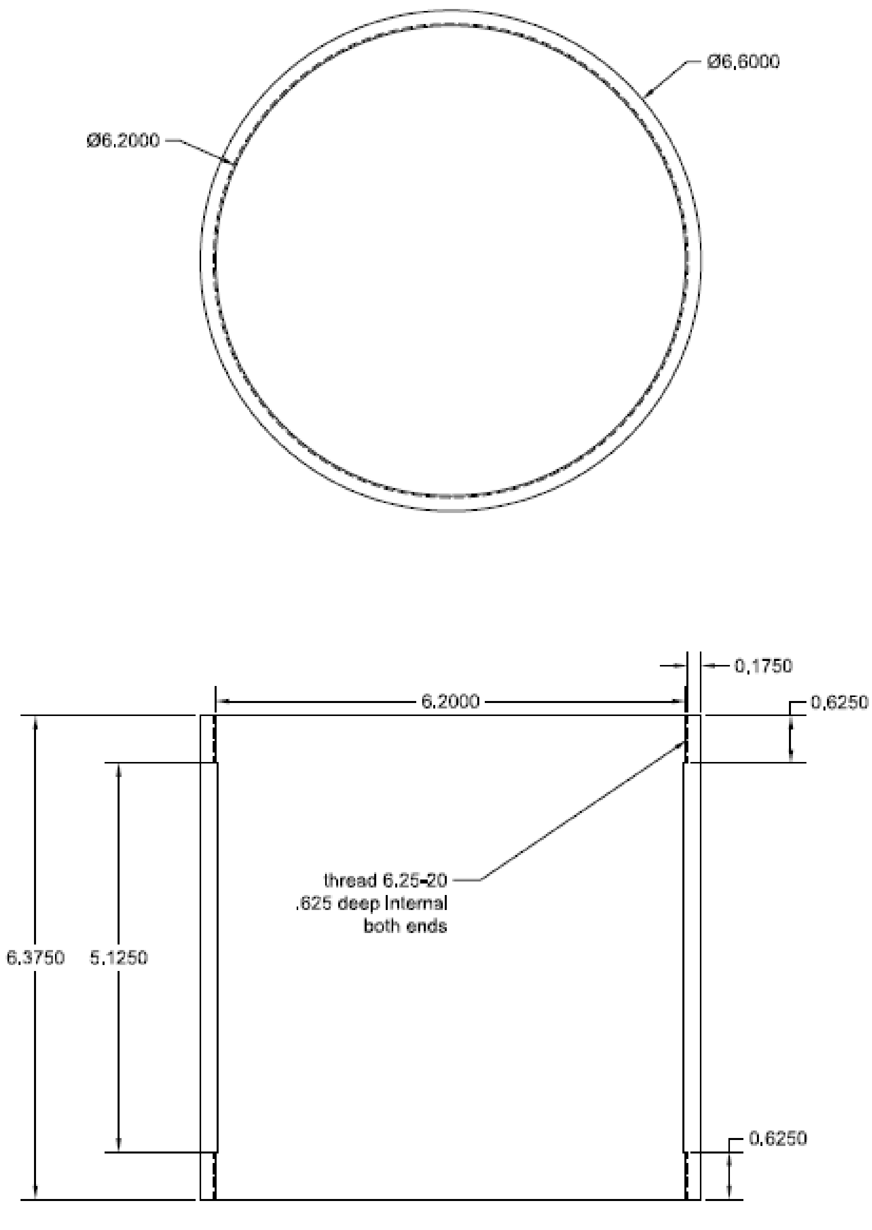


Figure 8: Vacuum Chamber Mechanical Drawing [3]

### 2.3. Tolerance Analysis

Most critical to the success of this project and the safety of its users is the vacuum chamber. When the chamber is at ~0.4 PSI, there exist significant radial and axial loads on the chamber exerted by the atmosphere. The stress on the different materials comprising the vacuum chamber must not exceed their yield stress by a large safety margin.

Initial verification of the chamber design was a rough approximation through hand calculation:

$$radius = \frac{160mm}{2} = 0.08m$$

$$thickness = 6mm = 0.006m$$

$$Atmospheric\ Pressure = 1\ bar = 10^5 Pa$$

$$\text{p = External Pressure, R = radius, t = thickness}$$

$$Circumferential\ Stress = \sigma_\theta = \frac{pR}{t}$$

$$\sigma_\theta = \frac{(10^5 Pa)(0.08m)}{(0.006m)} = 1.\overline{33}\ MPa$$

$$The\ chamber\ is\ closed\ with\ 6mm\ aluminum\ caps,$$

$$Axial\ Force\text{: } F = PA = (10^5 Pa)(\pi R^2) = 2010.619\ N$$

$$Axial\ Stress(\sigma_e) = \frac{1}{2}[3(\frac{pR}{t})^2 + (\frac{F}{\pi Rt})^2]^{\frac{1}{2}}$$

$$Substituting\ values,\ \sigma_e = 1.\overline{33}\ MPa$$

To confirm the mechanical integrity of this design, a Finite Element Analysis (FEA), Figure 9 below, was performed on a CAD model of the vacuum chamber. The chamber material was set to be 6061 Aluminum, the top to be Polycarbonate, and brass plugs inserted to simulate the effect of threaded fittings.

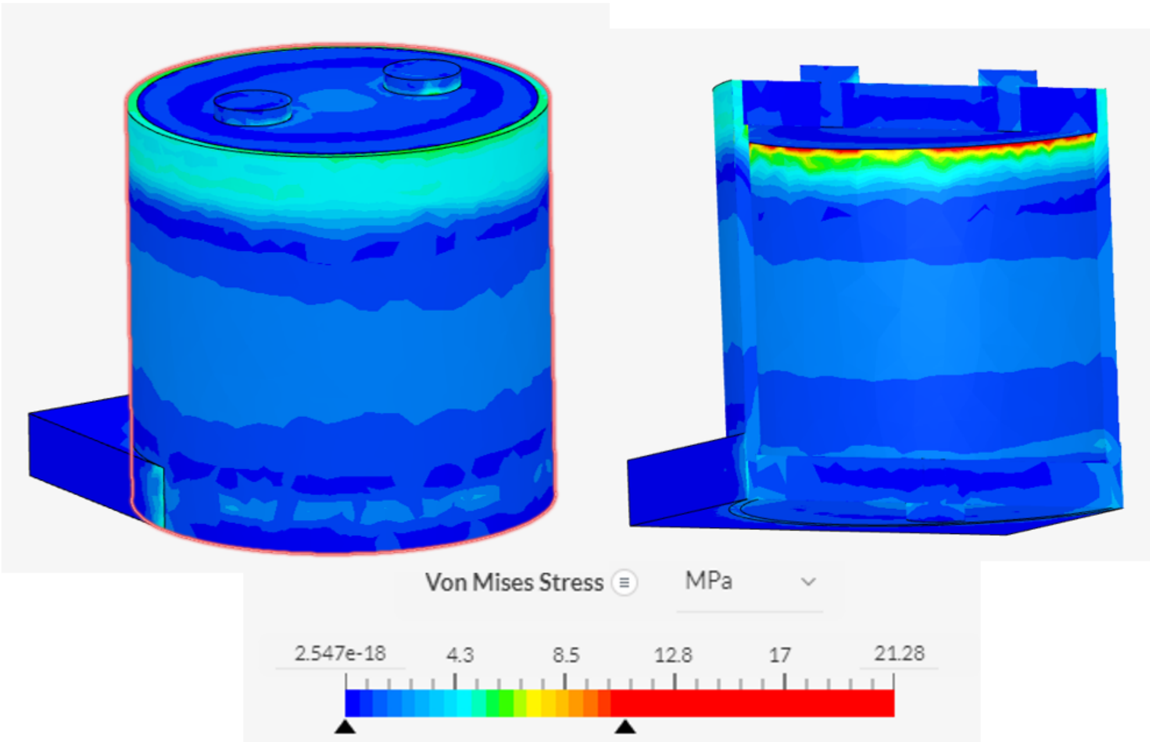


Figure 9. FEA of Vacuum Chamber showing a complete and cross-sectional view

The yield stress of 6061 Aluminum is ~240 MPa. The fatigue stress, evaluated over 500,000 load cycles is ~100 MPa. The FEA results show the greatest stresses to be less than 10 MPa, giving us a safety factor of ~10 for fatigue stress, and ~24 for yield stress. Not only is this safety margin very large, the FEA was performed assuming a perfect vacuum. In reality, the vacuum chamber will drop to a maximum vacuum of 0.4 PSI, or 97.4% vacuum.

## 3. Cost Analysis

Figure 10 below shows an itemized list of all costs for this project. The first section shows the cost of the components used by the Machine Shop, and the cost of their labor. The second section shows the cost of all electronics components. The final tally includes the team's labor cost at $41/hour for each teammate.

Given the abundance of parts in the ECE building, a lot 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 marked as $0. The total cost for this project is $20,076.45.

| | **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 | 6 | 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 | 4.2 | 4.2 | McMaster |
| 10 | Aluminum Scrap Stock | N/A | N/A | 0 | 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 | 11.99 | 11.99 | Amazon |
| 4 | Oil-Free Vacuum Pump | 1 | 0 | 0 | Borrowed |
| 5 | 12V Pneumatic Solenoids | 3 | 0 | 0 | Salvaged |
| 6 | 12V SMPS | 1 | 0 | 0 | Salvaged |
| 7 | 20x04 LCD Display | 1 | 0 | 0 | Salvaged |
| 8 | 2-Axis Joystick | 1 | 0 | 0 | Salvaged |
| 9 | LM317 Voltage Regulator | 1 | 0 | 0 | ESS |
| 10 | TIP122 BJTs | 3 | 0 | 0 | ESS |
| 11 | 2N2222A | 2 | 0 | 0 | ESS |
| 12 | ATMEGA328P | 1 | 0 | 0 | ESS |
| 13 | Buzzer | 1 | 0 | 0 | ESS |
| 14 | 5V Relay | 1 | 0 | 0 | ESS |
| 15 | AVR ISP 6 Pin Connector | 1 | 0 | 0 | ESS |
| 16 | Phoenix Contacts | 5 | 0 | 0 | ESS |
| 17 | Molex Connectors | 4 | 0 | 0 | ESS |
| 18 | 16MHz Crystal | 1 | 0 | 0 | ESS |
| 19 | 22pF Capacitors | 2 | 0 | 0 | ESS |
| 20 | 10uF Capacitors | 1 | 0 | 0 | ESS |
| 21 | 1uF Capacitors | 2 | 0 | 0 | ESS |
| 22 | 22uF Capacitors | 2 | 0 | 0 | ESS |
| 23 | 1K Ohm Resistor | 5 | 0 | 0 | ESS |
| 24 | 5K Ohm Resistor | 3 | 0 | 0 | ESS |
| 25 | 10K Ohm Resistor | 3 | 0 | 0 | ESS |
| 26 | 330 Ohm Resistor | 3 | 0 | 0 | ESS |

| | | | | | |
|---|---|---|---|---|---|
| 27 | SPDT Switches w/ Center Off | 3 | 0 | 0 | ESS |
| 28 | CD4051B | 1 | 0 | 0 | ESS |
| | | | | | |
| | **Machine Shop Component Cost:** | 75.42 | | | |
| | **Machine Shop Labor Cost:** | 1515.24 | | | |
| | | | | | |
| | **Electronics Components Cost:** | 35.79 | | | |
| | **Labor per Team Member ($41/hour*2.5*60):** | 6150 | | | |
| | **Labor Cost for Two Teammates:** | 12300 | | | |
| | | | | | |
| | **Total Project Cost:** | $20076.45 | | | |

Figure 10: Cost Analysis

## 4. 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 a local barista in understanding 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 |

# 5. Ethics and Safety

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"[2]. One safety hazard is the possibility of a burnt BJT. If the BJT overheats, there is a possibility of the solenoid getting stuck in the on or off position. We will solve this using a safety precaution built into the microcontroller that will use a voltage divider to monitor the voltage across the solenoid. This will allow us to end the procedure by use of the exhaust solenoid. Using this exhaust solenoid, there will also be safety measures in place to protect from abnormal amounts of pressure in the chamber. These measures will all be indicated by error codes that appear on the LCD display.

Another concern with our project is related to the use of nitrogen gas. We are using nitrogen with the purpose of infusing the coffee with it to achieve a flavor many coffee lovers desire. We must handle the nitrogen tank with care and make sure to never release large amounts of nitrogen in an indoor environment. While nitrogen gas makes up most of the air we inhale, releasing large amounts in enclosed environments can be dangerous. For this reason the nitrogen tank is equipped with a main shut off valve that we will use to control the amount of nitrogen to be released. For this project, the amount of nitrogen that would ever be exhausted into the atmosphere would create a negligible impact on the air around the machine.

Other than these safety concerns, there are many ethical matters that we must take into account when working on this project. The IEEE code of ethics provides the standard for us as engineers. Some important points to emphasize from the code that pertain to our project are "to seek, accept, and offer honest criticism of technical work" and "treat all persons fairly and with respect" [2]. An important aspect of the project is seeking criticism and looking for help. We will be constantly searching for people to help with specific aspects of the project such as the writing and mechanical components. It is also important that we are in consistent contact with our TA to hear and discuss criticisms of the project. Looking for help also ties into treating everybody involved with respect. This project involves many people who all must be treated with respect at all times. We must not only uphold the standards set by the IEEE, but also go beyond and practice good ethics in all scenarios, even those not outlined by the code of ethics.

## 6. Citations


1) C. Hauviller, 2007. Design Rules for Vacuum Chambers. https://cds.cern.ch/record/1046848/files/p31.pdf
2) IEEE Code of Ethics, IEEE, 2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html
3) Bennett, G. L. (2023). Drawing. Vacuum Chamber Mechanical Drawing. Urbana.