In-Home Cold Brew Coffee Maker

Sponsored by Keurig Dr. Pepper Inc.

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December 9th, 2022

Introduction and Project Overview

The Keurig In-Home Cold Brew Coffee Maker student team has spent the past year developing an autonomous nitrogen cold brew coffee machine. This project is sponsored by Keurig Dr. Pepper Inc., who is interested in joining the at-home cold brew market. Cold brew coffee has been rising in popularity in recent years, offering Keurig a unique opportunity to expand its current at-home pod-based line of coffee products to include cold brew based products.

Keurig Dr Pepper Inc. requested that our team, through the Multidisciplinary Design Program at the University of Michigan, design a coffee machine with the ability to cool water, mix cold brew concentrate with water, and infuse this coffee mixture with nitrogen gas to create a dense foam at the top. The system utilizes three main subsystems to operate: cooling, nitrogenation, and power. Along with this are two subassemblies: pumping and mixing.

Market Research

Cold brew has become one of the most popular trends in coffee. The market for cold brew was valued at around $321 million in 2017, but is expected to increase to $1.37 billion by 2023 [1]. Nitro cold brew, however, is a niche form of cold brew with a unique texture and crema-like foam that is also increasing in popularity. Nitro cold brew specifically had a market value of approximately $523 million in 2020 with a projected increase to $1.63 billion in 2025 [2]. With the increasing demand, Keurig hopes to expand their product line to include cold brew products.

There are currently no products on the market that accomplish all tasks Keurig wanted from our team; a machine that cooled water instead of heating it up, mixed it with liquid cold brew concentrate, and then infused the chilled liquid with gas. However, there are some products that can perform the required functions individually.

There are several commercialized gas infusion machines, the most common being the SodaStream, which can inject a liquid with carbon dioxide. Another less common at-home gas infusion machine is the BubblingPlus Surprise Bottle, as shown in Figure 1. This is a patented gas infusion design compatible with carbon dioxide, nitrous oxide, and single-serving gas canisters. At-home cold brew machines exist, but can take 18-24 hours to brew the coffee. Keurig has had a few past attempts at cold or iced coffee machines, like the Keurig Kold. This machine cooled water and combined with a pod containing carbonator beads and flavored syrup to produce a chilled glass of soda. This machine was reportedly discontinued due to customer complaints about the size, noise, price, and quality of drinks produced [3]. These competitors and previous machines were used as benchmarks while the team generated our novel system.

Figure 1. *BubblingPlus Surprise Bottle*

Scope

The team has designed a system capable of cooling, nitrogenating, and mixing the contents of a given cold brew concentrate pod with water. The concentrate pod design was out of scope. The functionality and integration of cooling and nitrogenation subsystems were of primary importance throughout the project. The output beverage appearance was secondary, and the taste was out of scope, as the concentrate was provided and the final product could not be tasted for safety reasons. The final deliverable will take the form of a functional benchtop process, as designing a market-ready consumer appliance was out of scope. In general, the team has been encouraged to explore novel solutions to add value to the final design; therefore, scope restrictions were limited.

Methods

The team (1) identified requirements, constraints, and standards, (2 brainstormed an initial design concept for nitrogenation, cooling, and mixing, and (3) focused on initial project management and planning for the winter semester. In the fall semester, the team focused on design development, prototyping, and verification, as shown in Fig. 2.

Project Procedure and Schedule

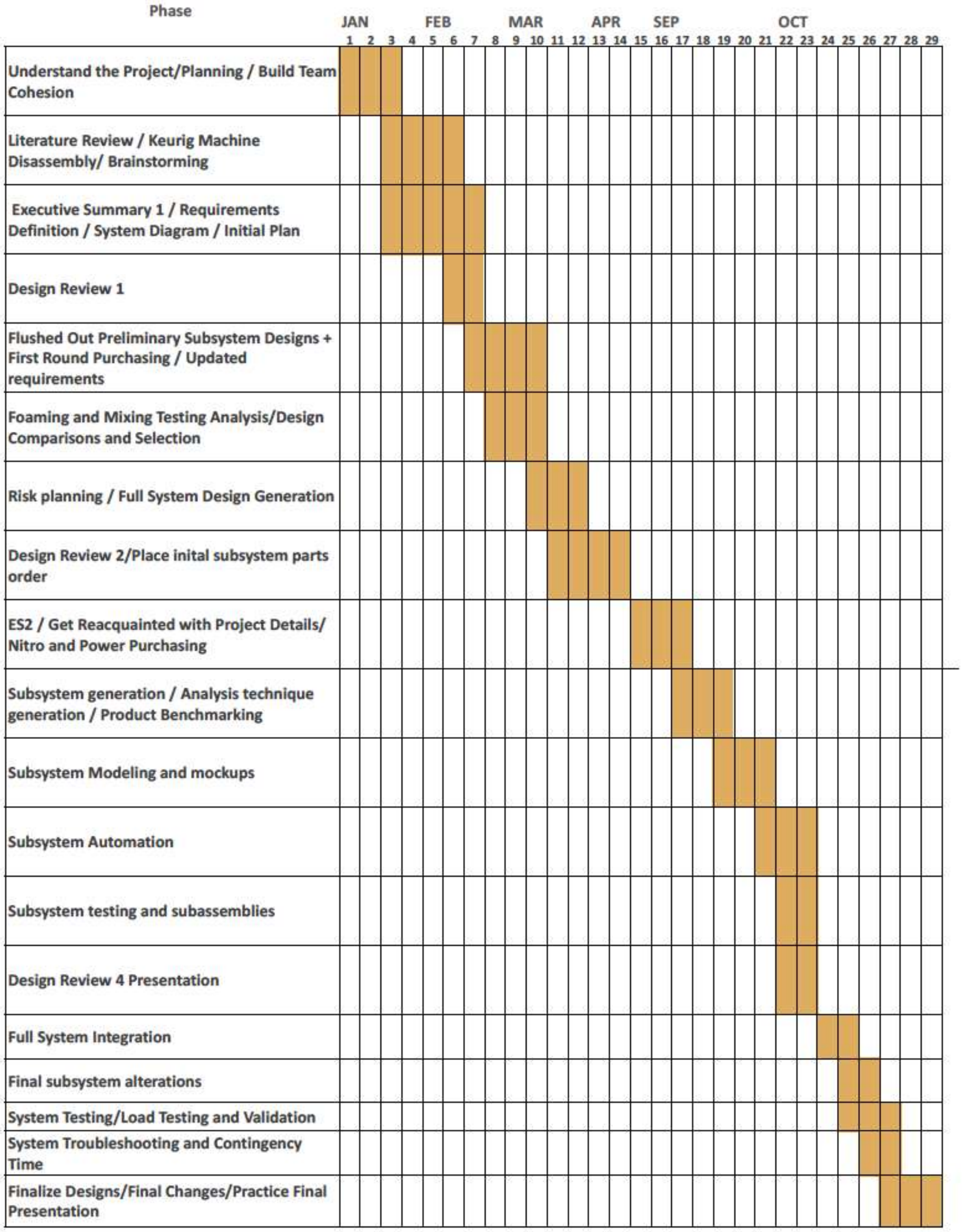


Figure 2. *Full Year Gantt Chart*

Our project started with a literature review ('Executive Summary 1'), where the team completed research on several different topics related to the project. These topics included 'Fluid Mixing and Pumping,' 'Fluid Cooling, Insulation, and Heating,' 'Foaming Components,' 'Control Systems and Components,' 'Food Safety,' and 'Market,' referring to the cold brew market and existing technologies.

We then used our research to generate designs for the main subsystems at the time, cooling, mixing, and nitrogenation, and the full system as well. After several design iterations, the team met to determine the top designs, and discuss how to actually implement them. We then began our first round of purchasing and testing. We received items for the nitrogenation and cooling subsystems, so the subteams began testing simultaneously. It was determined early after design selection that static mixing served as a simple and effective method of mixing, and it was not a focus of building and testing until after the cooling and nitrogenation subsystems were beginning to function properly.

When the cooling and nitrogen subsystems reached acceptable functionality, we began turning the Keurig machines into functional parts of our design, specifically using the K-cup puncture mechanism and assembly from the K-Express as our mixing subsystem. Once we determined we could pump water through each subsystem individually, we made the leap into full system integration.

The system was mocked up on a table to see how everything worked together before coming up with the final design. We determined a layered system would best to move the water between subsystems effectively. Shelving units were then purchased, creating a tiered frame to build our prototype. Once we figured out where everything would fit on the shelves, we assembled the system, ran verification tests, and completed our project.

Requirements Generation

When defining the requirements for the project, in general we prioritized full system function, novelty, and minimal functionality over requirements that could be met/adjusted by Keurig engineers after the conclusion of student work. All requirements and specifications are found in Appendix A. As a whole, they aim to address what makes a good cup of coffee, what makes a good coffee machine, as well as laws and standards.

There are two main requirements that the cooling subsystem must fulfill: cooling rate must be ≥3.0°F/min and temperature of water must be able to reach ≥50°F. The initial temperature requirement was set at 45°F by Keurig Dr. Pepper, and was later altered when Keurig MDP found evidence that Starbucks was serving their nitro-cold brew near 50°F. The cooling rate requirement was determined using the minimum temperature the system has to reach and the maximum brew time. Initially, the cooling rate had to be high enough for the system to chill water from 68°F down to 50°F in 8 minutes (cooling rate of ≥2.3°F/min), however, the time was brought down to 6 minutes, thus a cooling rate of ≥3°F/min. This is to give adequate time for other processes in the overall system, such as initial priming of the system, nitrogenation, and mixing.

For nitrogenation and mixing, all of the requirements were student generated and vetted with Keurig. Going into the project, nitrogenation and mixing were two of the more "abstract" subsystems in the sense that what meeting a requirement means is more unclear. Keurig MDP did extensive literature review and initial testing with the BubblingPlus to benchmark high quality nitrogenation and mixing. One of our most important findings through the BubblingPlus as well as Starbucks was that high quality foam had smaller maximum bubble sizes and was finer, and the foam had to have substantial thickness.

By taking measurements and analyzing the images pixel by pixel, we determined that a maximum bubble size of less than or equal to 1.5mm after 5 minutes after pouring was a good indicator of high foam quality and that in a similar time scale that foam should remain at 0.25± 0.10" of foam in a 3" diameter glass. This is more evident in Figure 2, where foams needed to be thick enough to not destabilize quickly such as in the case of gas infusing with one N_2 or one N_2O canister. In addition, the foam should be fine and uniform. For example, the foam in the photo two minutes post 1 N_2O canister infusion looks more appealing to the consumer than a foam with large bubbles such as the sample 1 minute after the two N_2 canisters were used. For all of these tests, the coffee was similar colorwise, so our mixing requirement of the color being between three Pantone swatches is a measure of homogeneous and consistent mixing, as well as stream uniformity to an extent.

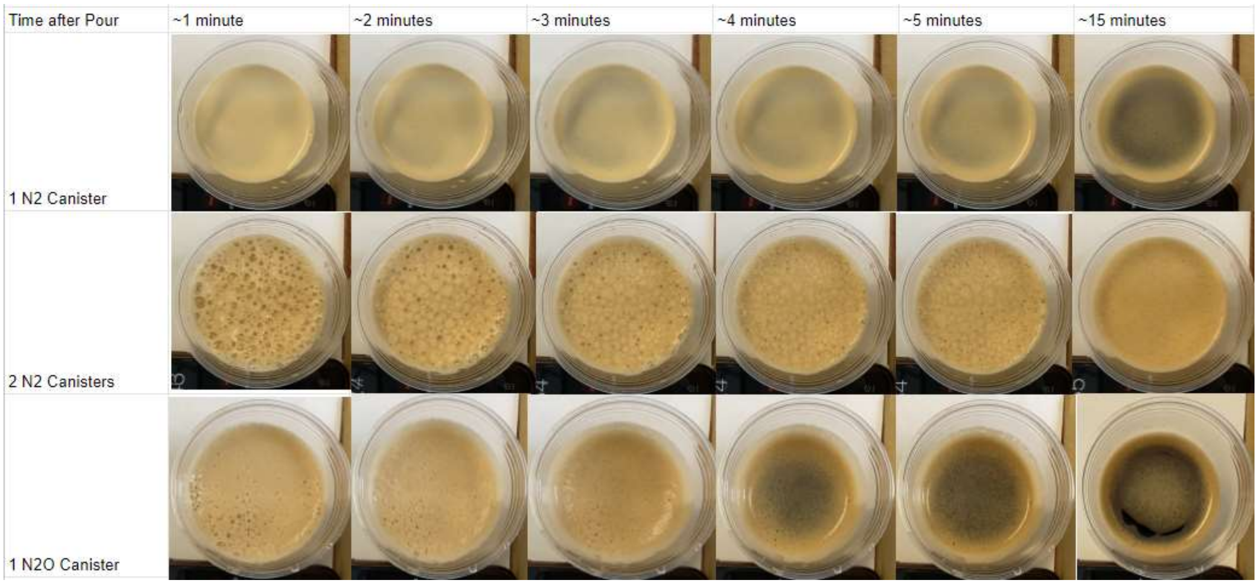


Figure 3. *Foam Quality Chart*

Outside of full subsystem function, cooling, and mixing, the remainder of the requirements were lower priority. For power, our target total wattage was 1500W, similar to existing Keurig machines. While we met this requirement, if we had a less power efficient but functional power system that could be optimized later this still would have been satisfactory. Usability was also a lower priority for the physical prototyping, as food safety is something Keurig could work on later with their vendors but was hard for the student team, given reliance on off the shelf components.

Given we were asked to do a benchtop prototype, things like the final size, noise, and steps-to-run were very low priorities as the prototype is unoptimized and many steps were easier to run manually. Finally, everything related to taste, while critically important to the final prototype, is out of scope for the student team as the benchtop prototype was not designed to be food safe and therefore hazardous to run taste tests.

Concept Generation and Selection

During the winter semester of the Keurig project, our primary goal was to select a reasonable and functional design for the cooling, mixing, and nitrogenation systems. We did this primarily through the use of Pugh Charts, a type of ranking matrix with different weights for different requirements. Each of these three subsystems had some unique and some universal ranking aspects that were proposed by the student team and verified with the mentors. Not only ranking the designs, but understanding which criteria were most important was a useful tool for the Keurig Team, especially because some of the final selections were unexpected compared to our initial assumptions going into the project.

Annotated design concepts may be found in the *Keurig MDP Running Design Concepts* slide deck.

Nitrogenation Pugh Chart and Design Selection

Table 1 contains the priority ranking of criteria used to evaluate nitrogenation subsystem concepts.

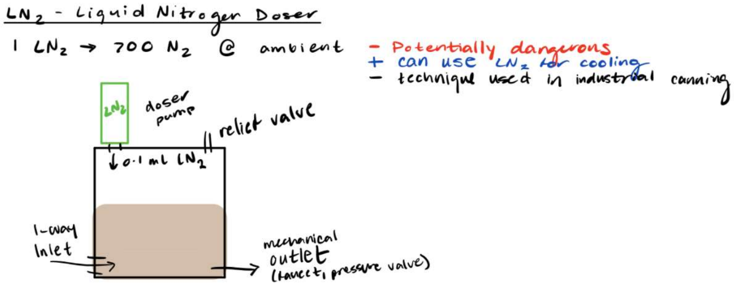
Table 1. *Nitrogenation Design Aspects Ranked by Priority*

Nitrogenation Design Aspect	**Score (1-4, 4=Highest Priority)**
Ease of Integration	4
Novelty	4
Foamability	4
Pre-Existing Theoretical Knowledge	3
Foam Stability	3
Cleanability	2
Estimate Parts	1
East of Part Manufacturing	2
Material Cost	2
Noise	1

Table 2 contains the final Pugh ranking for the top three concepts pictures in Figures 4-6.

Table 2. *Nitrogenation Pugh Chart*

Design Name	Ease of integration	Novelty	Foamability	Pre-Existing Theoretical Knowledge	Foam Stability	Cleanability	Estimated Parts	Ease of Part Manufacturing	Material cost	Noise	Total Score
5A	3	3	4	2	4	1	3	1	2	2	72
7A	4	3	4	2	4	2	3	2	4	1	82
10A	2	1	4	4	4	3	3	3	3	1	74
Weight	4	4	4	3	3	2	1	2	2	1	104



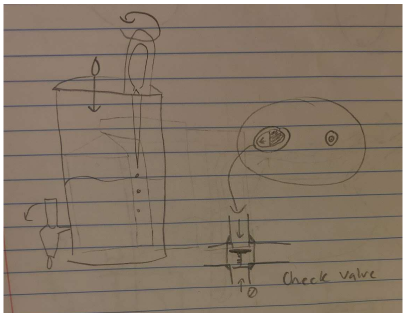


Figure 4. *Design 5a*

Figure 5. *Design 10a*

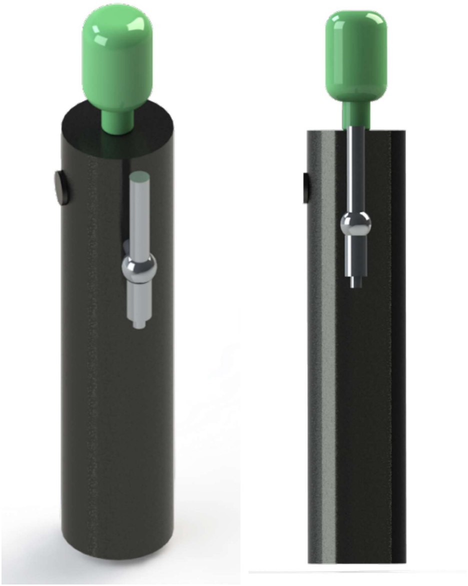


Figure 6. *Nitrogenation Design 7a - Final design choice*

For nitrogenation, all of the favored designs were variants of pressure vessels with a spout mechanism on the end. The need for a pressure vessel to handle the high pressure of nitro infusion is more obvious, but through literature review we found that a keg spout was very effective at maintaining the foam quality of the pour. Design 7a was a simple, clean concept, leading to its selection by the team. It is important to note the initial concept was similar to the BubblingPlus predicate device, but the final design does not infringe on intellectual property.

Cooling Pugh Chart and Design Selection

The cooling criteria shown in Tables 3 and 4 were built around the main aspects of cooling ability, pre-existing theoretical knowledge, and novelty. Since the team had little to no experience working with a condensing unit and even less with coolant, in addition to its size, a condensing refrigerator unit was avoided during the design process. This was done mainly for the safety of the students. Instead, a more safe and compact cooling unit created the main bulk of our ideas.

Table 3. *Cooling Design Aspects Ranked by Priority*

Cooling Design Aspect	**Score (1-4, 4=Highest Priority)**
Ease of integration	4
Cooling time	4
Cooling ability	4
Start-up time	4
Pre-Existing Theoretical Knowledge	3
Expected coefficient of performance	3
Food safety	3
Estimated Parts	1
Ease of manufacturing	2
Material cost	2
Noise	1

Our top scoring concepts, 2.A, 7.A, and 10.A are shown in Figures 7-9.

Table 4. *Cooling Pugh Chart*

Design Name	**Ease of Integration in Modular Design**	**Cooling Ability**	**Start-Up Time**	**Pre-existing Theoretical Knowledge**	**Ease of Manufacturing**	**Prototyping Cost**	**Noise**	**Novelty**	**Total Score**
2.A	3	4	4	4	4	2	2	1	67
7.A	4	3	3	4	4	3	4	1	66
10.A	1	3	4	1	1	2	4	4	59
Weight	3	4	4	2	2	2	1	4	

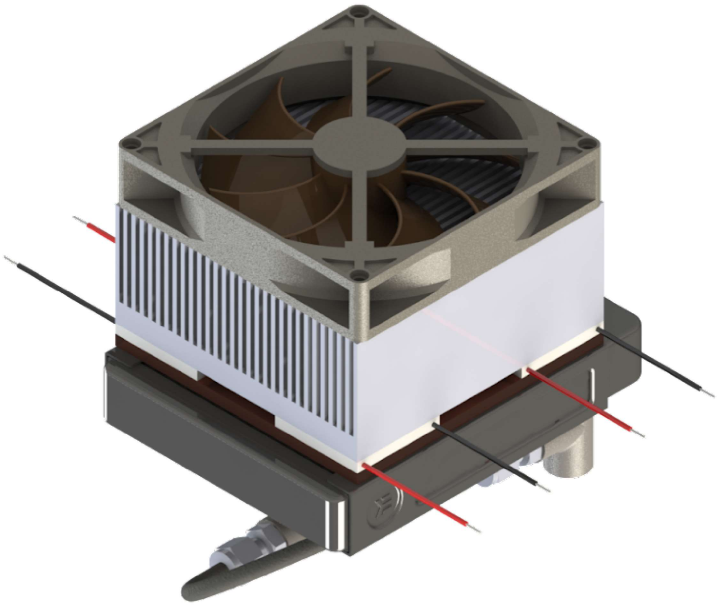


Figure 7. *Cooling 2.A is the chosen design used for our initial prototyping.* The system consists of a 120mm radiator, 4 thermoelectric coolers, heatsink and a fan. The water is cooled as it travels through the radiator.

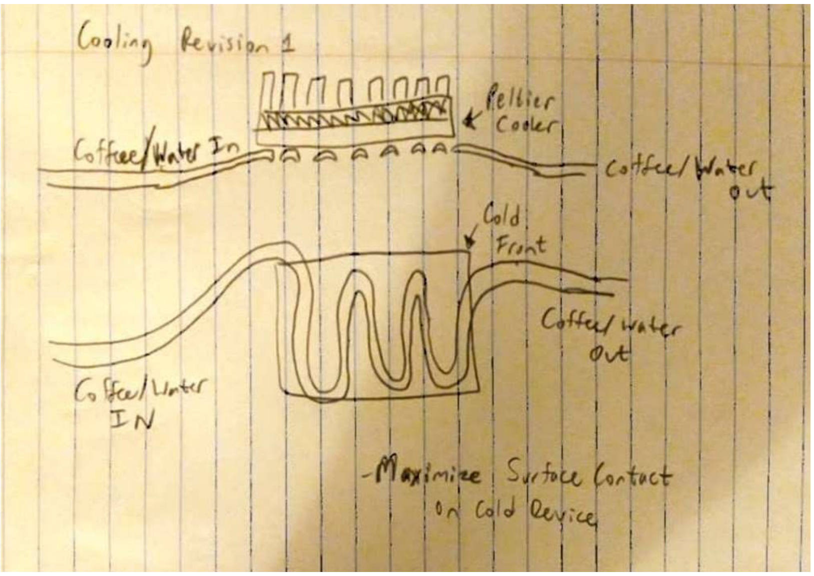


Figure 8: *Cooling 7.A is the design with the second highest score.* This cooling design, similar to Cooling 2.A, uses a cooling block, heatsink, and thermoelectric coolers to cool the water as it is flowing through it.

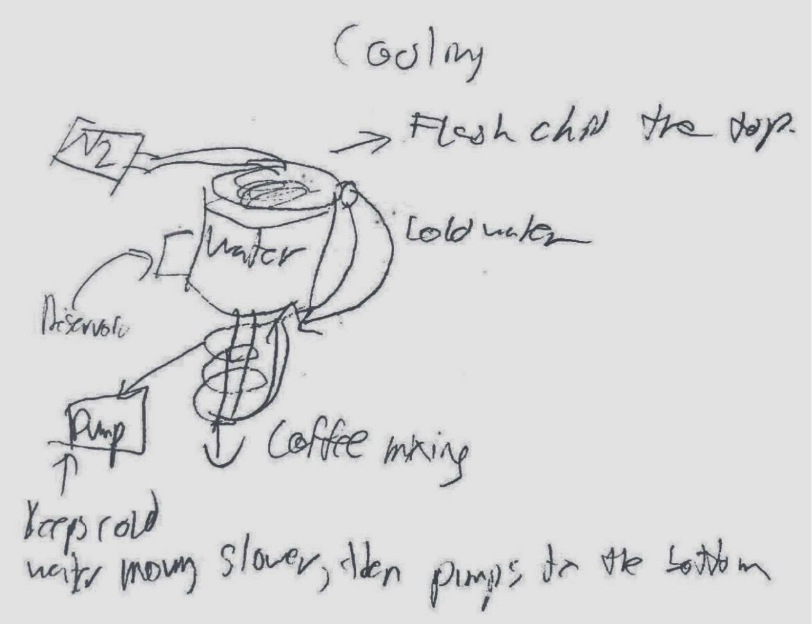


Figure 9. *Cooling 10.A is a design that scored high in novelty and total score.* This cooling design uses nitrogen gas to flash chill the temperature of the water.

Most advanced cooling technology is either not commercially available or too expensive given our budget. Therefore, the team found difficulty in designing ideas that were vastly different from one another, with an exception to a few like design 10.A (Figure 9). It was not difficult to narrow down most of our ideas, such as with designs 2.A (Figure 7) and 7.A (Figure 8) being similar. In the end, design 2.A was chosen due to the team's pre-existing knowledge of thermoelectric coolers (less temperature differential, lower cooling temperature).

Mixing Pugh Chart and Design Selection

Table 5 contains the design aspects the team considered when selecting a mixing subsystem concept. In the fall, the mixing subsystem prototyping was deprioritized to focus on novel cooling and nitrogenation implementation, and the concepts within this section were not prototyped in detail. The final mixing method functioned by connecting an existing Keurig brewer head in-line with the full system.

Table 5. *Mixing Design Aspects Ranked by Priority*

Mixing Design Aspect	**Score (1-4, 4=Highest Priority)**
Ease of integration	4
Novelty	4
Food Contact Area	2
Pre-Existing Theoretical Knowledge	3
Cleanability	2
Estimated Parts	1
Ease of part manufacturing	2
Material cost	2
Noise	1

The mixing requirements were built around the main aspects of ease of integration and novelty, with food contact areas and cleanability higher than normal. Compared to the other systems, mixing on paper has the greatest amount of surface area for food contact areas and we needed to account for that. Table 6 contains the Pugh evaluation results for the top three scoring subsystems, 5A, 7A, and 10A, shown in Figures 10-12.

Table 6. *Mixing Pugh Chart*

Design Name	Ease of Integration with Modular System	Pre-existing Theoretical Knowledge	Cleanability	Food Contact Surface Area	Estimated Part count	Ease of Part Manufacturing	Material cost	Noise	Novelty	Total Score
5A	3	4	2	3	3	4	3	4	1	52
7A	4	4	1	1	3	4	4	4	2	55
10A	4	3	1	2	3	2	3	2	3	51
Weight	3	2	2	2	1	2	2	1	4	72

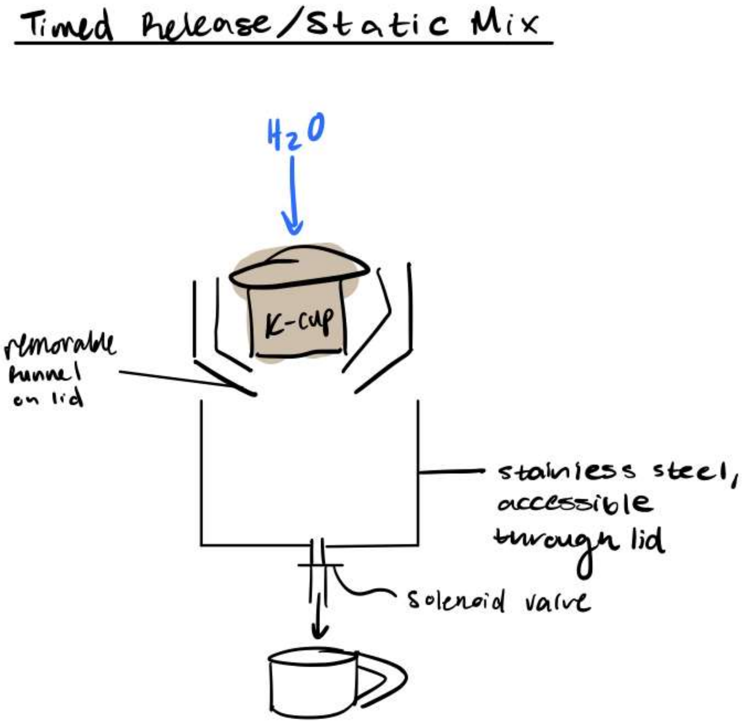


Figure 10. *Mixing 5.A is made up of components, a removable funnel on the lid and a stainless steel container below it. The lid is secured onto the container and a K-cup is placed. Once the water is cooled, the water flows through the K-cup and drains into the container.*

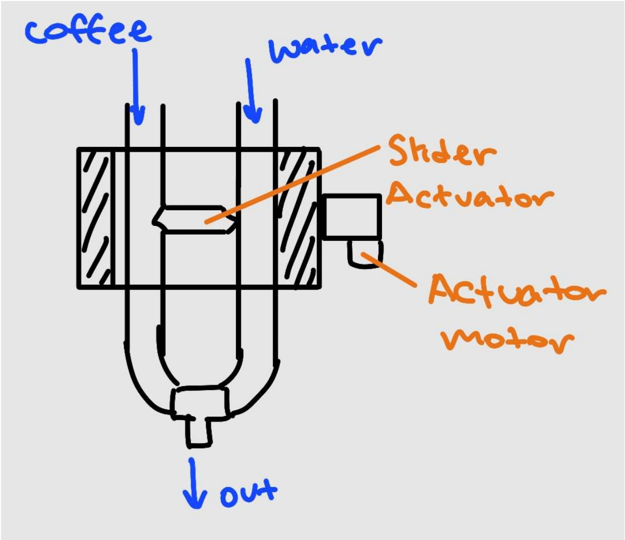


Figure 11. *Mixing 10.A consists of a motorized actuator with a slider. The slider pinches the coffee line closed until and opens when the water is cooled. Once opened, coffee concentrate and cooled water are mixed in the three-way tube and dispensed at the bottom.*

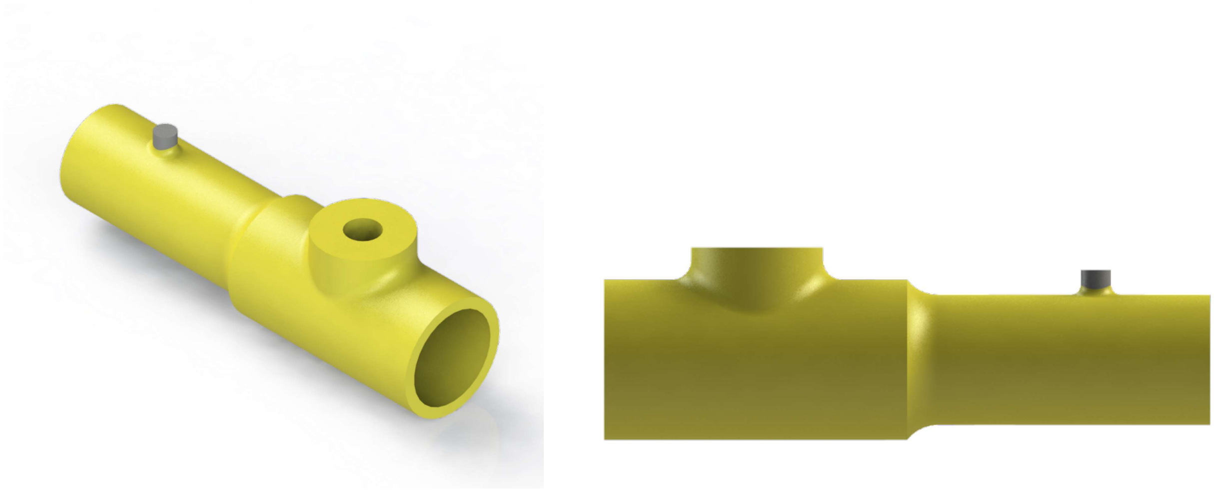


Figure 12. *Mixing 7.A uses the Venturi Effect to increase fluid flow through diameter change.*

Figure 13. *Pictures of in cup uniformity when concentrate is poured into water and vice versa.*

For mixing, the greatest debate was to use a dynamic mixing system, such as with a stir bar or actuator as in 10A, or if a static mixing system (just mixing them inline with tubing) is sufficient. We performed in-cup uniformity testing by simply mixing water and cold brew concentrate together and a homogeneous mixture was formed, which implied to us that a static mixing system would sufficiently mix the system. This ended up being correct and by making this decision we greatly simplified the electrical system and saved time in development.

Detailed Design

The design of each primary subsystem in the prototype build is detailed within the following section.

Cooling

The cooling subsystem is made up of two subassemblies; a hot side and cold side. In between the hot side and cold side are eight TEC1-12705 with four running at 12V, 5A and the rest running at 5V, 5A. The thermoelectric coolers are stacked in a way where TECs in contact with the cold side are running at 5V, and those in contact with the hot side are running at 12V. Note that the stacking orientation is crucial as incorrect power delivery may cause the TECs to burn out.

The hot side is responsible for cooling the thermoelectric coolers as they are cooling water for coffee. The subsystem consists of two 240mm radiators with fans, a pump with a built-in reservoir, and cooling block. The cold side of the cooling subsystem is responsible for chilling the water taken in (8 oz). This side consists of a cooling block, diaphragm pump, and two three-way ball valves for automation.

Nitrogen

Our prototype system design addresses the three major criteria we found to impact foam quality: pressure, tap design, and pour angle.

The prototype is constructed from pre-fabricated nitrogen cold brew keg components and pressure-rated components rated to achieve 40 ± 5 psi, which is indicated to adequately nitrogenate beverages according to nitro coffee home brewing suppliers [4, 5] and the Brewers Association [6]. Figure 15 outlines the prototype construction and component pressure ratings.

In addition, the prototype uses a pre-fabricated stout tap and [redacted], which are essential to produce high-quality foam. Stout taps are essential for high-quality foam, as they force the pressurized beverage through small holes in a component called a restricting disk. The restrictor disk reduces pour speed and agitates the mixture, creating foam [7]. The *DBGOGO* stout faucet used in our prototype contains a restricting disk. [redacted]

The team has supported tap criticality claims via observation. We observed foam stability when poured with and without the *BubblingPlus Surprise Bottle* tap. When pouring from the tap, we produced more desirable foam (smaller bubbles), as shown in Figure 14.

Figure 14. *Tap effects on foam quality.*

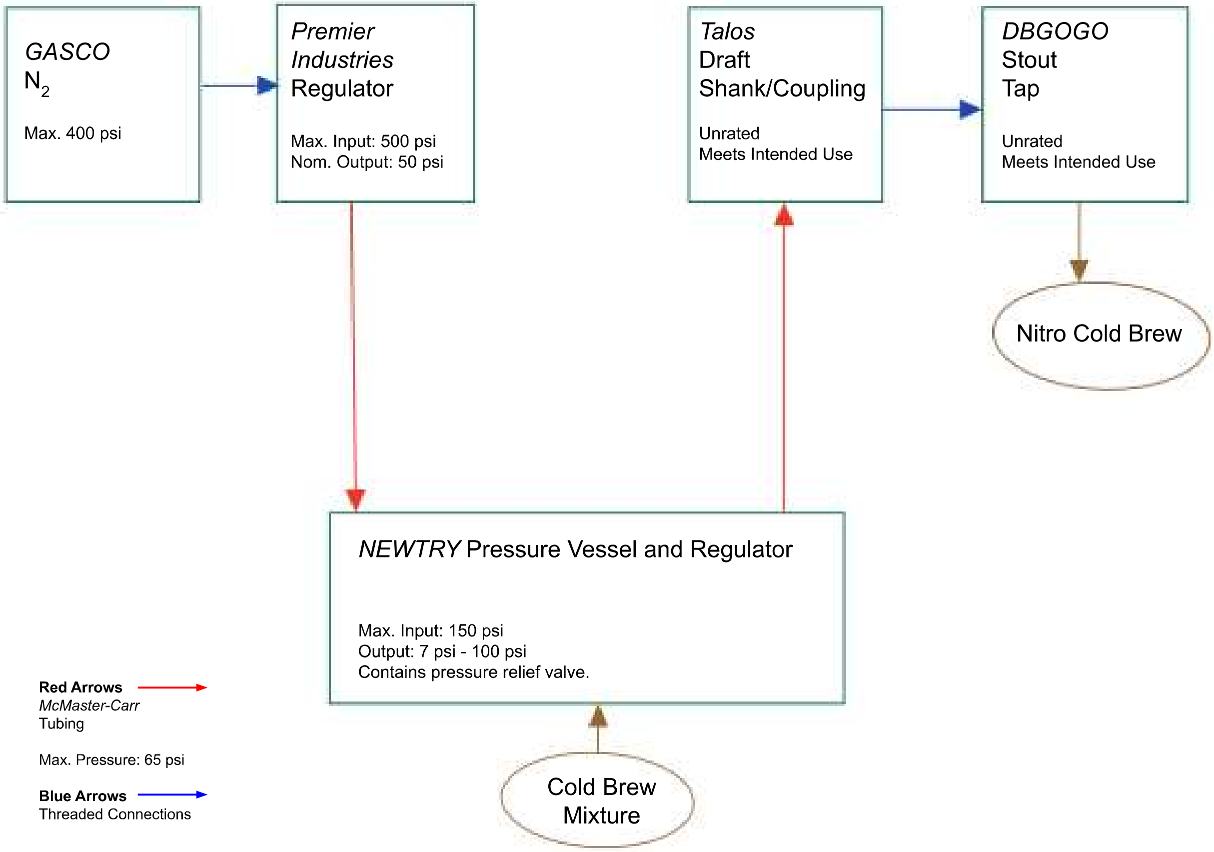


Figure 15. *Initial prototype nitrogenation subsystem block diagram.* The diagram indicates input and output pressure ratings for critical components. The *Talos* shank and *DBGOGO* tap are not pressure rated. However, they are being stressed at pressures expected during on-label use.

The prototype also facilitates angled pouring, which produces high-quality foam when used in combination with a stout tap. Using the *BubblingPlus Surprise Bottle*, we observed that a pour angle of 45° produces a higher-quality foam than a pour perpendicular to the glass' axis, as shown in Fig. 16.

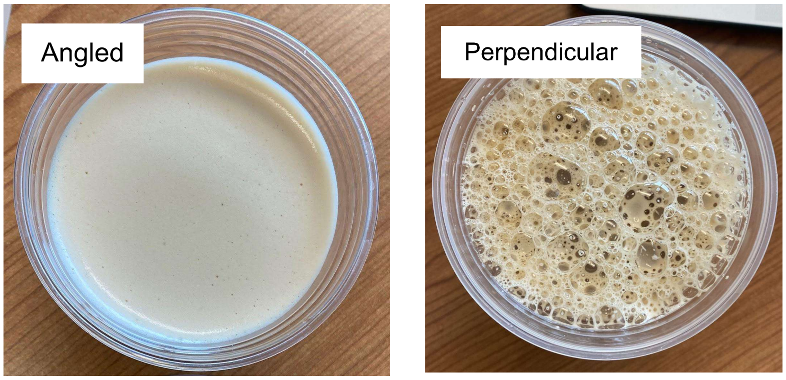


Figure 16. *Angled effects on foam quality.* Angled pours create smaller bubbles, resulting in a more desirable foam.

Research on stout beers confirms the criticality of pour angle [8]. The nitrogen tap is mounted on our final prototype, and its position allows for adequate positioning at the expected optimal pour angle.

The final nitrogenation subsystem is pictured in Fig. 17.

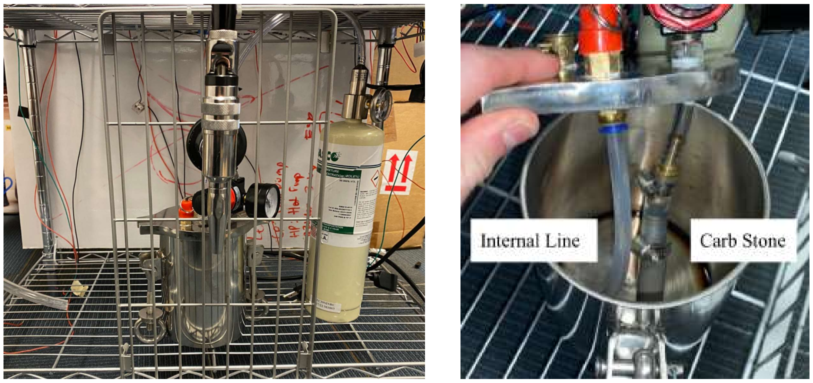


Figure 17. *Final nitrogenation subsystem.* Angled pours create smaller bubbles, resulting in a more desirable foam.

The full system pumping and instrumentation diagram can be found in Appendix B.

Automation

The automation system largely follows the original constraints and requirements provided by our sponsors. Specifically, this involved managing power and making as much of the process as autonomous as possible. This means controlling when all the electronic components turn on, developing the various stages of the autonomous processes, and having it all work within the 8 brew-time requirement, assuming the mechanical subsystems allow for it.

Managing the electronic components on the system was open-ended going into the fall semester. The power team had ideas including mosfets, or a BJT-amplifier to increase voltage and current output directly from a microcontroller and power these components directly. For the sake of simplicity, the method chosen by the team involved using relays (Fig. 18). These relays would be powered by a 5 V source and power on components when provided with a 3.3 V input signal. After receiving these relays, we were able to verify this set-up worked using a microcontroller and one of the 12 V pumps we stripped from the K-Express.

Figure 18. *These relays are used throughout the prototype. The left side controls/powers the relay, the right side is powering components.*

Planning the autonomous system itself was easy to start and required some tuning in order to finalize. The general process itself was developed by the team in September, and it is separated into cooling, mixing, and nitrogenation phases. The automation process still follows this order, as seen in Fig. 19.

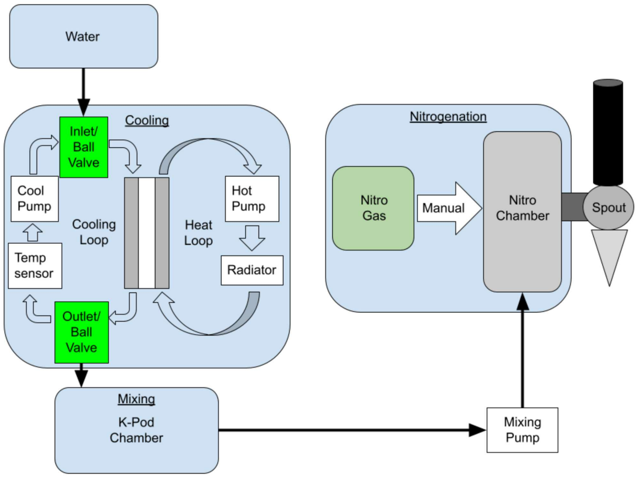


Figure 19. *General process.* All components are controlled with relays to automate the process.

The task then became how to properly adapt this process to an automated one with all our components. Our final setup uses two ball valves, which take 6.5 seconds to actuate, and call for long stretches of time where pumps are left running, such as the cooling system. Many of these stages rely on timing, and run solely based on an allotted amount of time as a result. 6.5 seconds to give the ball valves time to move, 27 seconds to let ~8 oz of water come in from the reservoir, and ~1 minute to allow water to pulse into mixing so as not let the rate of water into the reservoir be larger than the rate of water out of the reservoir.

In control theory, changing stages would occur when the direct event we are waiting for is detected happening by the system. Our temperature sensor is a good example of this. While we allow the system to leave cooling after 6 minutes, we monitor the temperature of the water until we reach the 45° F requirement, upon which we move along in the process. Our flowchart seen in Appendix D shows a basic outline of the autonomous process.

Other aspects of the automation system to note include the microcontroller and the electrical layout. The microcontroller used to make our automated system was the ESP32. The main inspiration behind this decision was the ease of the Arduino IDE, as all the electrical engineering students had experience with Arduino, the relatively high memory storage capacity, and small footprint of the system. The electrical layout on the poster board was mainly designed around where the components were placed on the physical frame. Two 5 V and GND rails are included to easily distribute the 5 V necessary to power the relays from a wall outlet. The 12 V sources from the power supplies and positive wire from the components they drive are attached to the relays directly and not through the board. Two relays each create shorts necessary to run the power supplies, which power the TECs. In this way, those relays turn on the power supplies instead of the TECs directly. A diagram of the set up is featured in Appendix E.

Implementation Strategies

After Design Review 2, the team split into 3 subteams focusing on each of the main subsystems; cooling, nitrogenation, and power. Cooling and nitrogenation focused mostly on creating novel subsystems based on our original designs, albeit they did not deviate too much from the original ideas. For cooling, the idea of using TECs alongside a radiator to dissipate hot side heat and heat sinks didn't change too much. The final prototype ended up using 8 TECs, stacked in 4 pairs rather than just 4 as shown in the original idea, which was necessary to achieve the desired cooling rate. This was discovered through extensive research and testing of different TEC configuration, wattages, and base units.

The general concept for nitrogenation did not undergo any major revisions. Going from a thinner cylindrical pressure vessel to a thicker one was more due to the vendor we got from that well-defined dimensions. For the sake of testing, we also used a larger nitro canister rather than individual containers to do more tests. The spout feature did not change much at all, it is positioned slightly lower on the system. The most significant non-geometric change to the nitrogen subsystem was the inclusion of a [redacted] to improve gas infusion into the coffee-concentrate mixture.

For the power subsystem, it was designed around cooling and nitrogenation. Rather than making our own power distribution board (PDB), to allocate more time to developing novel subsystems, we used a system of relays and PC power supplies to power our system. We used poster board to lay out all of the electrical components (primarily relays) and bus together the 12V and 5V lines we needed to power cooling and nitrogenation. All controls were done on an ESP32. While the original plan was to implement a more formal closed loop control system, we ended up using a more basic case-by-case basis in our code (‘FinalSetupCode.ino’, uploaded to team Google Drive)**.** If Keurig decides that they want more cup sizes, features, and most importantly flow rate regulators, then the need for a more formal control scheme rises. This was not necessary for initial prototyping and testing though.

For mixing, while our original plan was to fabricate our own static mixing chamber out of aluminum tubing, we ended up finding a much more efficient solution.

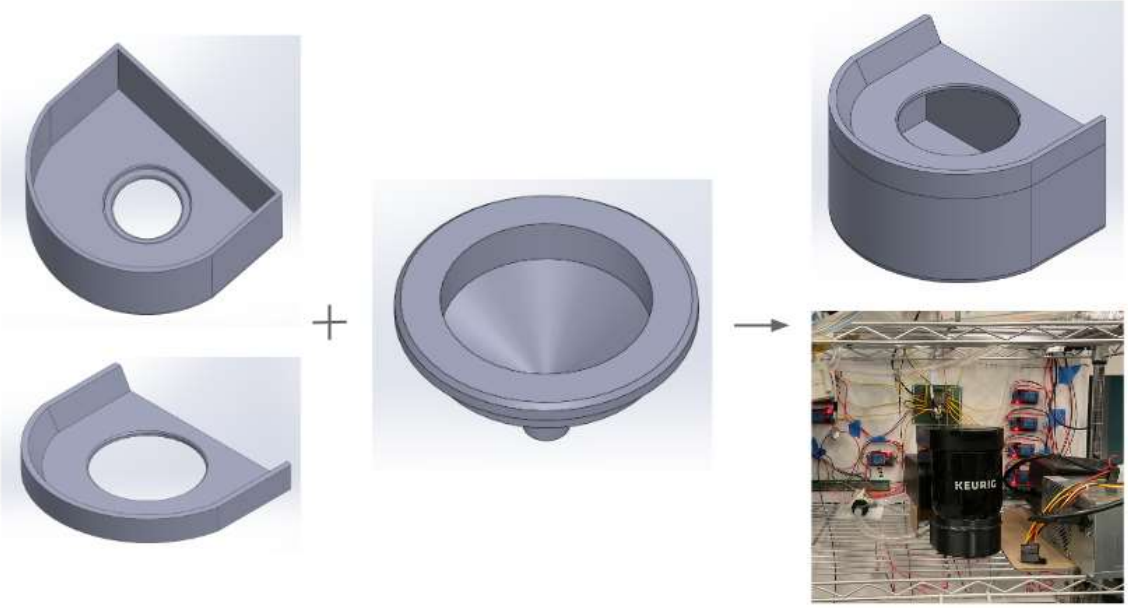


Figure 20. *K-Cup Mixing Insert*

As shown in figure 20, we found that using the head of a Keurig machine as the base and feeding a tube through the back also worked for “mixing.” This was then directly fed into the pressure vessel, where between the static mixing through the piping and within the vessel itself, the mixture became homogeneous and met the requirement. Of note: this system was prone to leakage.

Budget and Prototype Bill of Materials

Our budget for the project was $2500. We used $1978.60 in total, but we used $1,105 on materials that will be sent to Keurig on the final machine. A table of all materials being sent back is below, and the full budget is listed in Appendix C. The 3D printed parts of the design used 3D filament provided by MDP, and the posterboard used to attach electronics was also donated by MDP.

Table 7. *Prototype Bill of Materials*

Item	**Quantity**	**Price per unit**
Aluminum Water Block	2	$25
Radiator	2	$39.99
Water Pump	1	$44.99
3/8” Tubing	6 meters	$16.99
Nitro Tap	1	$51.19
Shank	1	$15.99
Teflon Tape	1	$6.99
Hose Clamps	1	$10.99
N2 Tank (not sent to Keurig)	1	$50.94
Pressure Vessel	1	$99.99
3/16” Tubing	25 feet	$11.75
DS18B20 Temperature Sensor (pack of 5)	1	$9.95
ESP32 Microcontroller (3 pieces)	1	$18.99
3pcs Relay	3	$10.49
Power Supply	3	$17.99
PS613163 Power Cord	3	$5.49
Pressure Regulator	1	$90
Thread Sealant	1	$7.70
Push-To-Connect	1	$13.99

Item	**Quantity**	**Price per unit**
Power Splitter	2	$4.95
550W Power Supply	1	$50.99
Printer Filament - for in-line reservoir and funnels	1	$0 (Donated)
Reducer	1	$6.99
Check Valves	1	$7.99
3 Way Ball Valve	2	$64.99
3/8” to 1/4” Male NPT	2	$8.21
3/8” to 3/8” Male Adapter	2	$8.99
Lever Nuts	1	$28.23
Aluminum Foil Tape	1	$10.98
TEC1-12705	2	$17.99
Thermal Paste	1	$5.48
Wire Ties	1	$4.49
Foldable Shelf	2	$10
3 Tier Shelving Rack	1	$34.96

Results and Discussion

Results for each requirement are sorted into three categories: green (meets specifications), yellow (partially meets specifications), and red (does not meet specifications). The full list of requirements and specifications may be found in Appendix A.

Green: Meets Specifications

Start-up Time (1.3)

The start-up time requirement states that the system should be ready within 30 minutes of powering it on. The current prototype system does not require an initial power-up sequence (the system is able to start pumping and cooling instantaneously, as shown in figure 6). Therefore, the requirement is considered to be met.

Back-to-back Brew Time (1.4)

In relation to the brew time requirement, back-to-back brew time requirement was not met. This requirement states that the brew time must be less ≤ 8 minutes which the initial brew could not satisfy. However, if the remediation for pump power, custom in-line mixing, and faster nitrogenation is achieved, the system should have no issue in meeting both the brew time and back-to-back requirement. This is because over 3 minutes of the time it takes to brew one coffee is from waiting for water to flow out of the mixing subsystem and to nitrogenate the coffee (instant with the BubblingPlus).

In-cup Temperature (2.1)

To verify if the system can chill the water down to 45±5°F, the system was primed with 8 oz of room temperature water. The system was then turned on and left to run until the system reached near steady state or close to 32°F (freezing). The system was stopped before 32°F as, though it is unlikely flowing water will freeze, any frozen water in the system may cause pressure build-up. Since the system is not built to withstand any pressure, any build-up of pressure will cause the tubing to disconnect from hardware. Figure 21 below shows that our system was able to chill water 10+°F above room temperature of 68°F down to 45°F in less than 7 minutes, meaning that the system meets the requirements.

Cooling Rate and Final Drink Temperature (2.1, 2.2)

To verify that the system is able to reach the specified cooling rate, an experiment was conducted with 8 oz of room temperature water (68°F) flowing through the cooling loop until the water's temperature reached the minimum temperature requirement (50°F). Though the cooling rate of the system is a negative exponential, for simplicity, we have decided to calculate the cooling rate of the system using a relationship. That is, room temperature (68°F) minus the minimum required temperature (50°F, linear) divided by the time it takes for the system to cool down the water from 68°F to 50°F.

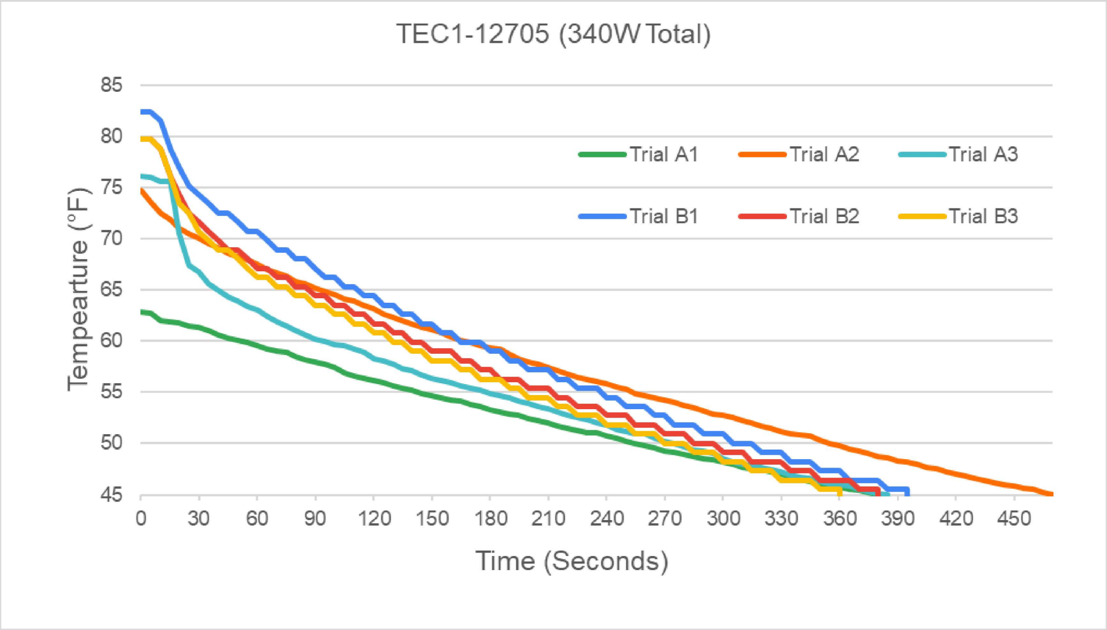


Figure 21. *Temperature vs time graph, showing the rate in which the water is chilled by the thermoelectric coolers for 7.5 minutes.* The rapid drop in temperature of Trial A3 is due to pump failure, which allowed the cooling block to pre-chill.

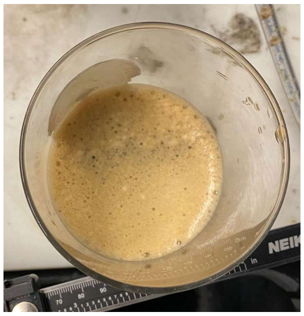
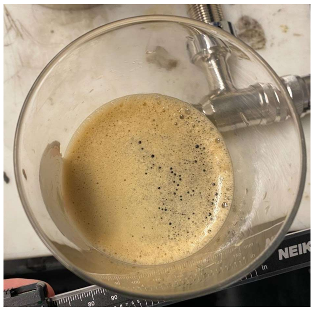
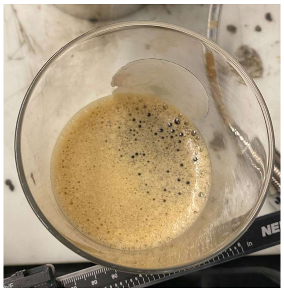
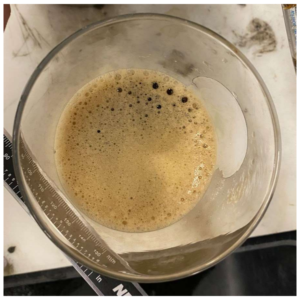
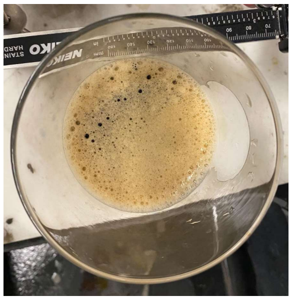
Figure 21 above shows the temperature vs time graph of the final prototype. The final prototype had a cooling rate of 3.59±0.63°F/min which exceeds the requirement of 3.0°F/min by 0.59°F/min. The high error comes from Trial A2 where the system took more than 7.5 minutes to chill the water down from 75°F to 45°F. The team speculates that half the thermoelectric coolers were not on during its measurement as the results of the B trials were after rewiring. Working under the assumption that the beverage does not change in temperature significantly after cooling, we consider the final drink temperature requirement to be met, as the cooling subsystem is able to chill water to 45°F, the lower temperature bound on Fig. 21.

Foam Quality (3.1)

Due to test safety concerns, nitrogenation subsystem testing was conducted in the Wilson Center Wet Lab behind a blast shield. The passing foam quality results were obtained from the isolated subsystem with a check valve open to the ambient air to simulate connection to the full system.

The subsystem was tested under 2 conditions: with and without agitation of the pressure vessel prior to pouring. Agitation was achieved by manually shaking the pressure vessel. The protocol for each trial was as follows: (1) pour cold brew mixture into a pressure vessel, (2) seal, (3) infuse nitrogen at 0.5 L/min for 50 sec, (4) agitate if applicable, (5) pour into glass at an approximately 45 degree tilt. Each condition was tested 3 times under the same operator. Table 8 shows the six trials.

Table 8. *Foam quality trial runs.*

Agitated		
		
Non-agitated		
		

Bubble size was measured using image analysis. Calipers were photographed parallel to the top surface of the foam. Then, a pixel measurement of 1 centimeter on the calipers was taken to use as a reference to proportionally convert a pixel measurement of the largest bubble to millimeters. This measurement method was analyzed using a second known reference measurement to calculate accuracy error (3%).

Foam quality visibly increased as distance from the tap insertion point increased. We expect this to be a result of operator error and pour instability, as the subsystem was tested without a mechanically fixed tap. The operator had to hold the glass with one hand and open and stabilize the tap with the other for the duration of the pour. In response, the maximum bubble size was sampled from the half of the top-surface area furthest from the tap insertion point. The pour setup and decrease in foam quality are shown in Fig. 22.

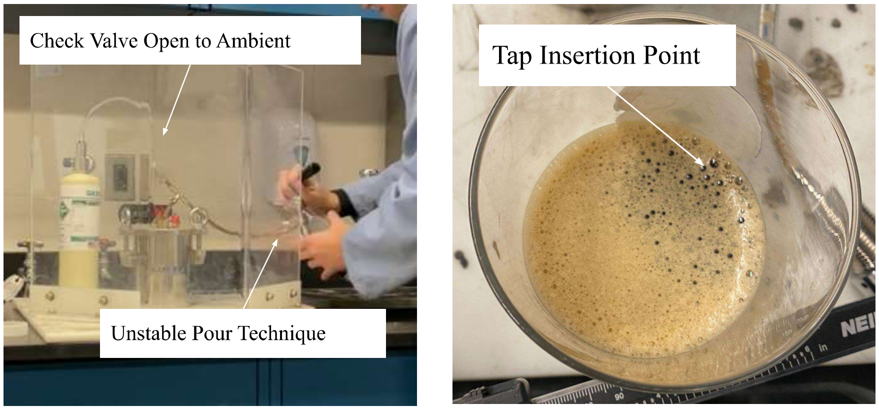


Figure 22. *Test setup results in decreased foam quality at tip insertion point.* Angled pours create smaller bubbles, resulting in a more desirable foam.

Table 9 contains the final foam quality data.

Table 9. *Maximum bubble sizes.* The maximum bubble size as specified by our requirement for foam quality is 1.5 mm.

Method	**Average Maximum Bubble Size (mm)**
Agitated	1.2 ± 0.5
Non-agitated	1.7 ± 1.0

The average maximum bubble size under both conditions is consistent within error to our requirement of 1.5 mm. On average, the agitated subsystem generates smaller bubbles, and therefore higher quality foam, than the non-agitated subsystem. Because both methods result in passing data, and the foam looks comparable to benchmark *BubblingPlus* and *Starbucks* nitro cold brew foam, we consider this requirement met. However, we recognize that the measurement system needs to be improved to decrease the accuracy error and improve our understanding of the subsystem's ability to meet the requirement. In addition, the difference in foam quality as a result of pour quality suggests further improvements may be made to increase tap stability.

Foam Thickness (3.2)

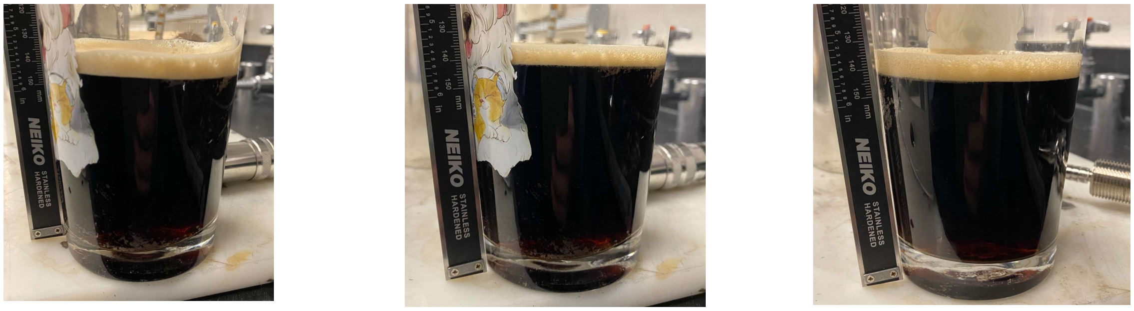
Foam quality is a complementary requirement to foam thickness, and we expect that the foam thickness requirement will be met when the foam quality requirement is met. This is because the quality indicator, bubble volume, has a direct correlation with foam thickness. Our observations with the *BubblingPlus Surprise Bottle* support this expectation: samples with adequate foam quality have adequate foam thickness, and samples with inadequate foam quality have a thicker, inadequate foam, as shown in Fig. 23.

Figure 23. *Foam quality vs. thickness..* High-quality foams tend to be thinner than low-quality foams. Foam produced by *BubblingPlus.*

Using the same trials conducted as described in the *Foam Quality* section, foam thickness was experimentally verified. Foam thickness was also measured using image analysis as previously described. Table 10 contains images of the foam thicknesses from the verification runs.

Table 10. *Foam thickness trial runs.* Agitated and non-agitated foam thickness is consistent within error.

Agitated



Non-agitated

Table 11 contains the average foam thicknesses.

Table 11. *Foam thicknesses.* The desired foam thickness as specified by our requirement is 0.25 ± 0.10”

Method	**Average Foam Thickness (in)**
Agitated	0.36 ± 0.15
Non-agitated	0.38 ± 0.17

The average foam thicknesses under both conditions are consistent within error to our requirement of 0.25 ± 0.10 in. On average, the agitated and non-agitated subsystems produce similar foam thicknesses. Similarly to *Foam Quality*, because both methods result in passing data, and the foam looks comparable to benchmark *BubblingPlus* and *Starbucks* nitro cold brew foam, we consider this requirement met. However, we recognize that the measurement system needs to be improved to decrease the accuracy error and improve our understanding of the subsystem’s ability to meet the requirement.

Power (4)
The power requirement states that the system needs to run on ≤1500 W per serving. The highest power consuming devices are the thermoelectric coolers running at 340 W (4 x TEC1-12705 MAX and 4 x TEC1-12705 at 5V). Other electronics (pumps, fans, ESP32, relays) all run on less than 50 W. When all the power supplies are running at their maximum possible output, the system runs at ~1338 W of power which is less than 1500 W.

Stream Uniformity (5)
The nitrogenation subsystem contains the system output (tap), the first location the cold brew concentrate and water mixture stream is visible to users. The prototype is able to pump the coffee-concentrate mixture from the input tank and pod to the tap. Based on preliminary static mixing observations, shown in Fig. 24, and visual inspection, shown in Fig. 25, we consider the stream uniformity requirement to be met.

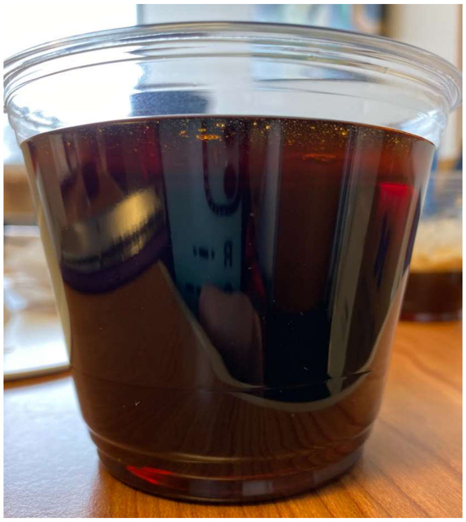


Figure 24. *Two-pour static mixing.* Pouring the 8 oz. of water, stabilizing, and pouring 2 oz. of concentrate produces a visibly uniform mixture.

Figure 25. *Final design stream*. Coffee color is uniform throughout pour, as the pressure vessel functions as the cup in the static mixing experiments.

When analyzing the RGB color values at random points at the top, middle, and bottom of the cup in Fig. 24, we determined the normalized variation in color for the mixed brew to be less than 2%, which gave us confidence in our design's ability to satisfy the requirement. To conduct the static mixing test, we first poured 8 oz. of water into a glass, then we let the fluid stabilize. Next, we poured in 2 oz. of cold brew concentrate without agitating the glass. The turbulent flow of both fluids resulted in a uniform mixture, which produces a uniform stream. The geometry of the pressure vessel is similar to the geometry of the cup, which we consider a contributor to the success of the final prototype's ability to mix concentrate and water. However, we note that, at the tap, though the coffee stream color is uniform as shown in Fig. 25, a majority of the foam dispenses at the end of the cycle. As such, the appearance and consistency of the stream as a whole does change color throughout the brew cycle.

Steps to Run (6.5)

The requirement for steps to run states that the fully integrated cold brew coffee maker will require 7 or less steps the user must follow before making one cup of coffee. The final prototype requires 7 steps to operate.

1. Fill reservoir with water
2. Open the pod chamber and place the cold brew concentrate pod before closing it once again
3. Open pressure relief valve
4. Press the “start” button to begin the automated process
5. Close pressure relief valve when the coffee-concentrate mixture is fully emptied into the nitrogen subsystem
6. Actuate nitrogen flow for 50 seconds
7. Manually open the tap at the end of the automated process to release drink

The requirement is met, and the steps to run will decrease should nitrogenation be electronically automated in the future.

Yellow: Partially Meets Specifications

Path to Food Safety: Materials (6.1)

For our physical prototype, most of our components are from sponsor-provided brewers, or made of materials that have food safe options. All piping is from either (1) Keurig and is made of PVC, or (2) a variant version of PVC (such as soft PVC). The 3/16” tubing used in the nitrogen subsystem is NSF 51 certified. These materials are generally food safe, and can be implemented into a final design. Similarly with the stainless steel for the nitrogenation tank, stainless steel is commonly used for silverware and cooking tools. However, not all stainless steel is food safe and the final assembled subsystem must have (a) food grade stainless steel and (b) no liquid thread sealant.

Many PVC and stainless steel products are found on the NSF website under the NSF ANSI 51 food safety standard [9]. However, most plastic parts within our device are purchased from Amazon, and they are not certified food safe. On the other hand, sensors tend to say if they are food safe or not more readily. The below table summarizes the food safety plan.

Table 12. *Food safety table.*

Beverage Contact Component	Is Mat'l Currently Food Safe?	Path to Food Safety
Keurig-provided Diaphragm Pump	Yes	Continue on-label use
Aluminum Water Cooling Block	Yes	Address geometry, stagnant water remains in cooling block as discussed in *Design for Cleanability (6.2)*
3/8” Tubing	No	Replace current silicone tubing with NSF-51 certified tubing, available from *McMaster-Carr*
Ball Valves	No	Replace with non-brass valves, stainless steel ball valves are available for at-home beer brewing
Nitro Tap	Yes	Continue on-label use
Nitro Shank	Yes	Continue on-label use
Teflon Tape	Yes	Continue on-label use
Pressure Vessel	Yes	Address geometry, stagnant water-coffee mixture remains at the bottom of the tank and must be emptied after each run
3/16” Tubing	Yes	Continue on-label use
DS18B20 Temperature Sensor	No	Food-safe DS18B20 sensors are available from *Adafruit*
Threaded NPT and BSPP Reducers	No	Replace with non-brass reducers, stainless steel reducers are available for at-home beer brewing
Check Valve	No	Replace with food safe check valve, available from *Ontario Beer Kegs*
PLA (3D-printed)	Yes	Replace manufacturing method to reduce porosity
PTFE Liquid Thread Sealant	No	Replace with food-safe PTFE sealant, available from *Saf-T-Lok* and *Anti-Seize*
[Redacted]	Yes	[Redacted]
PLA (3D-printed)	Yes	Replace manufacturing method to reduce porosity

Should the materials be certified and substituted accordingly, we have confidence the design can be produced with food safe material.

Noise Level (6.4)

The current requirement for the system’s noise level is 60 dB, roughly equal to the sound of a restaurant on a busy day. The system was tested for noise level using the *NIOSH Sound Level Meter* iOS app. A maximum sound level of 60.3 dB was measured, which does not meet the requirement. However, the team does not have confidence in this software’s ability to accurately measure sound levels, as the system does not qualitatively sound as loud as a restaurant on a busy day is tolerable. In addition, all parts are exposed within the shelving structure. We have confidence that if the system were to be fully enclosed, the design will meet noise level requirements.

Red: Does Not Meet Specifications

Brew Size (1.1)

There is no system to automatically regulate the amount of water that is pumped into the prototype other than a timer and the maximum water capacity of the prototype's internal reservoir of 12 oz. However, though the system is calibrated correctly to intake 8 oz of water, the system loses an estimated 1.1 oz at the cooling and mixing subsystem. As such, the system is unable to expel all water taken into the system. Thus, the team has deemed that this requirement was not achieved. A more power pump and non-gravity reliant system would remediate this issue.

Brew Time (1.2)

The brew time requirement states that the cold brew must be ready for consumption in ≤ 8 minutes. With the system taking on average 10.5 minutes to complete a single brew, the team was not able to meet this requirement. This is mainly due to the time it takes to pump in 8 oz of water, time it takes for water to empty from the mixing subsystem into the nitrogenation chamber, and the time it takes to nitrogenate the coffee. Remediation for the brew time would be to use one reservoir, similar to the K-Mini, removing the initial time for the system to intake 8 oz of water. In combination, a new design for in-line mixing should be made, and the gas regulator should allow for higher nitrogen gas flow.

Path to Food Safety: Design for Cleanability (6.2)

Given we had to go into contingency time to fully integrate the system, we did not have time to fully test the cleanability of our design. At the same time, we were able to get some takeaways through normal system performance and can offer suggestions. While we did not notice any sediment in the water system, we did notice that water got stuck throughout the system as outlined in the brew size requirement (1.2). Naturally if water is getting stuck consistently then sediment could also. Standing water is also an issue. Furthermore, we also noticed that concentrate got caught and solidified in our feed-in to the pressure vessel, which is likely due to the fact that the feed-in is made out of a 3D-printed part rather than stainless steel or PVC that would not lead to this issue. Overall, while further testing is needed with Keurig descaling solution, given the benchtop prototype has significantly longer piping and more "random" crevices than a final system, the system ended up not as cleanable as expected. This wasn't one of the highest priority requirements so we focused more on integration during our expected cleanability testing time ~Week 25.

Estimated Final Device Size (6.3)
The final prototype device size is 24” long x 14” wide x 40” tall. Since our final prototype device relies on gravity-feeding, we cannot reasonably assume the vertical dimensioning is any shorter. The final size of our device by requirement is that it has to fit in a 15” X 15” X 17” space, which were dimensions provided by our Keurig sponsors. Given we are constructing a benchtop prototype, our initial design is over a much greater space. However, in a final consumer ready product the design can be spatially optimized and have a much smaller power distribution system likely contained in a printed circuit board, the space constraint should not be a problem, as the parts that we have so far aren’t larger than what was in the supplied Keurig machines besides the power supplies and pressure vessel volume, but we did not optimize the prototype for final consumer ready size. If Keurig engineers take our design and refine it, we assume parts will get smaller and more compact to meet this requirement.

Taste Requirements (Stretch 2.1-2.5)
In the final product, the taste and smoothness of the nitro cold brew is important to evaluate, since nitrogenation can impact perceptions of taste and mouthfeel. However, within the scope of the student team’s responsibilities, taste is a tough requirement to verify due to University of Michigan research regulations and access to a tasting panel. Most importantly, the cold brew concentrate is out of the team’s design scope, so the final design does not influence the primary contributor to taste.

In addition, our final deliverable has not been tested for food safety, and it is unsafe for the student team or surveyed taste testers to ingest the coffee. Of the five taste requirements, this rules out testing STRETCH 2.1 and STRETCH 2.3. STRETCH 2.2, 2.4, and 2.5 are all feasible to test, as their taste metrics may be evaluated quantitatively without a taste test. However, the metrics have not been evaluated due to the complex equipment and time required for verification. The sponsors conveyed to the student team that evaluating stretch goals is a low priority, and as such we focused on other aspects of design.

Suggestions

While the cooling subsystem met both the cooling rate and temperature specifications, there are many improvements to be made. Though the cooling subsystem is able to chill 8 oz of water from room temperature to 45°F within 6 minutes, the likelihood of achieving similar rates with volumes greater than 8 oz is near 0%. If larger brew sizes are of importance, Keurig MDP recommends shorter tubes and covering the tubing with insulating materials for reduction of heat loss to ambient.

The team also recommends replacing the current TEC1-12705 thermoelectric coolers with TECs of higher power requirements (e.g. TEC1-12715). This however may give contradictory results due to the inability of the hot side not being able to cool the TECs fast enough. While experimenting with TEC1-12715, the team has found that one radiator was not enough to cool down 4 TEC-12715 running at 120W each (12V, 10A). This caused the water in the cold side to heat up rapidly or result in a lower cooling rate than TEC1-12705 with running at 62.5% capacity. This means that the more powerful TECs used, the more complicated and bulker the hot side cooling will be to cool down those TECs. Another method for improving cooling would be to redesign the system for a micro DC condensing unit. While the coolant is toxic if released, it is highly power efficient and has a greater cooling rate than TECs.

Automation is an area that can benefit from various changes. The current code heavily relies on timers, which can be replaced with sensors that more accurately measure those actions we need to happen before moving on in the code. This includes measuring 8 oz of water entering the system, measuring the water leaving cooling and entering the mixing system, and reading the ball-valves' signal pin to determine when it reaches a fixed position. All this can potentially cut down on time spent waiting for an action in the system, as well as ensure the system does not move on pre-maturely if an action was not completed.

Creating a method to automate the nitrogen gas infusion process is also noteworthy. Solenoids were purchased to automate the process on the prototype, which worked when tested in a lab environment. This required us to leave the nitrogen canister open when connected to the solenoid via a tube, meaning the solenoid had to maintain the pressure by itself. Unfortunately, back pressure was created and affected the solenoid's ability to stay connected to the nitrogen tank for long periods of time. A more direct connection between the solenoid and the canister without a tube would be beneficial to securing the pressure better. This addition would also automate the infusion process, which is not possible on our current system. An internal sensor in the pressure vessel, or gas flow sensor between the vessel and nitrogen canister, would be advised to determine how much gas has been used and turn off the gas infusion process that way.

In addition to flow automation, the nitrogenation subsystem could potentially be improved with reduced volume and a funnel-shaped geometry. The reduced pressure vessel volume may help the mixture come to pressure within a shorter infusion time and increase foam quality. The funnel-shaped geometry may help decrease volumetric loss at the bottom of the tank, as the coffee egress tube does not effectively evacuate all coffee from the flat surface.

The system as a whole could benefit from a custom in-line mixing subsystem, consistent decreased tube diameter, and increased pump power to help decrease volumetric losses and overall brew time.

Conclusion

The Keurig Dr. Pepper MDP team has spent the past year working towards this final prototype, and feel confident that we have produced a novel system that can be further improved, and used

as a basis for a future commercialized system. We would like to thank Keurig Dr. Pepper Inc. for the opportunity to work on this project. We would especially like to thank all of our sponsors, Nick Borsari, Dancho Ivanov, and Jason Tavoletti for assisting us throughout the project.

References

[1] N. Córdoba, F. L. Moreno, C. Osorio, S. Velásquez, and Y. Ruiz, "Chemical and sensory hgh evaluation of cold brew coffees using different roasting profiles and brewing methods," Food Research International, vol. 141, p. 110141, Mar. 2021, doi: 10.1016/j.foodres.2021.110141.

[2] "Cold Brew Coffee Market Size," Grand View Research, [Online]. Available: https://www.grandviewresearch.com/industry-analysis/cold-brew-coffee-market/methodology

[3] B. Bennett "Keurig Kold Review: Keurig Kold makes frighteningly expensive fizzy drinks," CNET, Oct. 02, 2015 [Online]. Available: https://www.cnet.com/reviews/keurig-kold-review/

[4] "Troubleshooting your Nitro Cold Brew Keg," First Tracks Cold Brew Coffee, Oct. 14, 2020. [Online]. Available: https://firsttrackscoldbrew.com/2020/10/troubleshooting-your-nitro-cold-brew-keg/. [Accessed: Oct. 03, 2022]

[5] "Why Isn't My Nitro Coffee Cascading When I Pour It," Keg Outlet. [Online]. Available: https://www.kegoutlet.com/why-isn-t-my-nitro-coffee-not-cascading-when-i-pour-it.html. [Accessed: Oct. 03, 2022]

[6] "Brewers Association Facts about Serving Nitrogenated Beer," Brewers Association, 2014 [Online]. Available: https://cdn.brewersassociation.org/wp-content/uploads/2020/11/BAtech20-DBQ-One-Pager-Nitro-Beer-201-4.pdf. [Accessed: Oct. 02, 2022]

[7] W. Forrest, "Nitrogen Draft Tap," Brew Your Own, Dec. 2008. [Online]. Available: https://byo.com/article/nitrogen-draft-tap-projects/. [Accessed: Oct. 02, 2022]

[8] T. Watamura, F. Iwatsubo, K. Sugiyama, K. Yamamoto, Y. Yotsumoto, and T. Shiono, "Bubble cascade in Guinness beer is caused by gravity current instability," Scientific Reports, vol. 9, no. 1, p. 5718, Apr. 2019, doi: 10.1038/s41598-019-42094-0. [Online]. Available: https://www.nature.com/articles/s41598-019-42094-0

[9] ANSI/NSF 51-1997 Food Equipment Materials. Ann Arbor, MI: NSF International, 1998.

[10] Standard Test Method for Calculating Dynamic Viscosity and Kinematic Viscosity of Transparent and Opaque Liquids. West Conshohocken, PA: ASTM International, 2021.

[11] Home Coffee Brewers: Specifications and Test Methods. Irvine, California: Specialty Coffee Association, 2021 [Online]. Available: https://static1.squarespace.com/static/584f6bbef5e23149e5522201/t/62fbd2d2aed180702280c014/1660670674796/SCA_Standard_310-2021.pdf. [Accessed: Oct. 02, 2022]

Appendix A: Requirements and Specifications

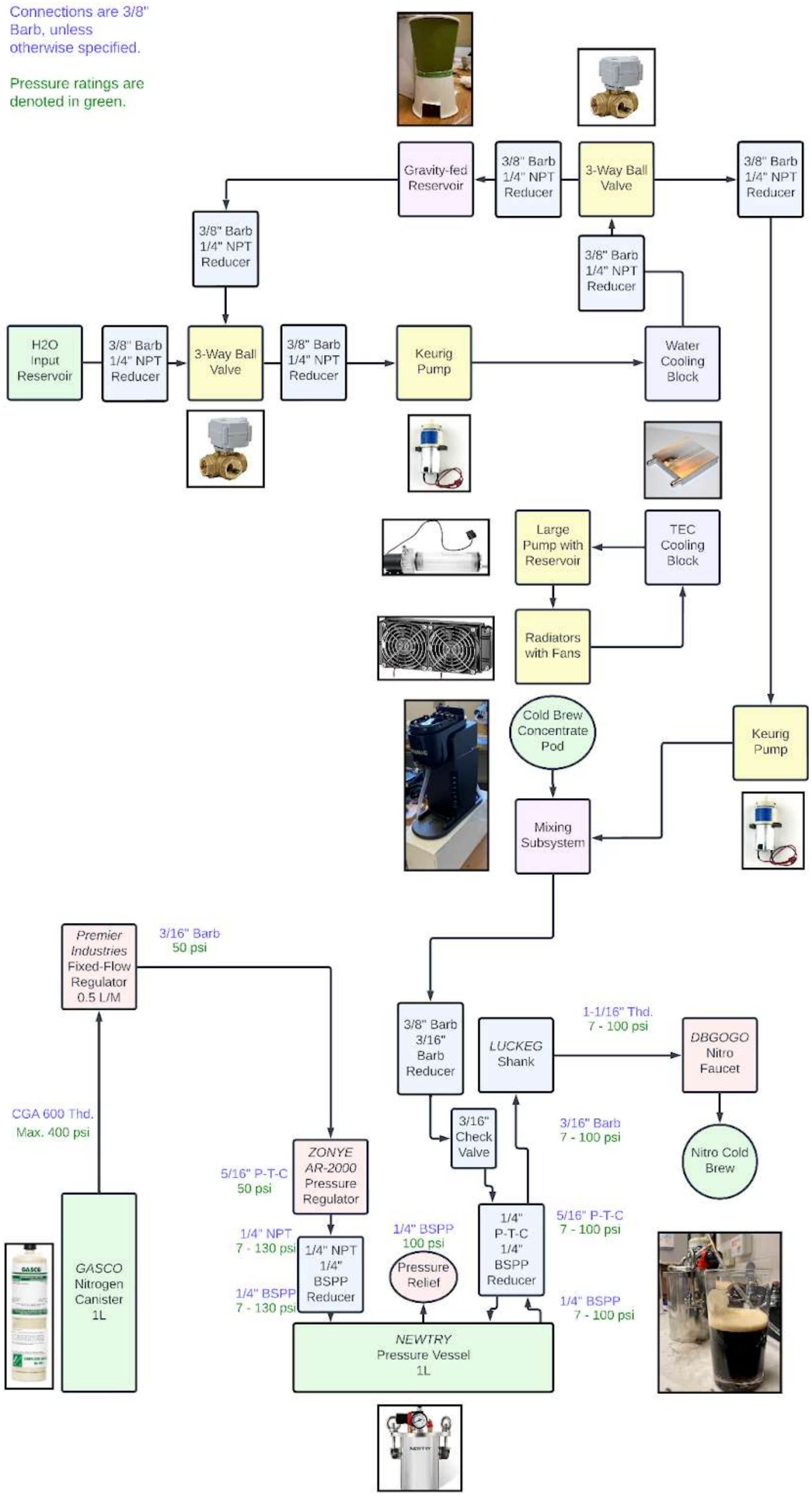
Complete List of User Requirements (Top 3 Critical Requirements **Bolded**)						
Requirement Number	Subsystem	Sponsor Priority *(4 =High)*	Requirement Target & Units	Origin of Validation Method	Subteam/ Individual Responsibility	Status
1.1	Full System Function	4	Brew an 8.0 ± 0.5 oz cup	Student Developed	Cooling	Red
1.2	**Full System Function**	**4**	**Brew time should be less than or equal to 8 minutes.**	**Student Developed**	**Power**	**Red**
1.3	Full System Function	3	Start-up time should be less than or equal to 30 minutes.	Student Developed	Cooling	Green
1.4	Full System Function	2	Back-to-back brew time should be less than or equal to 8 minutes.	Student Developed	Cooling	Green
2.1	Cooling	4	Final drink temperature should be 45 ± 5 °F	Student Developed	Cooling	Green
2.2	**Cooling**	**4**	**Average cooling rate should be greater than 3.0°F/min**	**Student Developed**	**Cooling**	**Green**
3.1	**Nitrogenation**	**4**	**The maximum bubble size should be less than or equal to 1.5mm, when measured 5 minutes after pouring**	**Student Developed**	**Nitrogenation**	**Green**
3.2	Nitrogenation	3	Should produce 0.25 ± 0.10" of foam in a 3" diameter glass, when measured 5 minutes after pouring	Student Developed	Nitrogenation	Green
4	Power	2	Maximum	Student	Power	Green

Complete List of User Requirements (Top 3 Critical Requirements **Bolded**)						
Requirement Number	Subsystem	Sponsor Priority *(4 =High)*	Requirement Target & Units	Origin of Validation Method	Subteam/ Individual Responsibility	Status
			operating power should be less than or equal to 1500 W.	Developed		
5	Mixing	4	Stream should be within a range of 3 Pantone standard colors throughout brew cycle	Student Developed	Nitrogenation	Green
6.1	Usability	2	Identify food-safe analogs to all food zone materials in prototype. Food zone materials shall be manufactured or composed of substances compliant with NSF 51 §4.	Recognized Standard Test [6]	Robert	Yellow

Complete List of User Requirements (Top 3 Critical Requirements **Bolded**)						
Requirement Number	Subsystem	Sponsor Priority *(4 =High)*	Requirement Target & Units	Origin of Validation Method	Subteam/ Individual Responsibility	Status
6.2	Usability	2	Identify a path to creating smooth and easily cleanable food contact surfaces in the final appliance design. If a food contact surface is textured such that it may hinder the removal of soil during cleaning, the material shall be demonstrated to be cleanable when tested in accordance with NSF 51 §5.2.1.	Recognized Standard Test [6]	Donghyun	Red
6.3	Usability	1	Estimated final device size should fit within a 15" x 15" footprint and be less than 17" tall.	Student Developed	Jed	Red
6.4	Usability	1	System should operate at less than or equal to 60 dB.	Student Developed	Robert	Yellow
6.5	Usability	1	System should take less than or equal to 7 user steps/cycle to operate.	Student Developed	Power	Green
STRETCH.1	Usability	0	Estimated retail cost of device should be < $300	Student Developed	David	Red
STRETCH.2.1	Taste	0	Sensory panel shall deem mouth feel satisfactory.	Sponsor Developed	Robert	Red

Complete List of User Requirements (Top 3 Critical Requirements **Bolded**)						
Requirement Number	Subsystem	Sponsor Priority *(4 =High)*	Requirement Target & Units	Origin of Validation Method	Subteam/ Individual Responsibility	Status
STRETCH.2.2	Taste	0	Viscosity should be between 5 - 15 (mPa•s)	Recognized Standard Test [7]	Jenny	Red
STRETCH.2.3	Taste	0	Sensory panel shall deem aroma satisfactory.	Sponsor Developed	Robert	Red
STRETCH.2.4	Taste	0	Total dissolved solids should be between 1.5 - 2.25%	Recognized Standard Test [8]	Jed	Red
STRETCH.2.5	Taste	0	pH should be between 4.70-4.80	Student Developed	Donghyun	Red

Appendix B: Piping and Instrumentation Diagram



Appendix C: Full Budget

Total Budget Used: $1,978.60

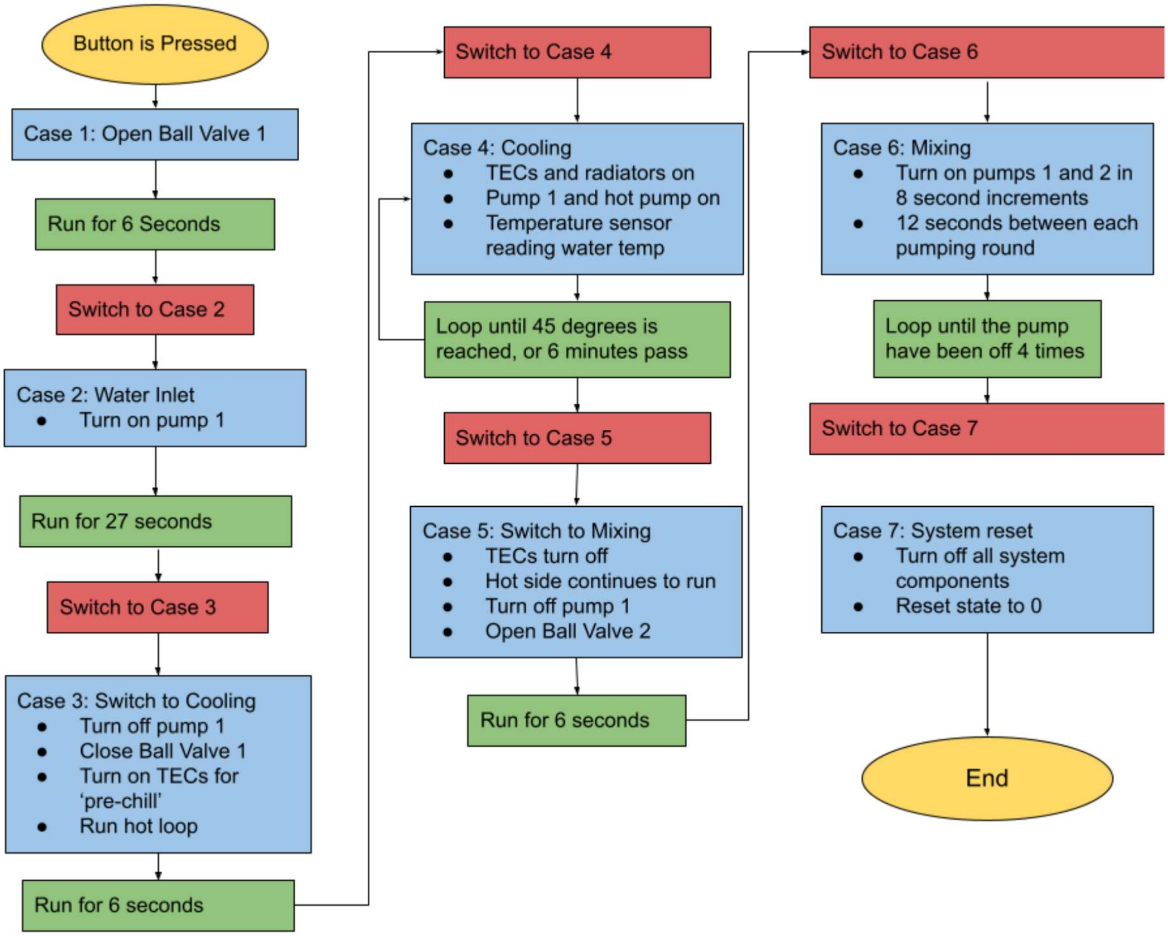
Item	**Quantity**	**Price per unit**
Purchase #1	**2/20/2022**	**Total: $276.98**
BubblingPlus	1	$249.99
Nitrous Oxide Canisters	1	$26.99
Purchase #2	**3/21/2022**	**Total: $15.58**
N2 Chargers	1	$15.58
Purchase #3	**4/6/2022**	**Total: $65.86**
TEC-12705	1	$19.69
Aluminum Water Block	1	$19
Aluminum Heat Sink	1	$8.19
Thermal Adhesive Tape	1 (Lost in Mail)	$5.99
DC Cooling Fan	1 (Lost in Mail)	$12.99
Purchase #4	**9/5/2022**	**Total: $187**
Aluminum Water Block	1	$25
Radiator	1	$39.99
Water Pump	1	$44.99
Power Supply	1	$39.99
3/8” Tubing	3 meters	$16.99
Thermal Paste	1	$6.99
Ball Valve	1	$9.29
Power Cord	1	$4.18

Purchase #5	**9/12/2022**	**Total: $349.51**
Nitro Tap	1	$51.19
Shank	1	$15.99
Teflon Tape	1	$6.99
Hose Clamps	1	$10.99
N2 Tank	1	$50.94
Flow Regulator	1	$101.67
Pressure Vessel	1	$99.99
3/16" Tubing	25 feet	$11.75
Purchase #6	**9/16/2022**	**Total: $153.21**
DS18B20 Temperature Sensor (pack of 5)	1	$9.95
Crimper	1	$24.99
Dowel Pins	1	$3.28
ESP32 Microcontroller (3 pieces)	1	$18.99
Heat Shrink Tubing Kit	1	$6.89
Power Terminals Connectors	1	$16.96
3pcs Relay	2	$10.49
4 pcs 3/16" to 1/4" NPT coupler	1	$8.49
Solenoid Air Valve	2	$9.35
3/8" Tubing	3 Meters	$16.99
Power Zener Diodes (30 pcs)	1	$6.99
Purchase #7	**9/28/2022**	**Total: $70.44**

Power Supply	3	$17.99
PS613163 Power Cord	3	$5.49
Purchase #8	**10/04/2022**	**Total: $36.98**
12705-TECS	1	$30.99
Resistors	1	$5.99
Purchase #9	**10/10/22**	**Total: $276.75**
Pressure Regulator	1	$90
3 pcs Relay Module	3	$10.49
Thread Sealant	1	$7.70
Push-To-Connect	1	$13.99
12715-TECs	1	$30.99
Power Splitter	2	$4.95
550W Power Supply	1	$50.99
Power Extension Cable	2	$8.89
Printer Filament - for in-line reservoir and funnels	1	$0 (Donated)
Silicon Wire	1	$6.98
Copper Wire	1	$16.95
Purchase #10	**10/21/2022**	**Total: $254.35**
[Redacted]	1	$14.99
Reducer	1	$6.99
[Redacted	1	$10.99
Hard Tube	1	$14.25
Check Valves	1	$7.99

2 Way Ball Valve	1	$34.76
3 Way Ball Valve	2	$64.99
3/8” to 1/4” Male NPT	2	$8.21
3/8” to 3/8” Male Adapter	2	$8.99
Purchase #11	**11/18/2022**	**$222.07**
Lever Nuts	1	$28.23
Aluminum Foil Tape	1	$10.98
Radiator	1	$38.99
Air Cooler	1	$24.99
TEC1-12705	2	$17.99
N2 Tank	1	$50.94
Isopropyl Alcohol	1	$8.49
Thermal Paste	1	$5.48
Glue Sticks	1	$17.99
Reimbursements		**Total: $69.45**
Wire Ties	1	$4.49
Foldable Shelf	3	$10
3 Tier Shelving Rack	1	$34.96

Appendix D: Full Code Flow Chart



Appendix E: Prototype Electrical Set-Up