Nostrum High Performance Fuel Injector Test System

Final Report

Kathryn Altes, Katie Lemmen,
Evan Millison, Joseph Williams

ME 450
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109-2125

Section 003: Team 7
Section Instructor: Professor Greg Hulbert
April 22, 2022

Executive Summary

Nostrum High Performance is an automotive part manufacturing company specializing in fuel systems. One of the bottlenecks in the production of their products is leak testing and run-in of fuel injectors. To speed up production, they requested the design and construction of a fuel injector testing machine that can test and run-in 16 fuel injectors at once. This would replace their current equipment that tests one fuel injector at a time. Requirements and engineering specifications were identified for the project. Critical specifications are listed in Table 1 below.

Table 1. Critical project requirements and quantified engineering specifications.

No.	Requirement	Specification
1	Remove the bottleneck from production	Test 16 fuel injectors total
2	Efficient to load	<2.5 minutes to load 16 injectors
3	Efficient to unload	<2.5 minutes to unload 16 injectors
4	Measure pressure drop across injectors to detect leaks	Closed system pressure >9 Bar for 1 minute (nominal = 10 Bar)
5	Limit required power	Power needed <= 1.9kW
6	Heat rejection and Cooling	Maintain operating fluid below its flashpoint (37°C)
7	Run-in frequency	1.2 ± 0.1 ms pulse width 333 Hz for run-in

Our final design has been chosen and is currently in the solution development & verification stage. An overview of the design is shown in Figure 1 below.

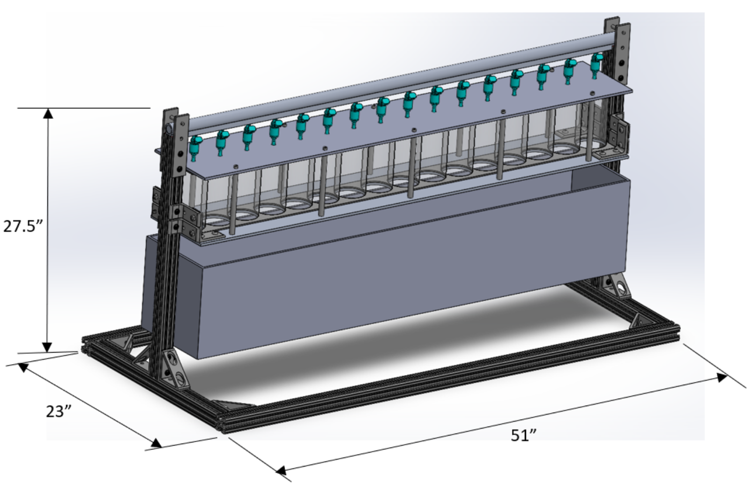


Figure 1. Final design concept CAD.

The last critical milestone is the project handoff, which is to be completed by April 22, 2022.

Table of Contents

1 Introduction

Nostrum High Performance is an automotive part manufacturing company specializing in fuel systems. Nostrum High Performance, like most Tier 1 fuel injector manufacturers, tests 100% of all fuel injectors produced prior to shipping. Newly-made fuel injectors must undergo a run-in/break-in period equivalent to several thousand firing cycles during which the pintle and pintle seat wear together to create a complete seal. After this run-in period, it is also necessary to check that the injector does not leak, as any amount of fuel leakage can cause a vehicle equipped with such injectors to fail emissions testing. Presently both the run-in and leak testing are done as part of the total injector testing and flow characterization at Nostrum's injector test machines, but since these machines can only test one injector at a time, this represents the bulk of the injector test time and a major bottleneck in production. To speed up production, they requested the design and construction of a fuel injector testing machine that can run 16 fuel injectors at once. This would replace their current equipment that tests one fuel injector at a time. The goal of this project is to eliminate the bottleneck of fuel injector testing in Nostrum's manufacturing. Critical design elements involved pump sizing and selection, filtration requirements, and heat rejection quantification and management within the test machine.

1.1 Background

The Fuel Injector Test System project we are working on is sponsored by Nostrum High Performance. Nostrum is an automotive part manufacturer that specializes in upgrading fuel systems in vehicles, specifically fuel injection systems. A large part of what they do is develop and manufacture performance fuel injectors.

Fuel injectors are a limiting factor in upgrading vehicles. When upgrading a car to produce more horsepower, most people consider adding a turbocharger, blower, supercharger, and in extreme cases, a Nitrous Oxide System [1]. These are all upgrades to the air intake system. To keep the engine running at peak performance, the air-to-fuel ratio must stay the same. Traditionally, stock fuel injectors operate around 80% of their total flow capacity [2]. At some point, the stock injectors will not be able to keep the air-to-fuel ratio the same with the additional air flow. This is when performance injectors are needed. When manufacturing these fuel injectors, the pintle seat and pintle ball have a 'close enough' tolerance (Figure 2). This means that the injectors need to have multiple cycles of fluid run through them to wear these two surfaces together to eliminate leaks. After this run-in time, the injectors are checked for leaks. If they pass, they are packaged and sent to customers.

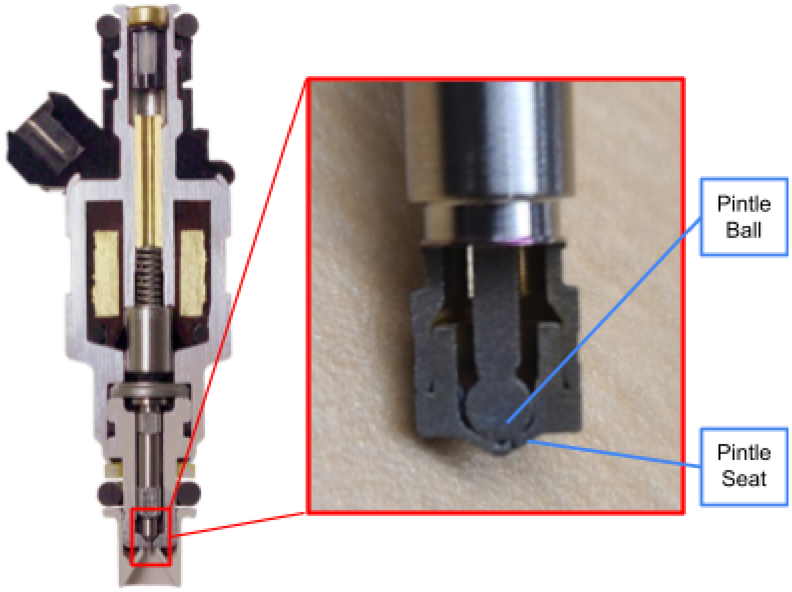


Figure 2. Cutaway diagram of where the pintle ball and pintle seat are in the fuel injector.

Currently, Nostrum has a test set-up that can only take a single injector at a time. In a total day, they can test around 30 injectors. However, a single vendor order can have 50-250 injectors, which would take multiple days to test. This is causing a delay in customer orders and limiting the number of injectors that Nostrum can produce. The fundamental problem is that there are more injectors being ordered and manufactured than can be tested in a timely manner. We were tasked with improving the current system to test more injectors at once.

Nostrum would like a new test rig that can test up to 16 injectors at the same time. This number was determined by looking at the average order size and the amount of time the run-in and leak testing currently take. A new rig that meets this requirement would, by our calculations, be able to test over 700 injectors in a single 8-hour period.

The team at Nostrum has looked into this problem for a while, they just haven't had the people to design it. They told us not to reinvent the wheel in terms of a test system. Our main purpose is to take their current system and build a bigger one. Expanding a pressurized system means that more heat will be produced, thus a better heat management system will need to be put in place. Also higher pressure means the pump needs to be upgraded to support the system.

1.2 Design Process

The design process chosen for our project was the standard model introduced in ME450 [3]. The standard model was chosen due to its streamlined design process. This process consists of six stages that can be revisited as necessary throughout the design. These stages are: need identification, problem definition, concept exploration, solution development & verification, and realization. These steps allow us to structure our timeline to efficiently solve the design problem within the semester. We have completed the first 3 stages of the design process. The project is currently in the solution development & verification stage for our final design. A full manufacturing plan has been completed. Once the design is built and verified our plans for validation can be executed and the final stage of development can be completed.

Other design processes were considered, but we found the standard model to be the most effective. The problem we are addressing does not require the analysis of multiple dependent variables which ruled out the use of the design spiral [4]. The cyclical nature of this design process would not be efficient for this project. Due to the simplicity of the problem, we also decided that a detailed breakdown of the issue was unnecessary and therefore decided not to use detailed design processes such as the product model [4].

1.3 Design Context

1.3.1 Stakeholder Identification

Our primary stakeholder is Nostrum High Performance. Nostrum will be using our test rig for the production and quality control of the fuel injectors they sell to both vendors and aftermarket customers. Its functionality will help to prevent the delivery of faulty and leaking injectors as well as maintain Nostrum's reputation. Additionally, the technicians that work for Nostrum will be using the testing rig multiple times a day, so their safety and well-being must be considered as well [5]. The secondary stakeholders are the aforementioned vendors and aftermarket customers. In particular, aftermarket customers are often looking to increase the power coming out of their engines through both high performance fuel injectors and increasing air intake. Leaking in the fuel injector will cause both these stakeholders to lose out on part of the additional power produced by these modifications and possibly even damage the engine itself [6]. The tertiary stakeholders are other motorists and both the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA). Both the EPA and NHTSA work to set and regulate emission standards for motor vehicles in the US, with the NHTSA also setting and regulating the safety of cars and automotive parts [7, 8]. Fuel injector leaks change the makeup of emissions and can lead to failure to pass emission testing [5, 9]. Additionally, the excessive fatigue leaking injectors can cause can lead to engine failure, which presents a danger to both the driver and the surrounding motorists [6].

1.3.2 Intellectual Property

Intellectual property has not played a role in this project. No part of this project will likely be able to be granted a patent, as the components will not only be widely available for purchase, but will not be altered in a sufficiently unique way to be classified as a new or novel technology. Even the design of the system we create will be similar to existing systems, just with considerations and specs to the needs of Nostrum. The extent intellectual property applies is that our final design will not be advertised to other competitors or made readily available on any open source webspace. This cannot be considered a trade secret, however, because Nostrum will not be actively protective of the design [10].

1.3.3 Information Sources

When starting this project, we talked directly to people at Nostrum High Performance, including Sam Barros, Lee Markle, and a few others. After learning more about their expectations of us, we felt that we needed to understand how fuel injectors work and why there is a demand for performance injectors. We conducted our own research, which was summarized in the background information. We also looked into current solutions - there are multiple systems on the market that can test multiple injectors at once, however their purpose is to test used injectors from cars and clean them so they can be reused. Additionally, since the automotive industry is heavily regulated, we looked at SAE International (formerly Society of Automotive Engineers), to see what regulations they had in place for the run-in and leak testing of fuel injectors. All of our sources are cited in-text where appropriate and a complete list is in the References section.

2 Requirements and Engineering Specifications

After conducting background research, literature review, and interviews with our primary stakeholder, user requirements were defined. These requirements were developed with extensive input from our sponsor. Specifications that can be validated were then developed and confirmed with our sponsor. The requirements and specifications are given in Table 2. These are ordered in terms of importance. The first seven are considered critical to the success of our project.

Table 2. Project requirements and quantified engineering specifications.

No.	Requirement	Specification
1	Remove the bottleneck from production	Test 16 fuel injectors total
2	Efficient to load	<2.5 minutes to load 16 injectors
3	Efficient to unload	<2.5 minutes to unload 16 injectors
4	Measure pressure drop across injectors to detect leaks	Closed system pressure >9 Bar for 1 minute (nominal = 10 Bar)
5	Limit required power	Power needed <= 1.9kW
6	Heat rejection and Cooling	Maintain operating fluid below its flashpoint (37°C)
7	Run-in frequency	1.2 ± 0.1 ms pulse width 333 Hz for run-in
8	Stay within budget	<$2500
9	Minimize run-in cycle time	Cycle run-in <= 5min
10	Safe to use	0 pinch points Documented safety plan for leaks
11	Comfortable to use	Limit repetitive motion to <1 minute during unloading & loading period
12	Filtration to remove debris	10-15 micron for primary 2-3 micron for secondary
13	Reasonably quiet	<70 dB during operation
14	Dimensions	Overall volume is within 5 feet wide x 2.5 feet deep x 2 feet tall

2.1 Justification for Requirements and Specifications

Remove the bottleneck from production (critical). The target of being capable of testing 16 injectors total was determined from discussions with our sponsor. They currently need to test approximately 30 injectors per day. With their current setup that tests one injector at a time, they have a maximum testing capacity of approximately 48 injectors per day, assuming the machine runs continuously for eight hours. Thus, the run-in of injectors is the current limiting factor to Nostrum being able to scale up and increase production of fuel injectors. Nostrum believes that a machine that can test 16 injectors will be sufficient for their future production needs. Additionally, 16 injectors is a number that can be achieved using traditional V8 fuel rails or using fuel rail extrusions. If this requirement is met, Nostrum would be capable of testing 300 injectors in a single 8-hour period.

Efficient to load (critical). The target time for efficient loading of injectors was primarily determined by the run time of the machine. It currently takes approximately five minutes to complete the run-in of an injector. If our machine tests sixteen injectors at once, then the other sixteen can be unloaded and installed with new injectors to test during that time. Thus half of the five minutes is dedicated to unloading the tested injectors, while the other two and a half minutes are for loading new injectors into the machine. In this way, the machine will not have any downtime.

Efficient to unload (critical). The justification for this requirement and specification is the same reasoning provided in the "Efficient to load" requirement justification. Figure 3 shows a visual representation of the timing of each process. These two requirements are critical because improving the efficiency of the overall process is the main goal of this project.

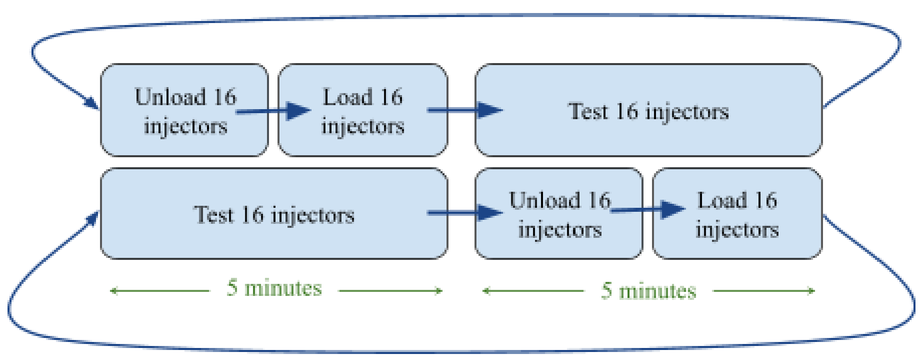


Figure 3. Timing diagram for unloading, loading, and testing the fuel injectors.

Measure pressure drop across injectors to detect leaks (critical). One of the main functions of this machine is to be able to identify any leaky fuel injectors after the run-in process. Thus, the pressure across the closed injectors needs to be measured in order to detect any leaks. Current processes, including the one at Nostrum, use a precise flow meter to detect leaks. However, these flow meters are expensive and thus out of scope for this project. After discussions with our sponsor, we determined that the best way to measure leakage is to monitor pressure using a pressure gauge. The nominal pressure of the system, 10 bar, was set by the sponsor. The specification of staying above 9 bar for one minute after the system is closed is a preliminary specification developed in conjunction with Nostrum. This specification may need to be modified during the validation phase once the system performance is observed.

Limit required power (critical). There is a constraint on the amount of power our machine can draw. Our sponsor wants the machine to be powered by a standard 120 volt outlet at 20 amps. After considering that a circuit should not be loaded to more than 80% of its rating, our machine cannot draw more than 1.9 kW of power [11]. Our preliminary calculations based on pressure and flow rate show that our machine should be able to meet this constraint, and the justification is provided in the Problem Domain Analysis and Reflection section.

Heat rejection and cooling (critical). As the pump increases the pressure of the system, energy is added to the working fluid. Thus, our machine needs to be able to regulate the temperature of the fluid. SAE J1832 and J2713 state that the working fluid needs to be between 21 ± 2℃ before any testing [12] [13]. However, these standards use n-heptane as the working fluid. For safety, Nostrum is having us use Viscor 16A, which has a higher flashpoint than n-heptane. Thus, the main temperature requirement set by our sponsor is to keep the working fluid temperature below its flashpoint of 37°C.

Run-in frequency (critical). The run-in frequency, or the frequency at which current is applied to open and close the fuel injectors, was determined by the sponsor. Nostrum wants the injectors to operate at 333Hz for proper run-in. This corresponds to a period of 3 milliseconds. Our sponsor provided the required Injection Pulse Width (IPW) of 1.2 ms, which corresponds to the period and IPW given by section 9 of SAE J2713 [15].

Stay within budget. Our sponsor provided us with a budget of $2,500. Although an important requirement, this is not considered critical because our sponsor stated that the budget can be increased if proper justification is presented.

Minimize run-in cycle time. The main goal of this project is to increase the number of injectors that Nostrum can produce. Aside from testing multiple injectors at once, the machine needs to test them quickly to achieve this goal. In order to reach our sponsor's desired number of cycles, the machine will have to run for approximately five minutes at 333 Hz. A five minute run-in cycle time also allows for no downtime, as sixteen of them can be loaded and unloaded within this time period.

Safe to use. It's important to consider the safety of the operator using our machine. After our interview with Nostrum, we learned that the most common injury from these run-in test machines is being pinched while loading the injectors. Thus, one specification for safety is that our machine must have zero pinch points. We must design a solution that prevents the operator's hand from being close to where the injectors are clamped in place. Additionally, our machine will be a high pressure fluid system. We will need to conduct validation testing with non-flammable fluids to ensure that our device will not leak. From discussions with Nostrum, we will also need to develop a safety plan that is given to the operator in case a leak does occur while the machine is in use.

Comfortable to use. Ergonomics is another important consideration for the operator of our machine. During our visit to Nostrum's facility, we viewed test rigs that required repetitive motion for long periods of time. In order to load and unload injectors, a screw had to be turned a large number of rotations. For the health of the operator, we want our machine to limit this type of repetitive motion to less than one minute per five minute loading and unloading interval.

Filtration to remove debris. In order to protect the fuel injectors and the pump, as well as to ensure the injectors are free of debris after run-in, a filtration system needs to be integrated into our machine. After communicating with Lee Markle and Jason Haines from Nostrum, we determined that we will need a 10-15 micron filter (likely before the pump) as well as a 2-3 micron filter (likely after the pump) to catch smaller debris.

Reasonably quiet. To protect the hearing of operators, as well as to maintain a reasonable noise level at Nostrum's facility, we want our machine's noise level to be less than 70 dB during operation. The maximum limit for our machine's noise level is 80 dB. These values were determined based upon OSHA 1910.95 and assuming the machine is being continuously used by an operator during an eight hour shift. OSHA 1910.95 requires employee noise exposures to be less than 85 decibels for an 8-hour time interval [14].

Dimensions. Nostrum's facility has a designated space where this machine will be placed. The measurements of that space, provided by Nostrum, are 5 feet wide by 2.5 feet deep by 2 feet tall. Thus, our machine is not to exceed those dimensions.

3 Concept Generation

After creating a detailed list of requirements and specifications for the project, we continued with concept generation. To generate a large quantity of diverse ideas, we used three generation methods. These included morphological charts, Design Heuristics, and BrainWriting.

First, we used the method of morphological charts. Morphological charts break the concept or design into smaller subcomponents [15]. Under each subcomponent a list of solutions is created. These solutions are then combined in various permutations to create a large number of different concept designs. We broke the concept into seven subsystems: fuel delivery, pressure system, filtration, fuel drainage, heat rejection, mounting, and valve type. During this process we realized that generating a diverse set of solutions to the subcomponents would be more beneficial than creating many different full concept designs. Therefore, all further concept generation using Design Heuristics and BrainWriting was done at the subcomponent level.

Design heuristics is a concept development method that employs the use of 77 different prompts to aid idea generation [16]. Multiple prompts can be used on the same base concept to create many new concepts instead of just one solution. One of the Design Heuristics used was to make components attachable or detachable. This led to one of our final designs for the mounting subcomponent of our system. We decided to create a removable fuel rail to attach the fuel injectors to the system. Another prompt that was given was using the environment. Using this idea we decided creating the system in Antarctica would solve our heat rejection problem. As shown by the examples above, the use of Design Heuristics allowed both practical and improbable solutions in our design space. This allowed the group freedom to search for new perspectives and come up with diverse solutions.

After individually coming up with our own ideas, we met together as a group and used the method of a BrainWriting pool to build off of each other's ideas. During the BrainWriting pool each group member wrote their ideas on the whiteboard and everyone was free to build off of all the ideas or combine them as they saw fit [17]. This increased the number of ideas created and fostered teamwork. The end product of these methods can be seen in Table 3. While we had many other ideas, the ones listed in the table were the ones we considered to be practical in our application. Combining one component from each subsystem resulted in a high volume of generated concepts. All of the generated concepts can be found in Appendix B.

Table 3. Morphological chart used for concept generation. Subsystems are listed in the left hand column with corresponding concepts on the right. These were the concepts that fit within our design specifications.

Fuel Delivery	Braided Nylon Fuel Lines	Braided Steel Fuel Lines	Hard Metal Fuel Lines
Pressure System	Hydraulic Pump	Mechanical Pump	Automotive Pump
Filtration	1 Filter: 10-15 Micron	1 Filter: 2-3 Micron	2 Filters: Primary: 10-15 Micron Secondary: 2-3 Micron
Fuel Drainage	Large Drainage Tank	Individual Glass Cylinders	
Heat Rejection	Chiller	Radiator	Fan
Mounting	Extruded Fuel Rails	OEM Fuel Rails	
Valve Type	Manual Valve	Solenoid	

4 Concept Selection

For concept selection, each subsystem was scored individually and then all chosen concepts were combined into the alpha design. After generating numerous design concepts, designs were narrowed down to two or three ideas for each subsystem and selected for further analysis using scoring matrices. The final concepts for each subsystem are currently within all of our specifications and Nostrum has responded positively to each concept when presented in meetings. The final design was selected by the highest scoring design for each subcomponent.

Fuel Delivery

The fuel delivery system is responsible for transporting the fluid throughout the system. Three concepts were considered when choosing the fuel delivery component. These included braided nylon fuel lines, braided steel fuel lines, and hard metal fuel lines. They were evaluated based on three equally weighted criteria due to their importance in the success of the full design. The three criteria considered were cost, ability to withstand fluid pressure of 150 kPa, and no fluid leaks in the system. These were based on the project requirements of meeting the budget and measuring pressure drop across injectors to detect leaks. The results of the analysis are shown in Table 4 [18].

Table 4. Scoring matrix for fuel delivery systems. Unless otherwise noted, the weight of each criteria is one.

Criteria	Braided Nylon Fuel Lines	Braided Steel Fuel Lines	Hard Metal Fuel Lines
Cost	Datum	-	-
Withstand Pressure of 150 kPa	Datum	0	0
No Leaks	Datum	0	0
Total	0	-1	-1

All fuel lines considered met the requirements needed to transport fluid throughout the system [18]. The cost for braided nylon fuel lines, however, was less than other alternatives and therefore selected as the optimal solution.

Pressure System

The pressure system is responsible for maintaining a fluid pressure of 10 Bar when testing the fuel injectors. Three concepts were considered when choosing the pressure system component. These included a mechanical pump, hydraulic pump, and automotive. They were evaluated based on four equally weighted criteria due to their importance in the success of the full design. The three criteria considered were cost, efficiency, heat rejection, and size. These were based on the project requirements of meeting the budget, limiting required power dimensions, and heat rejection and cooling. The results of the analysis are shown in Table 5 [19, 20, 21].

Table 5. Scoring matrix for pressure systems. Unless otherwise noted, the weight of each criteria is one.

Criteria	Mechanical Pump	Hydraulic Pump	Automotive Pump
Cost	Datum	-	+
Efficiency	Datum	-	+
Heat Rejection	Datum	0	0
Size	Datum	+	0

Total	0	-1	+2

The automotive pump was selected due to its cheaper cost and higher power efficiency [19]. It also was able to reach the baseline heat rejection and size requirements. The hydraulic pump also met requirements but due to its general use for much greater pressures it is inefficient for the application proposed [21].

Filtration
The pressure system is responsible for maintaining a debris-free fluid for entering the fuel injectors. This ensures there is no damage to fuel injectors during testing. Three concepts were considered when choosing the filtration component. These included a one 10-15 micron filter, one 2-3 micron filter, and two filters with one being 10-15 micron filter and the other being 2-3 micron filter. They were evaluated based on two unequally weighted criteria. The two criteria considered were cost and filtering. Due to the importance of maintaining a debris free fluid for the fuel injectors the weight of this criteria was twice that of cost. These were based on the project requirements of meeting the budget filtration to remove debris. The results of the analysis are shown in Table 6 [22, 23].

Table 6. Scoring matrix for filtration systems. Unless otherwise noted, the weight of each criteria is one.

Criteria	Weight	2 Filters	10-15 Micron Filter	2-3 Micron Filter
Cost	1	Datum	+1	+1
Filters Large and Small Debris	2	Datum	-2	-2
Total		0	-1	-1

The use of both the 10-15 micron filter and 2-3 micron filter was selected due to its ability to ensure all debris was removed from the fluid before flow through either the fuel injectors being tested or the pump. Although it would be cheaper to select just one filter, neither filter alone would be able to maintain the fluid and prevent damage to injectors and additional fatigue to the pump.

Fuel Drainage
The fuel drainage is responsible for collecting fluid that was passed through injectors and is cycled back into the system. Two concepts were considered when choosing the fuel drainage component. These included individual glass cylinders and a large drainage tank. They were evaluated based on four equally weighted criteria due to their importance in the success of the full design. The three criteria considered were cost, leak identification, fluid storage, and ability to withstand corrosion. These were based on the project requirements of meeting the budget and use of corrosive fluid Viscor 16A. The results of the analysis are shown in Table 7 [5, 24, 25].

Table 7. Scoring matrix for fuel drainage systems. Unless otherwise noted, the weight of each criteria is one.

Criteria	Individual Glass Cylinders	Large Drainage Tank
Cost	Datum	+
Leak Identification	Datum	-
Fluid Storage	Datum	0
Withstand Corrosion	Datum	-
Total	0	-1

The individual glass cylinders were selected due to their ability to withstand corrosion from constant exposure to Viscor 16A, and ease of use by technicians to identify leaking fuel injectors [5]. Although the cost is higher, it is currently within budget and worth the investment.

Heat Rejection

The heat rejection system is responsible for maintaining a working fluid temperature well below its flash point. Three concepts were considered when choosing the heat rejection component. These included a chiller, radiator, and fan. They were evaluated based on three equally weighted criteria due to their importance in the success of the full design. The three criteria considered were cost, ability to maintain fluid temperature, and size. These were based on the project requirements of meeting the budget, heat rejection and cooling, and dimensions. The results of the analysis are shown in Table 8 [26, 27, 28].

Table 8. Scoring matrix for heat rejection systems. Unless otherwise noted, the weight of each criteria is one.

Criteria	Chiller	Radiator	Fan
Cost	Datum	+	+
Maintain Fluid Temperature	Datum	0	-
Size	Datum	+	+
Total	0	+2	-1

The radiator was selected due to its low cost and smaller size [28]. The fan was also more cost effective and smaller than the chiller, but it would not be sufficient in maintaining the fluid temperature [27]. Depending on the amount of heat we need to reject, we may have to revisit this subsystem and possibly combine concepts.

Mounting

The mounting system is responsible for holding the fuel injectors while they are being tested. Two concepts were considered when choosing the mounting component. These included extruded fuel rails and OEM fuel rails. They were evaluated based on three equally weighted criteria due to their importance in the success of the full design. The three criteria considered were cost, ability to hold 16 fuel injectors, and efficiency of unloading and loading fuel injectors. These were based on the project requirements of meeting the budget, removing the bottleneck of production, efficiency of loading, and efficiency of unloading. The results of the analysis are shown in Table 9 [29, 30].

Table 9. Scoring matrix for mounting systems. Unless otherwise noted, the weight of each criteria is one.

Criteria	Extruded Fuel Rails	OEM Fuel Rails
Cost	Datum	-
Holds 16 Fuel Injectors	Datum	-
Efficient to Load/Unload	Datum	0
Total	0	-2

The extruded fuel rails were selected due to their cheaper cost and ability to hold 16 fuel injectors [30]. Both fuel rails are unloaded and loaded with the same efficiency, but OEM fuel rails are limited in their fuel injector capacity [29].

Valve Type

The valve type component is responsible for opening and closing the line providing fluid to the fuel injectors. Two concepts were considered when choosing the valve type component. These included a solenoid valve and manual. They were evaluated based on four equally weighted criteria due to their importance in the success of the full design. The four criteria considered were cost, automation ability, ease of implementation, and safety. These were based on the project requirements of meeting the budget, being comfortable to use, ease of assembly and being safe to use. The results of the analysis are shown in Table 10 [5, 31, 32].

Table 10. Scoring matrix for valve types. Unless otherwise noted, the weight of each criteria is one.

Criteria	Solenoid Valve	Manual Valve
Cost	Datum	+
Automation Ability	Datum	-
Ease of Implementation	Datum	+

Safety	Datum	+
Limit repetitive motion	Datum	-
Total	0	+1

The manual valve was selected due to its cheaper cost, ease of implementation, and safety [32]. The only consequence to this choice is that the system can not be automated. The benefits, however, far outway the inability to automate the system.

5 Selected Concept Description

The selected concept uses a combination of the multiple subsystems that were chosen during the concept selection process. By integrating these top subsystems into one concept, we were able to create the “Alpha Design”. It’s important to note that this is strictly a preliminary design. The components, the ordering of the components, and the materials used in the design are subject to change as the project progresses and more information is acquired.

The selected concept makes use of a removable fuel rail to attach the fuel injectors to the system, a choice that was guided by design heuristics. This testing method allows for 16 injectors to be in the machine being tested, while another 16 are simultaneously being loaded into a separate fuel rail. This process is shown in Figure 4, where the green fuel rails are detachable. Figure 4 also shows the other high-level components of the system. The motor and automotive pump combination were chosen for the pressure system. The pump is an automotive power steering pump. The fluid then passes through the radiator, which includes a fan to cool the fluid. Primary and secondary filters are used to filter debris from the system. The manual valve can be used to quickly close the system. Additionally, an emergency stop is included to quickly cut power to the motor for the pump. The injectors fire into glass cylinders, which are used to detect any leaks after the run-in process. An arduino system is used to supply current to the injectors, as well as to power an LED light that indicates the status of the run-in process.

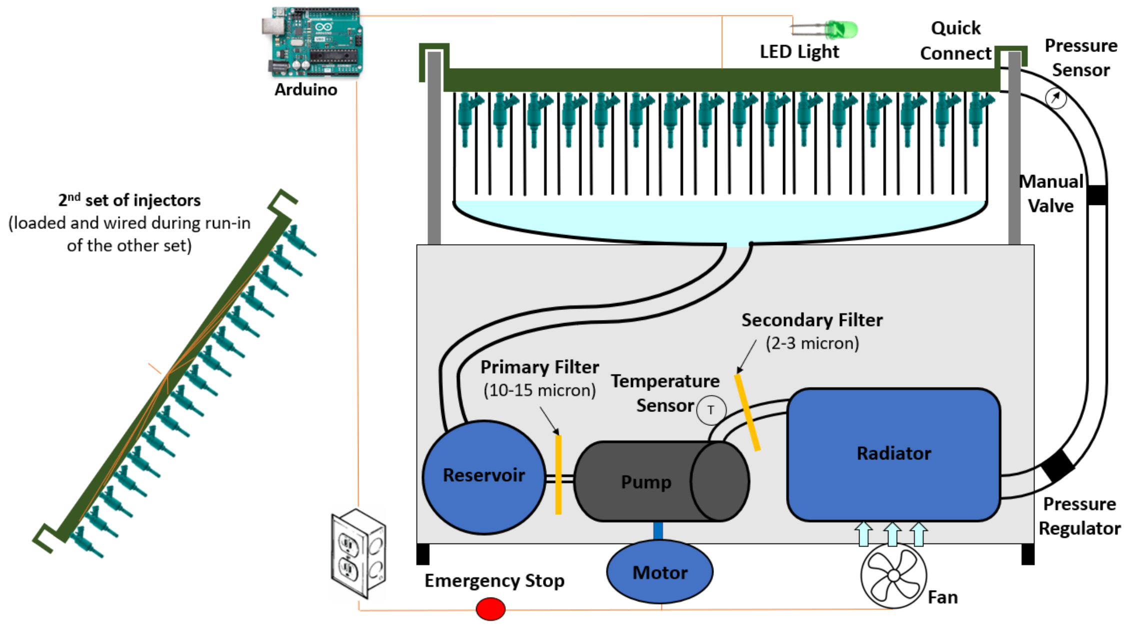


Figure 4. Overview of the selected design concept, which allows for simultaneous testing and loading/unloading of fuel injectors.

Figure 5 provides a more detailed fluid flow diagram of the selected concept. A temperature sensor will be integrated immediately after the pump in order to ensure that the fluid does not reach its flashpoint. A fuel pressure regulator is integrated after the radiator in order to ensure that the pressure supplied to the injectors is 10 bar; the remaining fluid is returned to the reservoir with the return line. A pressure sensor is placed immediately before the valves in order to confirm that the correct pressure is being supplied. A quick connect valve that is normally closed ("NC") is added between the manual valve and the fuel rail. This allows the fuel rail to be easily removable from the test machine.

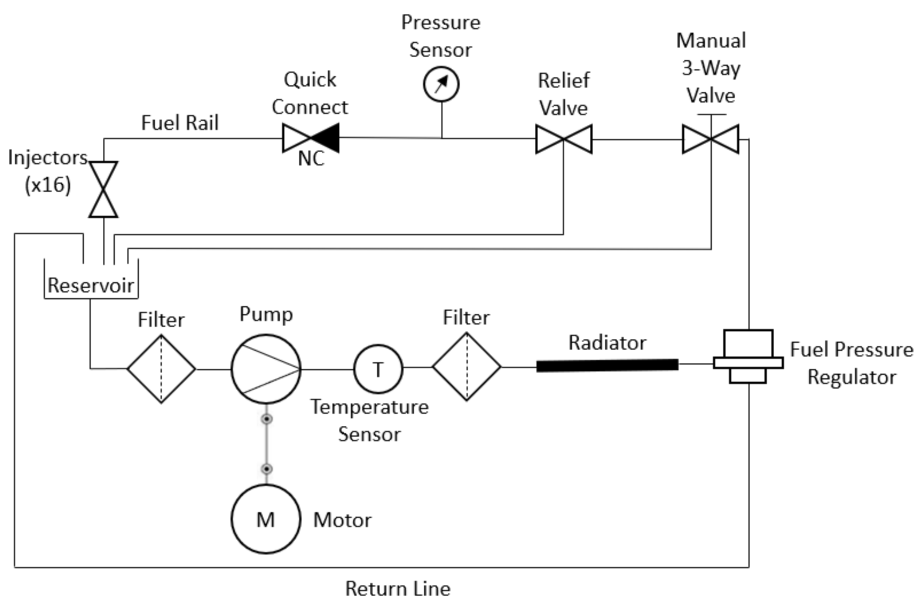


Figure 5. Fluid flow diagram of the selected concept.

Figure 6 provides a detailed overview of the electrical system. The power will be drawn from a single 120 volt outlet at 20 amps. This will directly power the motor for the pump, with an emergency cut off button in between that allows the operator to quickly disable the pump. The outlet will also directly power the fan used to provide airflow through the radiator. Lastly, the outlet will be used to power a motor driver, the specifics of which are to be determined. This driver will use an arduino controller to provide correct signals of current to the injectors. The arduino controller will also be used to power an LED indicator that shows the status of the run-in process.

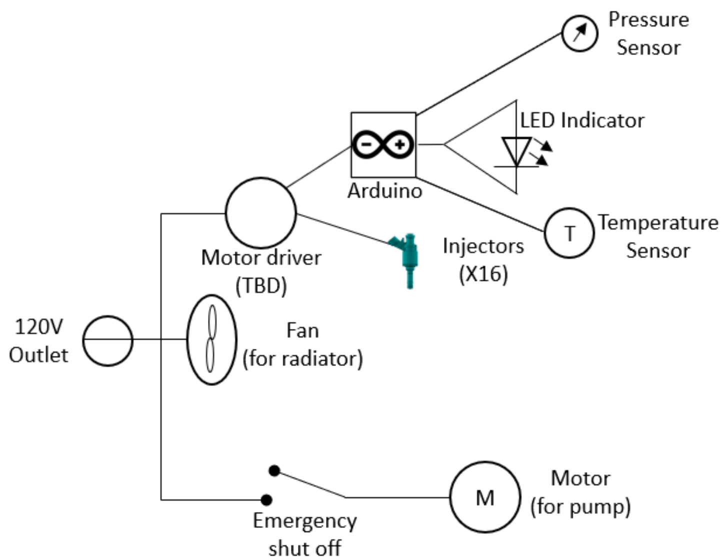


Figure 6. Electrical diagram of the selected design concept.

Although the selected design was chosen with some degree of sponsor influence, Nostrum's feedback was extremely useful in guiding our design process. Our sponsor's knowledge of topics related to the design problem helped guide our concept generation rather than over define it. Additionally, we looked into other injector leak testers, which our design is similar to but different due to our specification. For these reasons, we do not believe that an objective selection process would lead to a different concept selection. With the types of components specified, the number of injectors to be tested defined, and pressure requirements and expected flow rates provided from our sponsor, the selected concept is certainly well-enough defined to be analyzed using engineering principles.

6 Engineering Analysis

With our final design selected, we can begin to perform more analysis to verify that our concepts will work in theory. Thermodynamics, fluid dynamics, systems of control, and heat transfer will present the most useful theoretical models for our analysis. The thermal and fluid sciences will allow us to analyze our rig as a cycle and give us calculated specifications for purchasing the pump, radiator, drainage, fuel lines, and fittings.

Power Requirement

Equations below show preliminary calculations (based on flow rate and pressure) that show we expect to draw much less than 1.9 kW (~3 horsepower) of power to run the system. This also indicates how much power is going into the system and can be used as a benchmark of how much power needs to be removed from the system in order to run continuously in a safe manner. Calculation of the power requirement during operation of the test rig is shown below. The flow rate was given by Nostrum.

$$Viscor\ 16A\ density\ (approx.):\ 790\ {}^{kg}/_{m^3}$$

$$Flow\ Rate\ (from\ Nostrum): 7\ {}^{g}/_{s}$$

$$Volumetric\ Flow\ Rate = \frac{1}{790{,}000}\,{}^{m^3}/_{g}\ \cdot\ 7\,{}^{g}/_{s}\ \cdot 1{,}000\,{}^{L}/_{m^3} \cdot 60\,{}^{s}/_{min} = 0.54\,{}^{L}/_{min}$$

$$Power/injector = \frac{0.54\,{}^{L}/_{min} \cdot 10\ bar}{600} \cdot 1{,}000 = 8.9\ {}^{W}/_{injector}$$

$$Total\ Power = \frac{8.9\ {}^{W}/_{injector} \cdot 16\ injectors}{746} = 0.2\ horsepower$$

Sizing Pump

Nostrum has given that they want fuel injectors to be leak tested at a nominal pressure value of 10 bar (145 psi). The volumetric flow rate below shows that according to our analysis, the pump needs to supply 0.54 L/min per injector (2.3 gpm total) of volumetric flow to provide enough fluid to all 16 injectors during testing. The Minimum volumetric flow required calculated using flow rate given by Nostrum is shown below.

$$Volumetric\ Flow\ Rate = \frac{1}{790{,}000}\,{}^{m^3}/_{g}\ \cdot\ 7\,{}^{g}/_{s}\ \cdot 1{,}000\,{}^{L}/_{m^3} \cdot 60\,{}^{s}/_{min} = 0.54\,{}^{L}/_{min}$$

Because volumetric flow and pressure have an inverse relationship in pump performance, special care needs to be taken when selecting a pump, ensuring it is able to produce both our selected pressure and flow rate.

Fluid Temperature

In order for our design to be safely run it must be able to maintain a fluid temperature less than the flash point of Viscor 16A. It was assumed that the highest temperature reached would be directly after the fluid went through the pump. This is where the most power is being input into the fluid which would cause a temperature increase. To calculate the maximum temperature the fluid would reach Eq. 1 is used:

$$W_{pump} = mC_{p,fuel}\left(T_{out} - T_{in}\right) \qquad (1)$$

where W_{pump} is the power of the pump in kW, m is the mass flow rate in kg/s, $C_{p,fuel}$ is the specific heating capacity of the fuel in kJ/kg-K, T_{out} is the temperature of the fluid leaving the pump in ℃, and T_{in} is the temperature of the fluid entering the pump in ℃. For this calculation several assumptions were made. It was also assumed that the power input by the pump would be the maximum motor power of 1 HP. The pump should not require this much power, but it is the maximum amount that will be input into the fluid. Due to the slight change in temperature of the fluid it is also assumed that the specific heating capacity is constant. Lastly, the environment of the facility this machine is used will be temperature controlled and it is assumed that the fluid sitting in the reservoir will be at room temperature (20 ℃) before entering the pump. Using Eq. 1

and solving for T_{out} the maximum temperature reached by the fluid after one cycle was calculated to be approximately 23.5 ℃. More detailed analysis and calculations are shown in Appendix A.

Radiator Heat Rejection

One of the most important components of the project to consider was proper heat rejection. If the radiator selected did not reject enough heat, it would result in a safety hazard for all parties operating the machine. To verify our selected radiator we applied the ideal heat exchanger energy equation given by Eq. 2:

$$m_{fuel}C_{p,fuel}\Delta T = m_{air}C_{p0,air}\Delta T \tag{2}$$

where m_{fuel} is the mass flow rate of the fuel, $C_{p,fuel}$ is the specific heat capacity of the fuel, ΔT is the change in temperature of the fluids, m_{air} is the mass flow rate of air, and $C_{p0,\ air}$ is the specific heat capacity of air. Several assumptions were made when using this calculation. It was assumed that the radiator behaved as an ideal heat exchanger and the change in temperature of both the air and the fuel was the same. It was also assumed that air behaved as an ideal gas and cold air approximations could be applied. We used this assumption because the air did not have a large temperature change and also was not at an extreme temperature or pressure. Due to the small temperature change, it was also assumed that the specific heat capacity of the fuel could be taken as constant. Using these assumptions and solving for m_{air} , the required mass flow rate of the air through the radiator was found to be approximately 0.21 kg/s. Comparing this value to the maximum air flow rate of the radiator, it was found that the capacity of the radiator selected is 1.7 times more than the required air flow. More detailed analysis and calculations are shown in Appendix A.

Reservoir Volume

In order for the machine to run properly, it is imperative that enough fluid is provided to the system at all times. To ensure no air enters the system a required volume for the reservoir had to be calculated. Three calculations were done to find the total volume necessary for the reservoir. We first calculated the amount of fluid it would take to fill each injector cylinder half full. Using basic geometric equations it was found that the volume required would be about 340 in^3. Next the total volume of fluid in the fuel lines was calculated. Due to not knowing the exact length of fuel lines used in our system, we assumed that 15 feet of fuel lines were used. This was a safe assumption because it is three times the maximum length dimension of our final design. Using basic cylindrical geometric equations, the total volume of fluid within the lines was found to be approximately 55 in^3. Lastly, we considered the volume of fluid in the radiator. This value was provided by the radiator supplier and was 169 in^3. Adding all three component values together we found that a reservoir volume of 564 in^3 or approximately 2.5 gallons was required. Adding a safety factor of two the final reservoir selected was five gallons. More detailed analysis and calculations are shown in Appendix A.

Maximum Beam Bending Stress

Calculations were performed to ensure that the posts that hold the fixture can withstand the weight that they will support. In order to do this, a worst case scenario was considered, where the entire catch basin is filled with the working fluid. The bending moment of this weight between the two posts is given by Eq. 3:

$$M = (W/2)(L/2) \quad (3)$$

Where W is the weight of the basin filled with working fluid and L is the length between the two posts. Thus, M is the bending moment on each post. This moment can then be used to calculate the maximum bending stress induced in each post, given by Eq. 4:

$$\sigma_{max} = y(M/I) \quad (4)$$

Where y is the distance from the beam's neutral axis to its edge and I is the centroidal moment of inertia of the beam's cross section. These equations assume that each post has a square cross section. The maximum bending stress in each post was calculated to be 6.5 MPa, which is well below the yield stress of aluminum (approximately 240 MPa). This allows us to be confident that the chosen posts can hold the weight of the fixture.

7 Final Design

7.1 Detailed Design Solution

Based on the engineering analysis, all final design decisions could be made. It was decided that an automotive steering pump with the ability to handle a pressure of 10 Bar and a volumetric flow rate of at least 2.3 gpm should be selected to pressurize the system. We found that to power this pump, a motor of one HP should be used. Based on the pump selection and engineering analysis for heat rejection, it was determined that the radiator should be able to reject at least one HP of heat from the fluid. Using the reservoir calculations, we found a five gallon reservoir to be the most suitable for our application. Lastly, the maximum bending stress calculations validated the use of t-slots for our structural support and mounting purposes.

The structural layout of our design is shown in Figures 7-11 below. Fuel line fixtures are not shown. Our entire design will be limited to a movable work table. On top will be the fuel injectors and drainage setup. This includes the fuel rails, glass cylinders, drainage basin, and fuel rail mount. Underneath the table will be the radiator, pump, motor mount, filters, and reservoir.

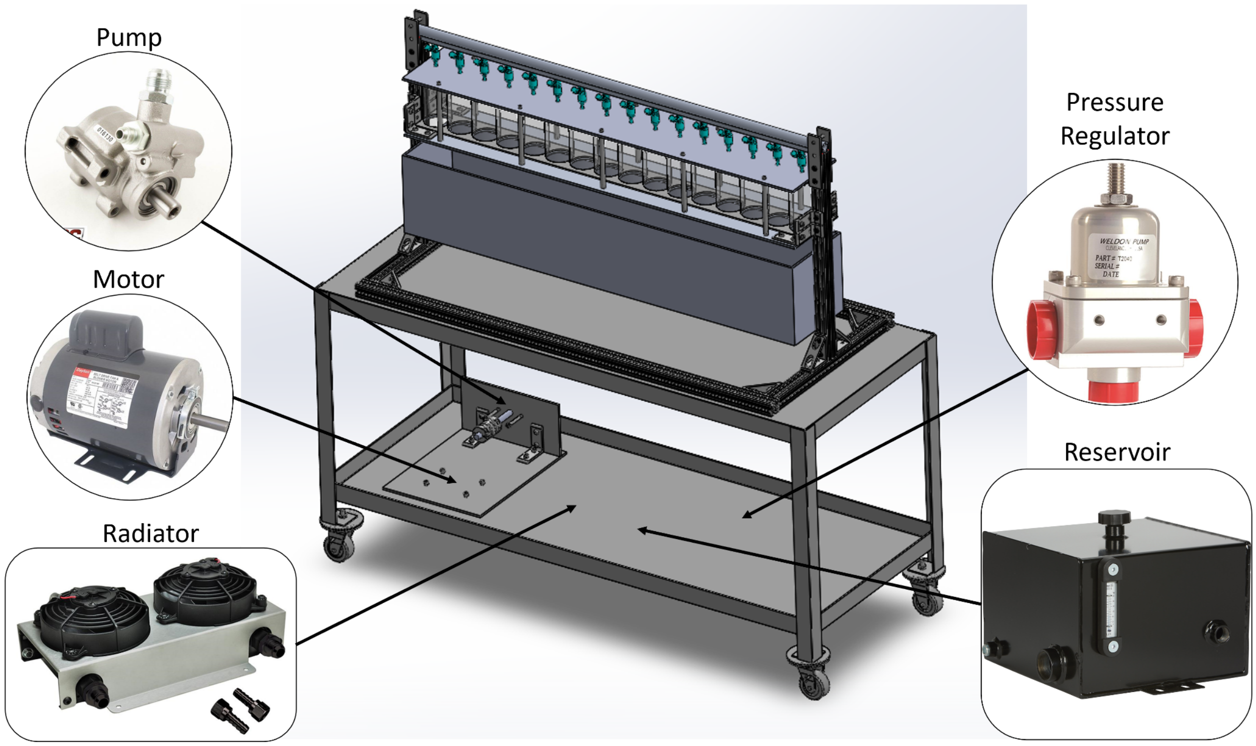


Figure 7: Full workspace setup for final design.

On top of the work bench is where all visual inspection of fuel injectors will be done. Two removable fuel rail extrusions will be created so the operator can load and unload fuel injectors with ease. Creating two fuel rails will also allow the operator to load and unload one rail while the other is in operation. The removable fuel rail will be secured to the system using a quick connection and locked in place during testing. Operators will be able to watch the fuel injectors run and notice any immediate defects in the fuel injectors. There will also be a pressure gauge for the operator to identify if there are any leaks from the fuel injectors.

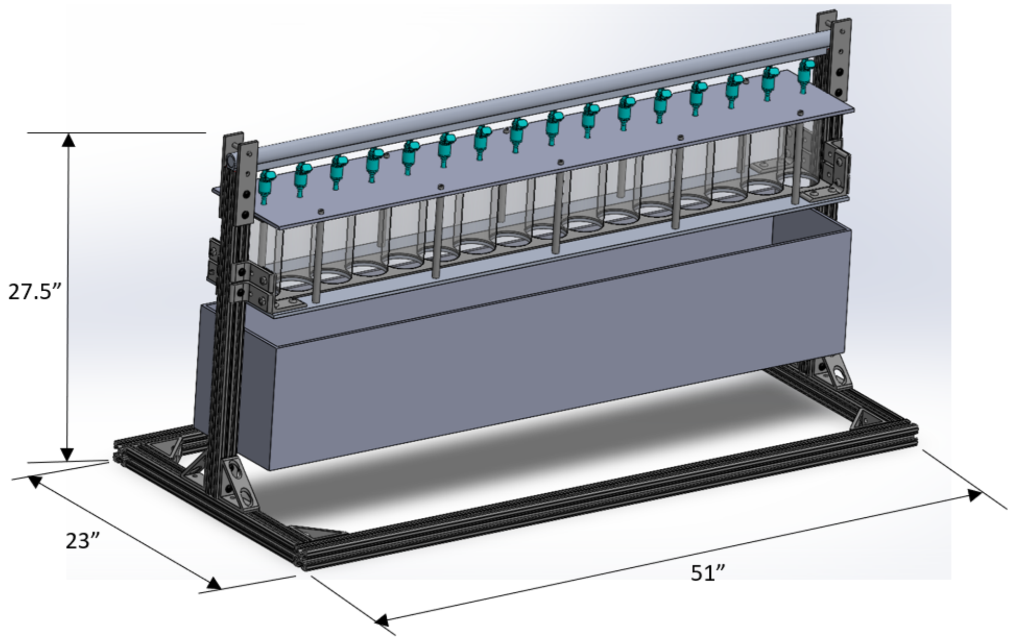


Figure 8: Mounting on top of table. This includes the fuel rails, glass cylinders, drainage basin, and fuel rail extrusion mount.

An important feature of our design is the glass cylinder mounting. The 16 cylinders will be in between two sheets of machined sheet metal insulated with Buna-N mats. The two sheets and Buna-N mats will be bolted together to secure the glass cylinders. The cylinder mounting will then be bolted to the t-slots where it can be adjusted to the proper height for any sized fuel injector. The motion for this component is shown in Figure 9 below. A drainage basin is placed directly below this mount. The drainage basin will collect the used fluid and the fluid will be redirected into the reservoir under the table using fuel lines.

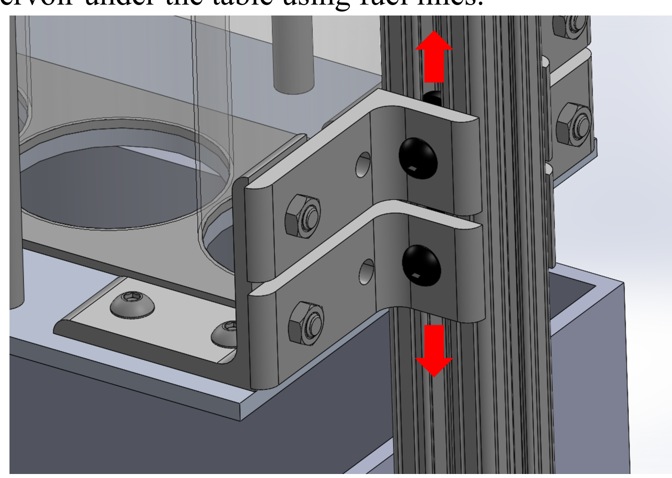


Figure 9: Vertical motion of glass cylinder mounting.

Another feature of our final design is the constraining of the fuel rail extrusions. Once placed on the t-slots, a pin will be used to constrain the vertical motion of the fuel rails. To constrain the lateral motion of the fuel rails a slot will be machined into the t-slot. This is demonstrated in Figure 10 below.

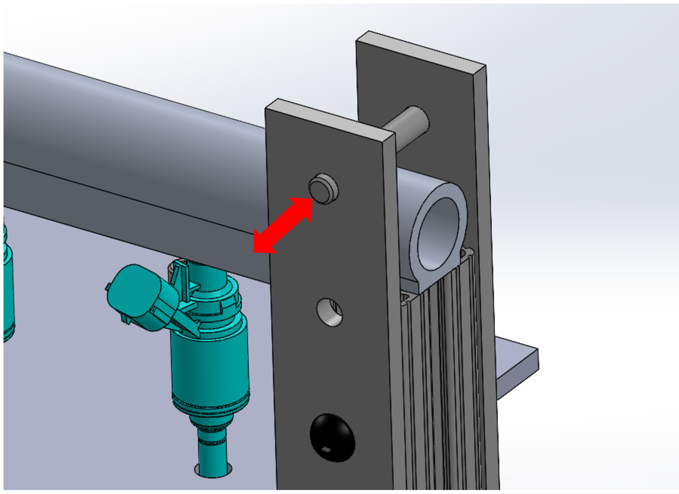
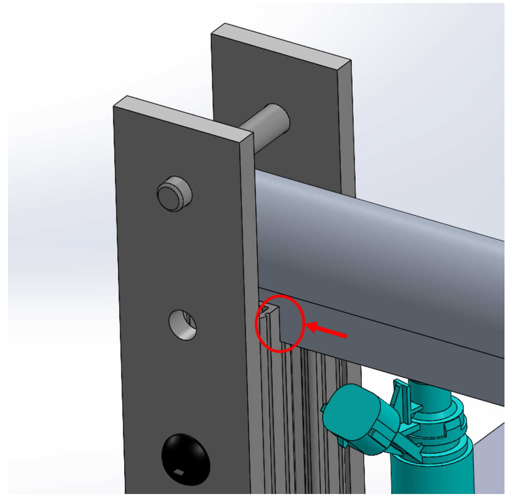



Figure 10: (Left) Highlights the pin constraining the fuel rail extrusion in the vertical direction. (Right) Highlights the slot machined into the t-slot to constrain lateral motion.

Another important component of the design is the motor and pump mount. This is responsible for holding the components in place as well as limiting the effect of vibrations on the system. Detailed CAD of the mount is shown in Figure 11.

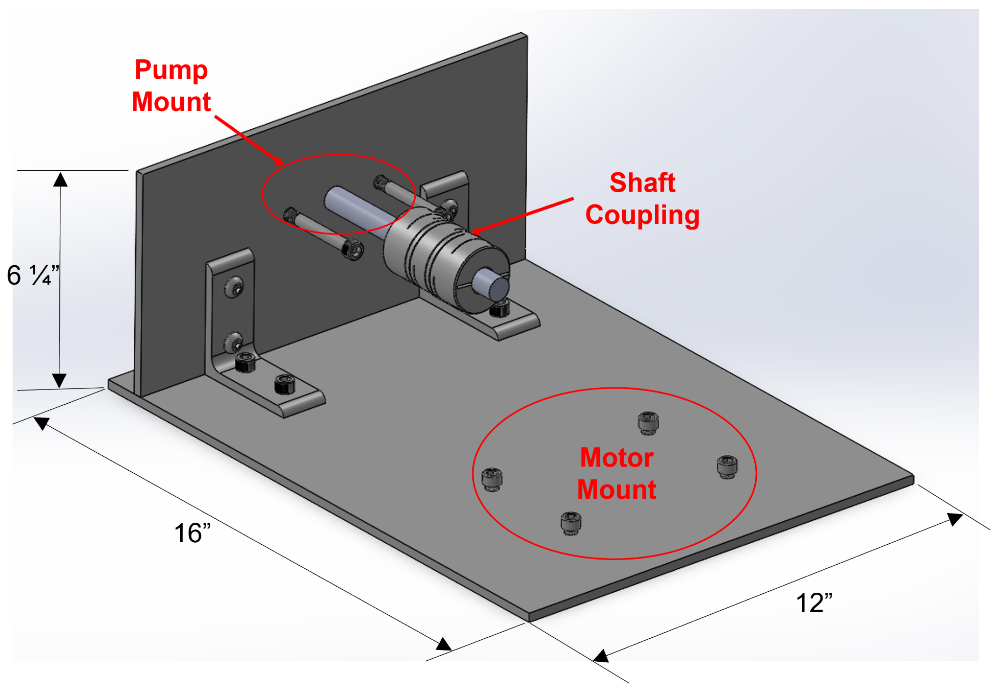


Figure 11: Mounting for the motor and steering pump.

All components underneath the workbench will be linked together using braided nylon fuel lines. These will transport the fuel in the pressurized system from component to component. The connection for our fuel lines can be visualized as seen in the fluid flow diagram below in Figure 12.

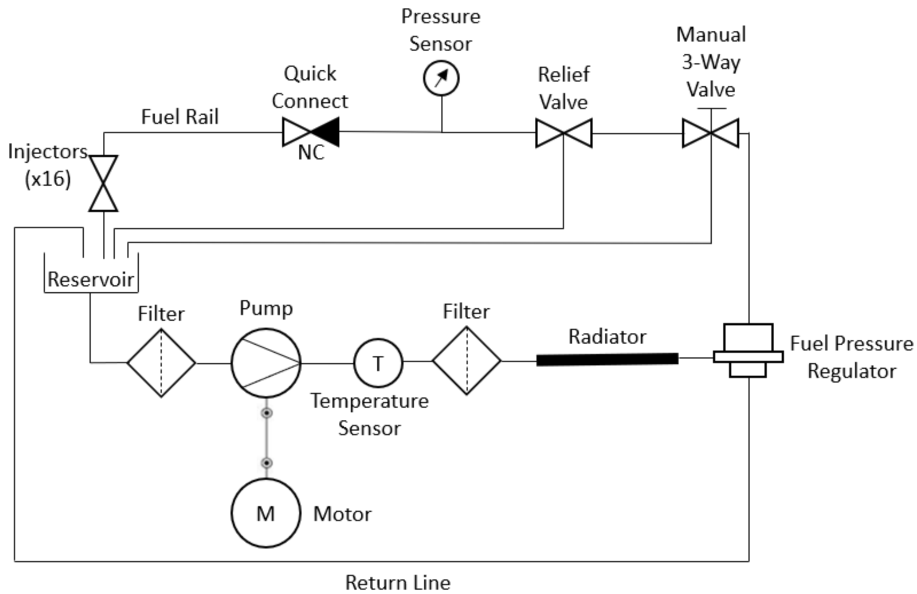


Figure 12: Fluid flow diagram for the entire testing system.

The electrical wiring diagram is also provided for the system in Figure 13.

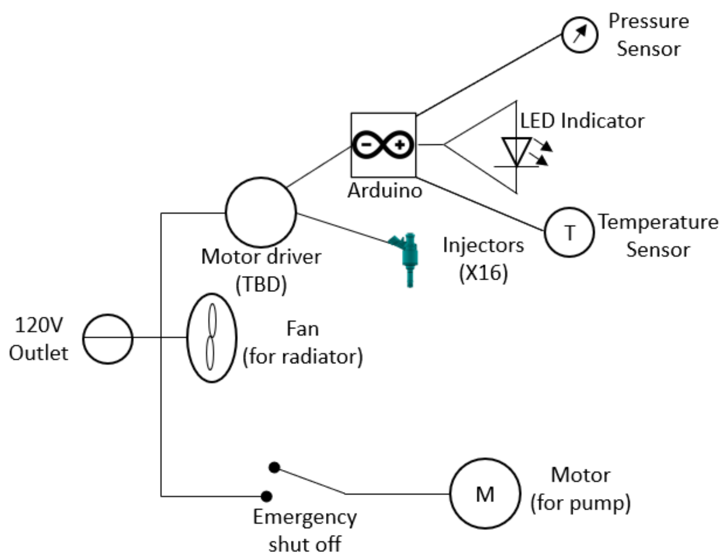


Figure 13: Wiring diagram for the entire testing system.

7.2 'Build' Description

From the above design description, the necessary parts have been selected and the process for building the prototype has been determined.

Bill of Materials

With the final design determined, the parts and materials needed were ready to be sourced. All major components are listed in Table 11, along with their price, part number, and whether they have been ordered yet. All of these parts have been finalized and selected. The frame and motor-pump mount assemblies are listed in more detail in Table 12 and 13 respectively.

Table 11. Overall Bill of Materials. Tables 12 (Frame), 13 (Motor-Pump Mount), and 14 (Fittings) walk through the bottom three entries in more detail.

Vendor	Name	Price	Part Number	Status
Summit	Pump	$200.00	PFN-SP1200X	Arrived
Summit	Radiator	$261.79	DER-15845	Arrived
Summit	Fuel Pressure Regulator	$290.00	WDN-T2040-200	Arrived
Northern	Reservoir	$179.99		Arrived
Ross Machining	Fuel Rail Extrusion	$108.00	RMR-020	Arrived
Ross Machining	Fuel Rail Drill	$129.95	RMR-076	Arrived
Zoro	Motor	$205.56	6K321	Arrived
RHM Fluid Power	3 micron filter	$108.50	A880031087	Not ordered yet
RHM Fluid Power	10 micron filter	$108.50	A880101087	Not ordered yet
Grainger	Dump valve (manual)	$31.85	1PZA1	Not ordered yet
AN Hose	-8AN Male to 3/8" Quick-Connect	$8.90	MQ-08-06	Not ordered yet
AN Hose	-8AN Male Flare to 3/8" Quick-Connect Female Socket Adapter Fitting	$13.90	MQFC-08-06	Not ordered yet
AN Hose	-8AN Male Flare to 3/8" Quick-Connect Female Socket Adapter Fitting	$13.90	MQFC-08-06	Not ordered yet
Grainger	Pop-Off valve	$152.50	69A1-150	Not ordered yet
McMaster	Steel Table	$622.94	5167T27	Not ordered yet
McMaster	Buna N sheet	$121.80	8635K364	Not ordered yet
McMaster	Coupling	$143.09	6208K687	Wrong size ordered
N/A	Fixture	$1,081.41	N/A	N/A
N/A	Motor-Pump Mount	$113.31	N/A	N/A
N/A	Fittings	$250.12	N/A	N/A
	Total:	**$4,146.01**		

Table 12. All parts required for assembling the Frame, otherwise known as the fixture that holds the injectors as listed below. A majority of these materials have been sourced from McMaster.

Vendor	Name	Quantity	Price per item	Total Price	Part Number	Status
McMaster	1.50” X 1.50” X 24" Ultra-LiteT-Slotted Profile	2	$22.08	$44.16	47065T808	In Shipping
McMaster	1.50” X 1.50” X 20" Ultra-LiteT-Slotted Profile	2	$18.40	$36.80	47065T808	In Shipping
McMaster	1.50” X 1.50” X 51" Ultra-LiteT-Slotted Profile	2	$46.92	$93.84	47065T808	In Shipping
McMaster	15 Series Tall Gusseted Inside Corner Bracket	8	$16.03	$128.24	47065T762	Arrived
80/20	15 Series 3 Hole - Inside Corner Bracket	8	$6.21	$49.68	4376	Not ordered yet
McMaster	15 Series 4 Hole - Tall Inside Corner Bracket	4	$8.43	$33.72	47065T241	Arrived
McMaster	15 Series 4 Hole - Straight Flat Plate	4	$8.94	$35.76	47065T261	Arrived
McMaster	5/16-18 x .625" Button Head Socket Cap Screw	1	$14.51	$14.51	91255A580	Arrived
McMaster	5/16-18 Double Slide-In Economy T-Nut	3	$11.54	$34.62	3136N275	Arrived
McMaster	18-8 Stainless Steel Screw, 5/16"-18, 3/4" Long	1	$8.26	$8.26	92949A581	Arrived
McMaster	Steel Thin Hex Nut, Grade 5, 5/16"-18 Thread Size	1	$5.30	$5.30	94846A203	Arrived
McMaster	Dowel Pin, 4037, 4140 Alloy Steel, 5/16" Diameter, 2-1/2" Long	1	$9.64	$9.64	98381A593	Arrived
Amazon	Bottomless Cylindrical Glass, Glass Lamp Shade of 3" x 6"	16	$18.00	$288.00	3" x 6"	Not ordered yet
McMaster	Multipurpose 6061 Aluminum, 1/4" Thick, 12" x 48"	2	$109.41	$218.82	9246K425	Arrived
McMaster	7" Steel Socket Head Screw	10	$4.52	$45.20	91251A908	Arrived
McMaster	Steel Thin Hex Nuts (1/4 -20)	1	$2.70	$2.70	94846A201	Arrived
McMaster	LDPE Unthreaded Spacer	2	$16.08	$32.16	92825A143	Arrived
			Total	**$1,081.41**		

Table 13. All of the materials needed for building the Motor-Pump Mount, which is the structure that mounts and connects the motor to the pump.

Vendor	Name	Quantity	Price per item	Total Price	Part Number	Status
McMaster	1/4" 12" × 24" Sheet	1	$53.38	$53.38	8975K142	Arrived

	Metal					
McMaster	5/16"-18 Thread Size, 3" Long	1	$8.01	$8.01	91251A595	Arrived
McMaster	5/16"-18 Steel Hex Nuts	1	$9.14	$9.14	98797A030	Arrived
McMaster	5/16"-18 5/16" Long	1	$9.26	$9.26	91251A577	Arrived
McMaster	15 Series 4 Hole - Tall Inside Corner Bracket	2	$8.43	$16.86	47065T241	Arrived
McMaster	5/16"-18 Thread Size, 3/4" Long	1	$9.33	$9.33	91306A387	Arrived
McMaster	5/16"-18 Thread Size, 1/2" Long	1	$7.33	$7.33	90696A288	Not ordered yet
			Total	**$113.31**		

Table 14. All of the materials needed for building the hoses, including fittings and adapters. More information on how these parts were selected can be found in Appendix C.

Date	Vendor	Name	Price	Part Number	Notes:	Status
		Hose Fittings				
4/20/22	Racetronix	-10 AN F Hose Fitting	$68.48	FIT-680110	x8	Not ordered yet
4/20/22	Racetronix	-8 AN F Hose Fitting	$20.43	FIT-680108	x3	Not ordered yet
		Adapters				
4/20/22	Amazon	-10 AN to 1.5" MNPT	$6.49			Not ordered yet
4/20/22	Summit	3/4" MNPT to -10 AN M	$12.82	EAR-AT981609 ERL		Not ordered yet
4/20/22	Summit	-8 AN F to -8 AN M	$15.83	EAR-995188ER L		Not ordered yet
4/20/22	Summit	-10 AN F to -10 AN M	$15.83	EAR-99511010E RL	x2	Not ordered yet
4/20/22	Summit	-10 AN M to 1/2" MNPT	$9.98	SUM-220047B		Not ordered yet
4/20/22	Summit	1/2 MNPT to -8 AN M	$4.99	SUM-220847B		Not ordered yet
4/20/22	Racetronix	-10 AN M to -6 AN M	$2.85	ADF-10J6J		Not ordered yet
4/20/22	Summit	-6 AN M to -6 AN F	$14.62	EAR-995166ER L		Not ordered yet
		Hose				

4/20/22	Racetronix	AN-10 Hose	$57.04	TFT1168-10B	sold per foot, buy 8 ft	Not ordered yet
4/20/22	Racetronix	AN-8 Hose	$20.76	TFT1168-08B	sold per foot, buy 4 ft	Not ordered yet
		Total	**$250.12**			

Manufacturing Plan

The frame, the glass cylinder fixture, and the fuel rails can be made simultaneously. Once these are completed and all the other components have been placed, hoses can be built and attached. For assembly, CAD pictures are shown to give the viewer a better understanding of what the text is describing.

Frame

The frame is the first component to be manufactured.

- Tools: horizontal bandsaw, 3/16’’ hex drive, 7/16’’ wrench or socket drive
- Steps:
    1. Locate two 15 Series 3 Hole (L-shape) brackets, four 5/16-18 x .625" Button Head Socket Cap Screws, and two 5/16-18 Double Slide-in Economy T-Nuts. Take a screw and slide it through the single hole on the shorter side of the L-bracket and start to thread a nut onto the back of the bolt. Repeat for the other three L-brackets. Take one L-bracket with the nut started onto the bold and slide the nut into the channel of the 24’’ bar. Two L-brackets should be on one side of the bar with two on the opposite side. Make sure they are oriented in the correct direction. Slide all L-brackets to roughly where they should sit and use the 3/16’’ hex drive to tighten the bolt fully.

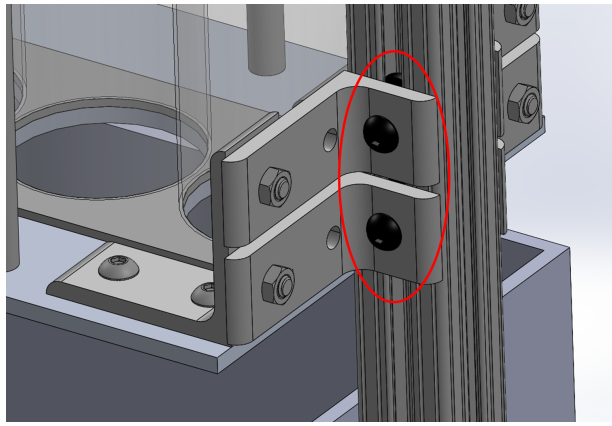


Figure 14. L-bracket assembly.

2. Locate two 15 Series 4 Hole - Straight Flat Plates, four 5/16-18 x .625" Button Head Socket Cap Screws, and two 5/16-18 Double Slide-in Economy T-Nuts. Slide two bolts through the lower two holes of the plate and start to thread a nut onto the end. Repeat for the other plate. Slide the nuts into the slot with the two open holes pointed up.

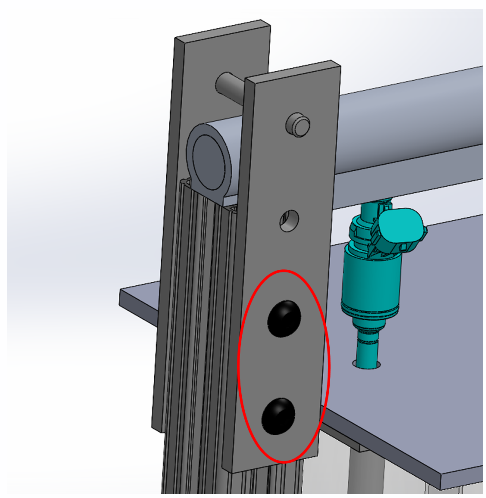


Figure 15. Straight Flat Plate assembly.

3. Locate two 15 Series Tall Gusseted Inside Corner Brackets, four 5/16-18 x .625" Button Head Socket Cap Screws, and two 5/16-18 Double Slide-in Economy T-Nuts. Slide two bolts through the two holes of the same side of one bracket and start to thread a nut onto the end. Repeat for the other bracket. Slide the nuts into the slot with the square side facing down.

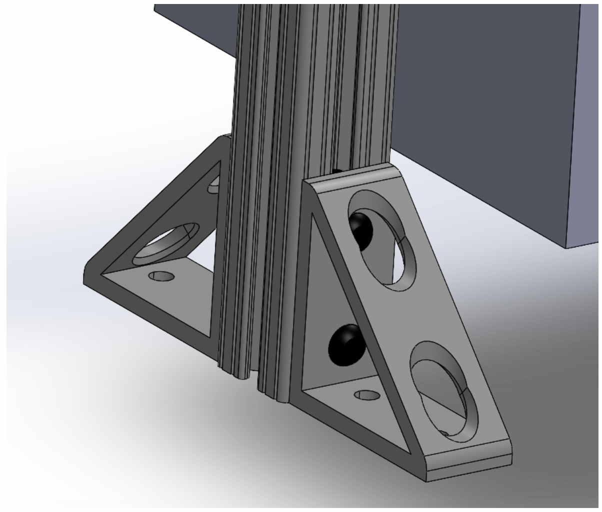


Figure 16. Corner Bracket assembly.

4. Repeat steps 1-3 for the second 24" bar.
5. Grab the two 20" bars and four 5/16-18 x .625" Button Head Socket Cap Screws, and two 5/16-18 Double Slide-in Economy T-Nuts. From step 3, slide the bolts into the two remaining holes of each of the corner brackets and start the nuts on the ends. Slide all four nuts into one channel of the 20" bar. Repeat for the other side.
6. Locate two more 15 Series Tall Gusseted Inside Corner Brackets. Slide two bolts through the two holes of the same side of one bracket and start to thread a nut onto the end. On the inside of the t-bar, slide the nuts into the slot with the square side of the bracket facing out. Repeat for the other bracket and slide in on the opposite side with the bracket facing out as well.
7. Finally, grab the two 51" rails. For each rail, take four 5/16-18 x .625" Button Head Socket Cap Screws, and two 5/16-18 Double Slide-in Economy T-Nuts. Using the 15 Series Tall Gusseted Inside Corner Brackets on the outer ends of the 20" rail, slide the bolts into the two remaining holes of each of the corner brackets and start the nuts on the ends. Slide the nuts into the end of the 51" rail. Repeat for all the corners.

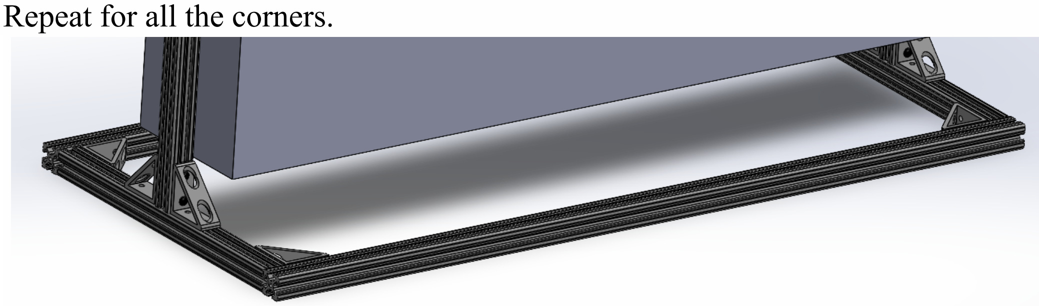


Figure 17. Base assembly.

8. Now is the time for final position adjustments and tightening down all the bolts to make a stable frame.

Glass Cylinder Fixture
Due to the limited time for assembly, we are outsourcing the laser cutting process of the aluminum plates in our glass cylinder fixture to a machine shop. This may involve formatting the CAD into a DXF file depending on what the machine shop requires. After the plates are cut, assembly can begin.

- Tools: 3/16’’ hex drive, 7/16’’ wrench
- Steps:
    1. Start by locating the laser cut aluminum plate. Attach this plate to the frame fixture using L-brackets, 5/16"-18, 3/4" Long Stainless Steel Screws, and 5/16"-18 Steel Thin Hex Nuts.

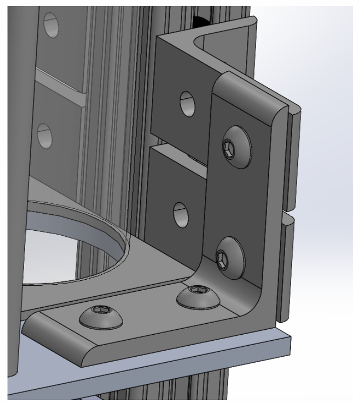


Figure 18. L-bracket assembly.

2. Lay a sheet of Buna-N mat. and cut to fit holes of the aluminum plate.
3. Carefully place glass cylinders around each hole of the aluminum plate.
4. Locate the other Buna-N mat. and other sheet of aluminum. Cut and lay sheet of Buna-N mat. onto the aluminum plate.
5. Take the aluminum plate and place it on top of glass cylinders with the Buna-N side touching the glass cylinders.
6. Run the 7" Steel Socket Head Screws through the corresponding holes of the aluminum plate (with LDPE spacers between each plate) and thread the nuts onto the ends.
7. Ensure that the glass cylinders are correctly positioned. Tighten the bolts down snugly using the 3/16’’ hex drive and the 7/16’’ wrench to create a seal. Don’t tighten down too much, as we do not want the glass cylinders to shatter.
8. The bolts in the t-slot (circled in red below) may need to be loosened to adjust the height of the Glass Cylinder Fixture.

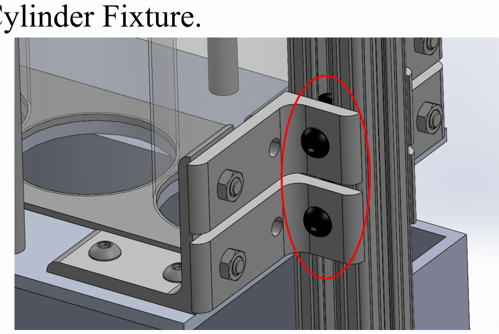


Figure 19. L-bracket assembly.

Motor-Pump Mount

- Tools: Shear, drill press or manual, center drill, F(17/64") drill bit, automatic center punch, hand tap wrench, 5/16''-18 tap 1/4'' hex drive, 3/16'' hex driver, ½'' wrench, marker.
- Steps:
    1. Locate the 1/4" 12" × 24" Sheet Metal. Mark the length needed for each of the two pieces (16" and 6") and cut to size using the shear.
    2. Measure the location of the holes and mark them with the marker.

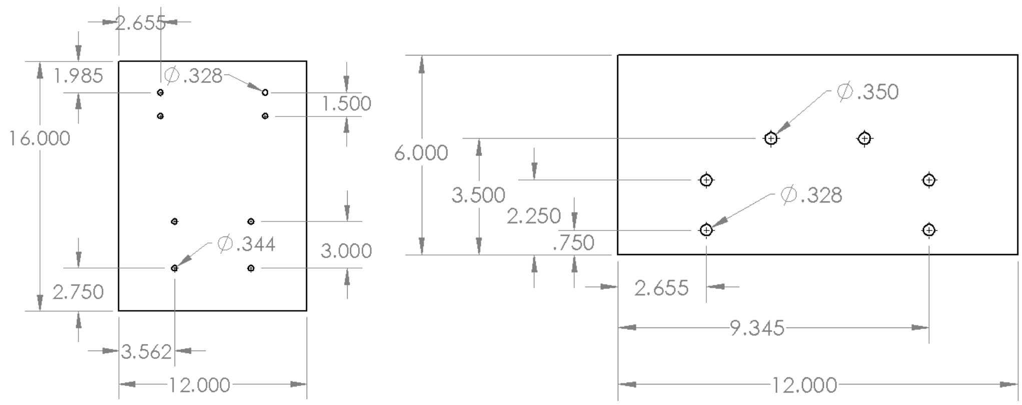


Figure 20. Sheet metal plates with hole locations.

3. Use the automatic center punch to put a slight indent in the metal sheet on these marked locations as a guide for the center drill so it doesn't wander.
4. Secure the sheet to the drill press or manual mill.
5. Line the center drill up with one of the marked centers and make a starter hole.
6. Change the center drill with the F drill bit and drill through the sheet
7. Thread all holes on the base plate (motor plate) using the 5/16''-18 tap and the tap wrench.
8. Deburr the holes once all are drilled and threaded.
9. Locate the 6'' piece of sheet metal, two 15 Series 4 Hole - Tall Inside Corner Brackets, four 5/16"-18 Thread Size 3/4" Long fasteners, four 5/16"-18 Thread Size 1/2" Long fasteners, and four 5/16"-18 Steel Hex Nuts. Take one long fastener, slide it through the L-bracket and the plate.
10. Locate the 16'' plate with tapped holes. Line the L brackets on the 6'' plate up with the tapped holes on the 16'' plate. Use four 5/16"-18 Thread Size, 3/4" Long bolts to secure the two plates. It should look like Figure 21 when the bolts are tightened down.

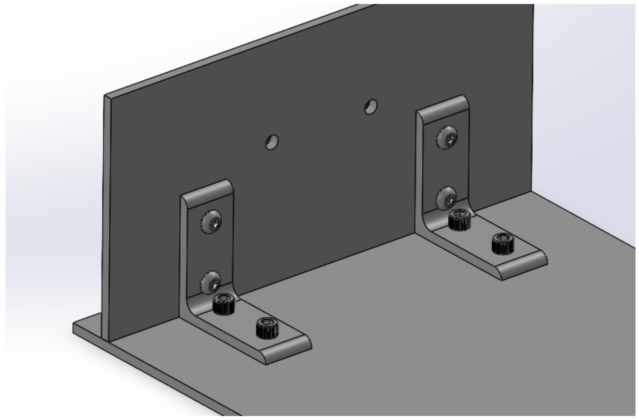


Figure 21. Finished assembly of motor-pump mount

Fuel Rail Extrusions

- Tools: Drill press, center drill, 11 mm injector drill bit, automatic center punch, marker
- Steps:
    1. Mark where the center of the holes need to be drilled with the marker.
    2. Use the automatic center punch to put a slight indent in the metal as a guide for the center drill so it doesn't wander.
    3. Secure the rail to the drill press.
    4. Line the center drill up with one of the marked centers and make a starter hole.
    5. Change the center drill with the 11 mm injector drill bit and drill through to the center. Do NOT drill completely through the fuel rail.
    6. Repeat steps 3-5 for all the holes.
    7. Deburr all the holes once they are drilled.
    8. Repeat steps 1-7 for the second fuel rail.

AN Hoses

- Tools: Grinder or cable cutter (whichever you have available), vice, crescent wrench
- Steps:
    1. Hold a hose between the component it is connecting to estimate the length. Make sure there is a bit of slack.
    2. Cut hose to length with grinder or cable cutters, ensuring the cut end is as smooth as possible.
    3. Install base end of AN fitting (number 8 in Figure 22) on outside of hose. This should just twist on, and there should be a small lip between the end of the base and the cut end of the hose.

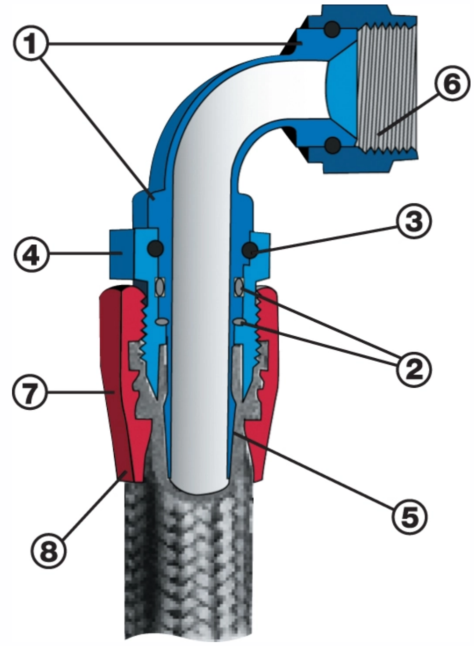


Figure 22. Diagram of a general AN fitting [33].

4. Place base with hose installed into a vice and begin installing the second end of AN fitting (number 4 in Figure 22) with a crescent wrench. This second end will go into the hose and needs to be threaded into the hose with the crescent wrench.
5. Installation is complete once both parts of the AN fitting meet and cannot be threaded anymore.
6. Repeat for the other end of the hose.
7. Use this process for all component connections.

Wiring Harness

Based on the decisions we have made with our sponsor during the semester about the scope of the project and the final deliverables they want, we will not be building the wiring harness.

7.3 Comparison of Final Design and Build

The build is the application of the high level final design. The final design is a theoretical application where the build is the design in practice. The build helps to highlight any oversights that were made in the initial design as well as make some design changes that aid in assembly of the product. Once the bill of materials and assembly plan are created, it is much easier to identify weaknesses of the design and where possible improvements can be made. The build also allows us to see where certain parts of the design are improbable or impossible to produce. For example, after completing the bill of materials we found that we would not be able to meet the initial budget of our project. This, however, was not identified by the final design inspection. Selecting components such as the radiator and pump for the bill of materials also made us use engineering analysis to identify the specifications required for these parts.

Although the entire final prototype was not able to be physically built due to time constraints, the structure that supports the fuel rail extrusion was constructed and is shown in Figure 23 below.

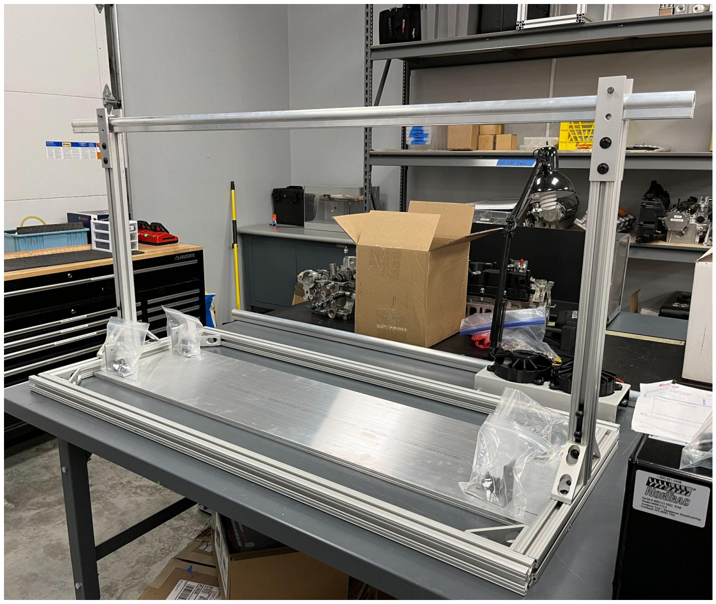


Figure 23. T-slot structure that supports the fuel rail extrusion

8 Verification and Validation Plans
Upon completion of assembling our final prototype, we need to verify and validate the design. Almost all of our verification plans are low cost and easy to implement. We are confident in their ability to verify our requirements. Almost all of the requirements that could currently be verified were met by our design. The only verification we could not meet was the budget. Components for our design were much more expensive than initially expected. These additional costs were discussed and approved by Nostrum.

8.1 Verification Methods

Test 16 fuel injectors total. This specification is a straightforward one to measure. If the developed machine can run-in 16 fuel injectors total, then the requirement has been met.

<2.5 minutes to load 16 injectors. Time trials can be used to validate this specification. After briefing three operators on how to use the machine, we will time how long it takes for each operator to load sixteen injectors into the machine. If all three operators complete this task within two and a half minutes, then the requirement has been met.

<2.5 minutes to unload 16 injectors. A similar method of time trials can be used to validate the unloading time specification. If all three operators unload the sixteen injectors within 5 minutes, then the requirement has been met.

Closed system pressure >9 Bar for 1 minute (nominal = 10 Bar). A pressure gauge that is integrated into the system will be used to verify this measurement. Once the fluid is at 10 Bar, the system will be closed by closing all fuel injectors as well as the or manual valve. If the pressure gauge reading does not drop more than 1 Bar over a 1 minute interval (assuming zero leaky fuel injectors), then the requirement has been met. The pressure drop value, or the time interval, may need to be adjusted once the machine is built and the system performance is observed.

Power needed <= 1.9kW. This constraint is a result of the limitations of a 120 volt outlet at 20 amps. Thus, if our machine can be powered by a standard outlet, then this requirement has been met. This is also verified by our power calculations above.

Maintain operating fluid below its flashpoint (37°C). This specification can be validated by integrating a thermocouple at the highest temperature location and ensuring that the fluid is less than 37°C. The highest temperature location is at the outlet of the pump. This is also verified by our fluid temperature engineering analysis above.

1.2 ± 0.1 ms pulse width; 333 Hz for run-in. This specification may be difficult to verify. If the arduino is sending signals to the injectors within specification (supplying current for 1.2 ms every 3ms), then the requirement has been met. This may be able to be confirmed by reviewing the command window of the arduino, as well as measuring the volume of the fluid that has been discharged from the injectors and using known flow rates to calculate the number of cycles. Due to fuel injector operation being moved outside of the scope of our project it is difficult to create a verification plan for this specification.

<$2500. This budget specification can be determined by keeping an updated bill of materials with each part cost. If the total cost is below $2500, then the requirement has been met. Our project failed to meet this requirement. The cost of many additional fixturings and verification components to the system resulted in us going over budget. The additional costs were discussed and approved by Nostrum.

Cycle run-in <= 5min. Time trials can be used to validate this specification. For three time trials, if the machine is able to complete the required number of cycles within five minutes, then the requirement has been met.

0 pinch points; Documented safety plan for leaks. This specification may be difficult to verify based upon the definition of a pinch point. It may be easiest to verify if the design does not allow an operator's hand to be near the injectors while loading is in progress. Also, the documented safety plan can be verified by having Nostrum engineers as well as Nostrum operators review the plan and ensure that it is easy to understand.

Limit repetitive motion to <1 minute during unloading & loading period. This specification may be difficult to verify based upon the definition of repetitive motion. Once we understand what is considered repetitive, which may be easiest to define after conducting interviews with operators, we can conduct three time trials and ensure that the operator's repetitive motion is limited to less than one minute while loading and unloading injectors.

10-15 micron for primary; 2-3 micron for secondary. The easiest way to validate this specification is to confirm each filters' specifications with the supplier. If the primary filter is rated to capture 10-15 micron particulate, and the secondary filter is rated to capture 2-3 micron particulate, then the requirement has been met.

<70 dB during operation. To validate this specification in a cost-effective manner, a phone decibel meter can be used to measure the noise level of our machine. If the measured noise is less than 70 dB, then the requirement has been met. For the safety of the operator, we will want to ensure that the machine is no louder than 80 dB. A phone decibel meter can provide a reasonable estimate of this noise level while remaining within the scope of this project.

Overall volume is within 5 feet wide x 2.5 feet deep x 2 feet tall. The last specification is a straightforward one to validate. The overall dimensions of the machine can be measured with a tape measure. If the machine is within the specification values (and thus if the machine fits in Nostrum's facility), then the requirement has been met.

8.2 Validation Methods

The design problem we set out to solve was eliminating the bottleneck of testing and running in fuel injectors. To validate this operation we propose analyzing the new fuel injector cycle time. Once our final design is fully built Nostrum should time the new cycle time of operating our machine. They can then compare this with the entire fuel injector production cycle time and see if the overall production cycle time of a fuel injector decreased. If the cycle time decreases, our design can be validated.

9 Discussion

There are quite a few lessons we learned throughout this process. First, we discovered that we need to schedule more time for assembly. We had a well organized schedule until objectives began to be pushed back and we had very little time left to assemble compared to what we originally planned. Second, we learned that we need to have multiple options for purchasing. One example is our motor. We had a motor all lined up to purchase but when our sponsor went to purchase it, it was out of stock. This lost us a few days as we had to search for a new one and send that one to our sponsor to be ordered. In the future, we would have a secondary option for larger components that are harder to find. The next thing we learned was to reach out to suppliers directly. Oftentimes, what is found online is only a portion of the documentation that they have on that product. Our sponsor also asked that we consolidate material orders. This makes it easier for us because we don't have all the back and forth but it is also easier for them as they are not ordering a few things every few days. The last lesson that we learned so far is to fully understand the working fluid and the process. We did not understand that when the fluid comes out of the injectors, it comes out as a mist. This means that the cylinder that the fluid is being dispensed into must be close to sealed to prevent large amounts of fluid from escaping the system.

If we had more time and resources to better define our problem, we would definitely do things differently. First off, we would have watched (or possibly used) Nostrum's current system to see what the flaws of that system was so we didn't make any of the same mistakes. It would also be helpful to better understand how to program the driver with the run-in cycle for the fuel injectors. Due to time constraints this was moved out of scope for our project, but in order to properly test the system we would need to fully understand the run-in cycle. To get information on the run-in cycle we would need to further discuss with our sponsor the programming for their current testing systems.

The key strength of our design is that it contains mostly off the shelf parts. This allows Nostrum to be able to easily modify and replace broken parts in the future. Another strength of our design is the removable fuel rail. This allows the operator to run one set of fuel rails while simultaneously loading and unloading the other fuel rail. As the design stands, after leak testing the system will open the fuel injectors to drain the viscor. If we had more time and resources, we would be able to explore adding a line of compressed air to the rig to power a subsystem that works to flush viscor out of the detachable fuel rail. This would result in a cleaner fuel rail removal process.

10 Reflection

10.1 Social and Environmental Context

As mentioned above, the market for high performance fuel injectors is motivated by the need for more power from a given car engine. For an average consumer, a car is the second largest purchase they will make in their lives, dwarfed only by the purchase of a house or apartment [34]. Performance vehicles usually are sold at a premium, so it is not financially realistic for many people to purchase these vehicles to meet their needs recreationally. Fuel injectors sold by Nostrum give consumers a more equitable and affordable alternative to buying expensive luxury cars to see higher performance on the road. Additionally, fuel injectors are an essential part for a car to function, so shortages and back up in the supply chain can delay the repair of existing cars with existing injectors that have become damaged. Our part in the design of the leak testing rig will help to reduce delays in orders and therefore increase supply.

On the other hand, the increase in use of fuel will increase the amount of carbon emissions the modified car will put into the atmosphere and therefore increase the individual contribution to global warming. Additionally, the testing rig itself will be using electricity to run the pump, filters to remove debris from the run-in cycle, and raw materials that will need to be processed and transported to Ann Arbor. The use of fuel injectors could potentially extend the life and use of an existing car, however, comparatively producing fewer emissions to the manufacturing of a new car that also meets the consumers needs.

To mitigate the environmental impact, our design can incorporate as many locally sourced materials as possible, supporting local businesses and reducing unnecessary emissions from shipping components across large distances [35]. This will not be feasible for all parts of the rig, particularly the more specialized components, such as the filtration system. Additionally, minimizing parts that need to be custom machined will curb both emissions and use of lubricants and other hazardous materials associated with their manufacturing [35]. This will limit the design space to what we can find readily available on the market, however.

10.2 Team and Sponsor Dynamics

In our team, cultural similarities definitely help reduce conflict or differing opinions, but could have led to less diverse and unique ideas. For example, on more than one occasion two team members would come up with identical or very close to identical concepts during the design process. This does not necessarily mean that our final design or concepts inadequately explored the design space, but perhaps did not explore it as well as we could have with a more diverse group background. Stylistically, there are a few differences in our writing which allows our team to better communicate ideas, but can cause a report or presentation to be less cohesive.

Culturally, our team and our sponsor were relatively similar, though with a notable exception. Our team has an automotive background so in starting the project and doing research, our team was able to understand a lot of basic terminology and concepts. However, the more specialized terms, parts, and mechanisms were foreign to our team and had to be learned. There were a few occasions where this dynamic led to oversight on our team's part. For example, fuel injectors are designed to atomize fluid rather than spray liquid, meaning the injectors must be fully enclosed to prevent the working fluid from escaping as gas during operation. Our team originally designed the testing lid to leave the glass cylinder portion open to reduce complexity, but had to add a lid to account for this phenomenon. Luckily, our frequent communication with our sponsor allowed this to be picked up and corrected in a timely manner.

Additionally, our sponsor is a company which must be focused on profit. Social impact is relegated to an afterthought, and the test stand will be made and used internally in the near future. Outside of the rig itself, Nostrum would have the most consideration for the fuel injectors themselves, and our comparatively small footprint will be neglected. Due to the relatively small impact of the testing rig itself and the fact that Nostrum has set a budget, our team will be focused more on performance of the testing rig. They are providing the money to see the realization of the testing rig, and it is important that we, above all else, eliminate the bottleneck in their production.

10.3 Inclusion and Equity

Another important consideration is the power dynamic between our team, Nostrum, and the technicians that will be operating the testing rig. Our team was not in contact with the technicians that ultimately will use the testing rig, so there is not much of a power dynamic to consider other than the power our team holds in how safe we design the testing rig. Safety and ease of use is a part of our specifications, though ultimately Nostrum will have final say in what is prioritized and what is not. Also, Nostrum controlled the purchasing of parts, which inherently led to all parts our team requested to be individually reviewed and approved. This was beneficial in the sense that they could ensure they were happy with the end product they received and prompted our team to consider more options and design constraints. Unfortunately, this also contributed to a delayed timeline that stalled the manufacturing of the physical rig.

As engineering students, our team's perspective could be described as more white-collar than the technicians that will end up using the testing rig. This is important to keep in mind, as it means that although we can consider safety of the rig, our ability to fully consider usability in the context of the work environment and real daily use is limited. Among our team, this is relatively consistent with minor differences from short stints as interns for automotive companies. To alleviate this fact, our team tried to communicate and include Nostrum as often as possible due to their unique knowledge of their workers and daily undertakings of a technician.

Considering these dynamics, our team had to balance who made the final decision to what parts were ordered. Nostrum ultimately decided if and when things were ordered as the party providing the money, but our team ultimately decided what parts would be considered.

10.4 Ethical Considerations

Both Nostrum and their customers will benefit from our testing rig. Nostrum will be able to increase their output and therefore profit, and their customers will be receiving the quality product they want. Within Nostrum, their technicians will benefit from a more ergonomic design and less repetitive work. Additionally, the testing of these fuel injectors will ensure the quality of injectors that reach the road, so both regulators and motorists will benefit. Looking at the negative aspects of our testing rig, the emissions from material processing and shipping will contribute to global warming. Oftentimes developing countries will see more adverse effects of climate change in their everyday livelihood compared to a more wealthy and developed country [35]. This means that in a very small way, we will not only be negatively affecting the environment, but negatively affecting vulnerable populations that live in places where climate change is most apparent.

Above all else, our sponsor is focused on profit. Because the testing rig is meant to test for leaks in their product before delivering to customers, it is important the rig is made with longevity and repeatability in mind. Social impact surrounding the manufacturing is an afterthought because only one test stand will be made for use in the near future. When thinking of social impact, Nostrum would have the most consideration for the fuel injectors themselves, and our comparatively small footprint will be neglected. Due to the relatively small impact of the testing rig itself and the fact that Nostrum has set a budget, our team will be focused more on performance of the testing rig. They are providing the money to see the realization of the testing rig, and it is important that we, above all else, eliminate the bottleneck in their production.

Ethically, the only other dilemma that we could face would be how high we decide to set safety factors with regards to the pressurized system and flammable working fluid. If we become too lenient, the testing rig itself could present an immediate danger to the technicians operating the machine. Fortunately, Nostrum has a large amount of acquired knowledge within their lab and can help to check our calculations and allowances are within an acceptable range.

Our team's personal ethics align well with each other, as well as with the professional ethics expected from us by the University of Michigan and future employers. One of the main ethical duties outlined in various Code of Ethics is that we, as engineers, shall hold safety above everything else [36]. This was why we included safety factors in our calculations, as well as emergency stops and safety restraints in the design. Also, we chose this project because we all had an interest and experience in the automotive industry. We felt a little out of our league with the specialized injectors but overall, we learned so much from this project. If we had any questions at all, Nostrum was always willing to provide an expert to us with an answer.

11 Recommendations

Although a majority of the build aspects of this design have been described in detail, there are a few considerations that our sponsor should make moving forward. One recommendation for the build of this design is to bend a large aluminum sheet (that is slightly sloped downward in one direction) for the catch tank under the glass cylinders. In this way, the fluid can be collected and drained into a hose that flows into the reservoir. Another consideration that needs to be made is the connection between the fuel rail extrusion and the quick-connect. An aluminum adapter could be press-fit into one end of the extrusion that has a threaded hole for the quick-connect to attach. The other end of the fuel rail could be plugged with a press fit aluminum plug. In terms of machining, we recommend that our sponsor use the CAD and dxf files provided to have the aluminum parts manufactured by a third party. In this way, the provided manufacturing plan can be followed in order to assemble all of the remaining parts.

One revelation we had was that our team and our sponsor had very different expectations about the class structure and the project outcome. Our sponsor wanted a finished, fully working machine at the end of the semester. The way the class is structured, there is not a lot of time built in for testing and validation. About halfway through the semester, we realized that we were not going to be able to deliver a fully working system, as we did not have the knowledge or skill set to program, debug, and drive the system. As a team, we discussed possible ways this particular Nostrum High Performance project could work with the University of Michigan. We believe that the Multidisciplinary Design Program (MDP) would best suit their needs. This program allows a full year for the project, one semester for design and one semester for build and testing.

12 Conclusions

The goal of this project was to design a device that can test 16 fuel injectors at once to eliminate the bottleneck in production. The requirements and engineering specifications for this project have been clearly defined and outlined in Table 2 above. Using these parameters, we have created a final design to meet Nostrum's needs. The initial mounting for the design has been assembled, and a completed manufacturing plan for the full assembly has been developed. The design makes use of a removable fuel rail extrusion that allows for quickly changing the fuel injectors that are being tested. This is shown below in Figure 24.

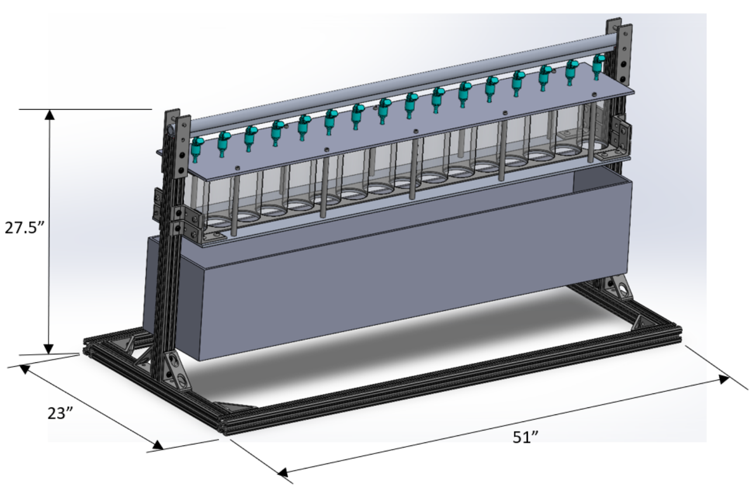


Figure 24. Final design concept CAD.

Using analytical verification and validation methods, our method is proven to solve the initial design problem and meet the engineering specifications in Table 2. After the prototype is constructed, empirical testing can be performed (using methods outlined in this report) to further ensure that our chosen design meets the requirements and specifications.

13 Acknowledgements

We like to thank Nostrum High Performance for their support: Sam Barros, Lee Markle, Jason Haines, and others. Thank you to our section instructor, Professor Hulbert, for his help and guidance throughout the project.

14 References

[1]"Fuel Injector Upgrade - Are They Worth It," Mike's Carburetor Parts, November 27, 2019, https://www.carburetor-parts.com/Fuel-Injector-Upgrade--Are-They-Worth-It_b_24.html#:~:text=A%20fuel%20injector%20upgrade%20consists,delivering%20a%20higher%20flow%20rate.&text=Stock%20fuel%20injectors%20won't,will%20be%20out%20of%20reach.

[2]"What You Need to Know Before Purchasing Fuel Injectors," High Performance Injectors, February 2, 2017, https://highperformanceinjectors.com/blogs/news/what-you-need-to-know-before-purchasing-fuel-injectors

[3] Sienko, K., Skerlos, S., 2022, "ME 450 Course Introduction," ME 450 Lecture, University of Michigan, Ann Arbor, MI.

[4]Wynn D., Clarkson J. (2005) Models of designing. In: Clarkson J., Eckert C. (eds) Design process improvement. Springer, London.

[5] Barros, S., Haines, J., Markle, L., 2022, "ME450 NHP Tour and Project Description", Nostrum High Performance, Ann Arbor MI, January 21, 2022.

[6]"Fuel Injector Problems," Hummel's Automotive Diagnostic and Repair, October 15, 2020, https://hummelsautorepair.com/do-you-have-problems-with-your-fuel-injectors-here-are-signs-that-you-do/

[7] "About NHTSA", NHSTA, 2020, https://www.nhtsa.gov/about-nhtsa

[8] "What EPA is Doing About Climate Change", EPA, January 11, 2022, https://www.epa.gov/climate-change/what-epa-doing-about-climate-change

[9] David Kwabi, "Fundamentals of Combustion," ME 433 Lecture, University of Michigan, Ann Arbor MI, 2022

[10] "Overview of Intellectual Property Categories", University of Michigan Engineering, February 19, 2014, https://www.youtube.com/watch?v=-8G1iwkWzBs

[11] "NEC CODE Rules and Design Practice", National Forest Service, June 14, 2002, https://www.fs.fed.us/database/acad/elec/greenbook/3_basicdesigns.pdf

[12] Society of Automotive Engineers, 2018, "Direct Injection Gasoline Fuel Injector Characterization". J2713.

[13] Society of Automotive Engineers, 2016, "(R) Low Pressure Gasoline Fuel Injector". J1832.

[14]United States Department of Labor, 2008, "Occupational noise exposure.". 1910.95. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95

[15] Kelly, D., "How to Use a Morphological Chart", February 14, 2014, https://www.youtube.com/watch?v=cRZQ09aCiFs

[16] Christian, J.L, S.R. Daly, S. Yilmaz, C. Seifert, and R. Gonzalez, "Design heuristic supports two modes of idea generation: Initiating ideas and transitioning among concepts." American Society for Engineering Education. 2012, https://www.designheuristics.com/

[17] "Brainwriting", Mycoted, 2022, https://www.mycoted.com/Brainwriting

[18] ”Hose & Hardline”, JEGS, 2022, https://www.jegs.com/i/JEGS/555/110920/10002/-1?gclid=Cj0KCQiAmpyRBhC-ARIsABs2EAohA8RjV6W-eDOCkpzNce-iUBXkWJj-4Vn8umbdOcoXt-DAtmDtj70aAqESEALw_wcB
[19] ”Circulation Pumps for Fuel and Flammable Liquid”, McMaster-Carr, 2022, https://www.mcmaster.com/pumps/circulation-pumps-for-fuel-and-flammable-liquid/for-use-with~gasoline/voltage~120v-ac/maximum-pressure~150-psi/maximum-flow-rate~100-gpm/current~12a/
[20] “Power Steering Pumps”, Summit Racing, 2022, https://www.summitracing.com/parts/pfn-sp1200x
[21] “Hydraulic Pumps”, McMaster-Carr, 2022, https://www.mcmaster.com/hydraulic-pumps/hydraulic-pumps-4/
[22] “FLHAXB”, Sun Hydraulics, 2022, https://www.sunhydraulics.com/model/FLHA
[23] “FLHAXA”, Sun Hydraulics, 2022, https://www.sunhydraulics.com/model/FLHA
[24] “Aqueon Standard Glass Aquarium Tank 40 Gallon Breeder”, Petco, 2022, https://www.petco.com/shop/en/petcostore/product/aqueon-standard-glass-aquarium-tank-40-gallon
[25] “KETELAMP Hurricane Candle Holder”, Amazon, 2022 Glasshttps://www.amazon.com/KETELAMP-Hurricane-Cylinder-Multiple-Specifications/dp/B07NYZ5R9Z/ref=asc_df_B07NYZ5R9Z/?tag=&linkCode=df0&hvadid=366418668605&hvpos=&hvnetw=g&hvrand=9427582203301511654&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9016855&hvtargid=pla-803842767735&ref=&adgrpid=75139008406&th=1
[26] “Being Labs Recirculating Chiller”, Southern Labware, 2022, https://www.southernlabware.com/being-labs-recirculating-chiller-3l-20-c-to-20-c.html?gclid=CjwKCAjwlcaRBhBYEiwAK341jRBEKXGHQWOp0w4ncytdP2hu0sWR_aCQBQND3-et7cIoN7v4WcwikBoC66kQAvD_BwE
[27] “PELONIS 3-Speed Box Fan”, Amazon, 2022, https://www.amazon.com/PELONIS-PFB50A2ABB-V-Full-Force-Circulation-Conditioner/dp/B087C2LJ25/ref=sr_1_2_sspa?keywords=box+fan&qid=1647461518&sr=8-2-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUExS0NOTVYwQ0lCV1QyJmVuY3J5cHRlZElkPUEwMDkzODgwMzBYWDNJTlFET0NFWSZlbmNyeXB0ZWRBZElkPUEwNjcwMTIyMTNUV1RNUklIU0ZGRyZ3aWRnZXROYW1lPXNwX2F0ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=
[28] “ POLARIS RZR 1000 XP Turbo 2016 Aluminum Radiator”, Pure Adrenaline Motors. 2022, https://pamgear.com/products/polaris-rzr-1000-xp-turbo-2016-aluminum-radiator?pr_prod_strat=copurchase&pr_rec_id=ee16076e7&pr_rec_pid=7537891606782&pr_ref_pid=7537893114110&pr_seq=uniform

[29] “LML/LGH Bosch® OEM New Fuel Rails”, Injectors Direct, 2022, https://www.injectorsdirect.com/product/lml-lgh-bosch-oem-new-fuel-rails/
[30] “Fuel Rail Extrusion”, Ross Machine Racing, 2022, https://www.rossmachineracing.com/fuelrail.html
[31] “DC24V 3/4" NPT Brass Solenoid Valve”, Toolots, 2022, https://www.toolots.com/2w-200-20-24v.html?cid=10800353410&gclid=CjwKCAjwlcaRBhBYEiwAK341jUzuvnBAIeIERIYNELWj5O1KNGhwu3ptdNUgCEdHC_Onq1ss8rJNjBoC4GUQAvD_BwE
[32] “Threaded On/Off Valves”, McMaster-Carr, 2022, https://www.mcmaster.com/manual-valves/threaded-on-off-valves-13/
[33] “AN Fittings 101: Get Your Hose On!”, BangShift, 2015, https://bangshift.com/general-news/tech-stories/fittings-101-get-hose-need-know-getting-started-car/
[34] Hedges, K., Thakor M., ”Five Expenses That Will Consume 50 Percent of Your Lifetime Earnings”, Forbes, August 2, 2010, https://www.forbes.com/sites/work-in-progress/2010/08/02/lifetime-earnings-home-car-children-education-retirement/?sh=29d2ac1c507d
[35]“The Causes of Climate Change”, NASA, 2014, https://climate.nasa.gov/causes/
[36] ”Code of Ethics for Engineers”, National Society of Professional Engineers, 2019, https://www.nspe.org/sites/default/files/resources/pdfs/Ethics/CodeofEthics/NSPECodeofEthicsforEngineers.pdf

15 Appendix A

Fluid Temperature Calculations

The maximum output of the pump was 1 HP which is equal to 0.746 kW. The mass flow rate used was given by nostrom as 7 g/s per fuel injector. Using 16 fuel injectors the mass flow rate for the entire system was calculated to be 0.112 kg/s. The specific heat capacity of gasoline at room temperature was used for our calculations at 2.08 kJ/kg. The results are shown below.

$$W_{pump} = mC_{p,fuel}(T_{out} - T_{in})$$

$$0.746\ kW = 0.103\ {}^{kg}/_{s} \cdot 2.08\ {}^{kJ}/_{kg-K}\,(T_{out} - 20.0\ °C)$$

$$T_{out} = 23.5\ °C$$

Radiator Heat Rejection Calculations

The variable m_{air} is the required mass flow rate of the air through the radiator to cool the working fluid. The mass flow rate of the fuel (m_{fuel}) used was given by nostrom as 7 g/s per fuel injector. Using 16 fuel injectors the mass flow rate for the entire system was calculated to be 0.112 kg/s. The specific heat capacities of gasoline ($C_{p,fuel}$) and air ($C_{p0,\,air}$) at room temperature were used for our calculations at 2.08 kJ/kg-K and 1.004 kJ/kg-K respectively. The variable $m_{max\ radiator}$ is the maximum airflow produced by the radiator. This was calculated by converting the volumetric flow rate given by the supplier into the mass flow rate. An air density of 1.225 kg/m^3 was used for this calculation.

$$\sum mh_{in} = \sum mh_{out}$$

$$m_{fuel}\left(h_{in,\,fuel} - h_{out,\,fuel}\right) = m_{air}\left(h_{out,\,air} - h_{in,\,air}\right)$$

$$m_{fuel}C_{p,\,fuel}\left(T_{in,\,fuel} - T_{out,\,fuel}\right) = m_{air}C_{po,\,air}\left(T_{out,\,air} - T_{in,\,air}\right)$$

$$m_{air} = m_{fuel}\frac{C_{p,\,fuel}}{C_{po,\,air}}$$

$$m_{air} = 0.112\ [kg/s]\,\frac{2.08\ [kJ/kg-K]}{1.004\ [kJ/kg-K]} = 0.21\ [kg/s]$$

$$m_{max\ radiator} = 630\ [cfm] \times 0.00047\left[\frac{m^3/s}{cfm}\right] \times 1.225\left[kg/m^3\right] = 0.36\ [\mathrm{kg/s}]$$

$$\frac{m_{max\ radiator}}{m_{air}} = \frac{0.36}{0.21} = 1.7$$

$$m_{max\ radiator} = 1.7 \times m_{required}$$

Reservoir Volume Calculations

The injector cylinders were calculated as having a diameter of 3 inches and height of 6 inches. The connection pipes were calculated as a cylinder with a diameter of ⅝ inches and height of 15 feet.

$$Injector\ Cylinders:\ \pi(\frac{3\ in}{2})^2 \times (\frac{6\ in}{2}) \times (16\ Injectors) = 340\ in^3$$

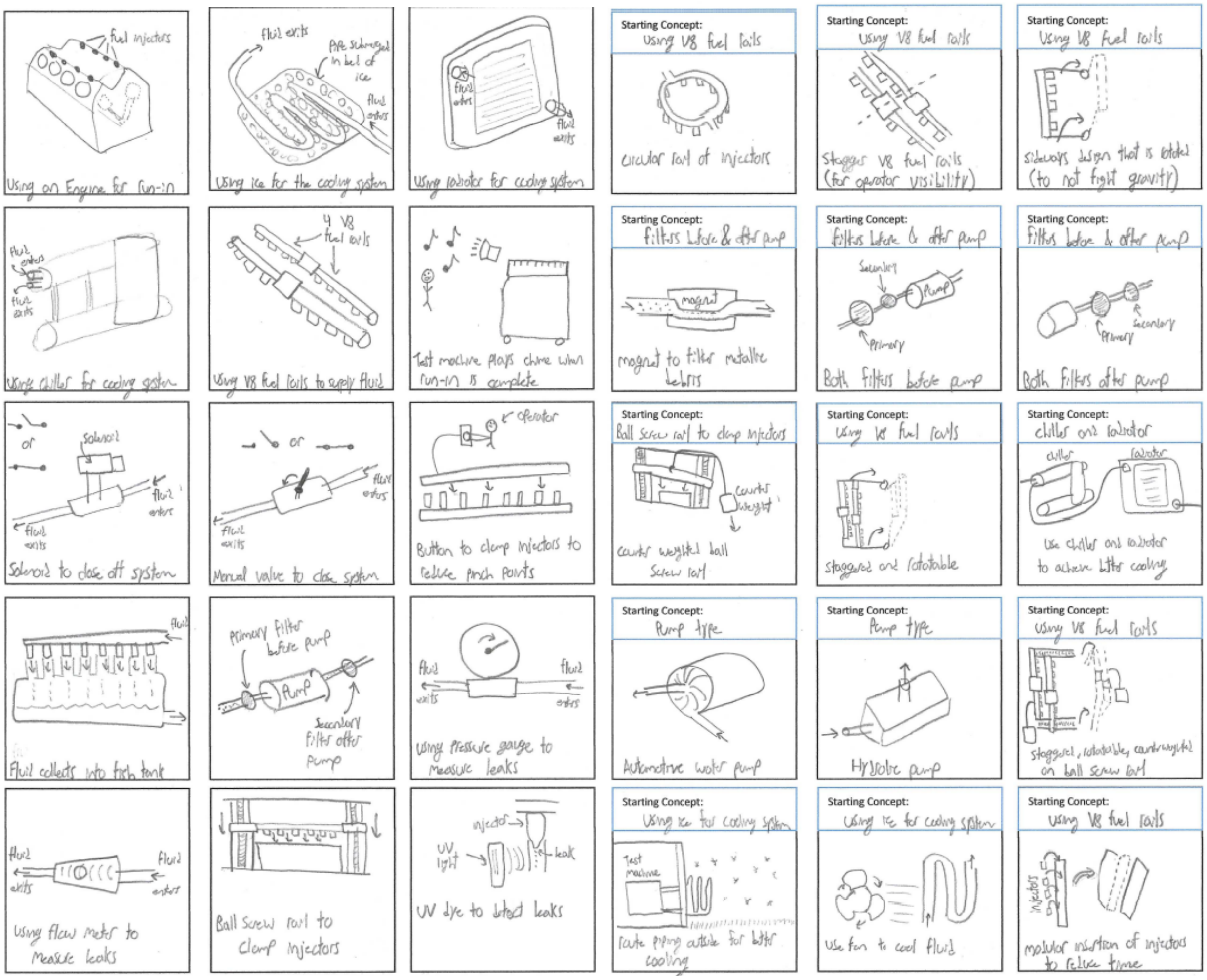
$$Approximate\ of\ Connection\ Pipes:\ \pi(\frac{5/8\ in}{2})^2 \times (15\ ft) = 55\ in^3$$

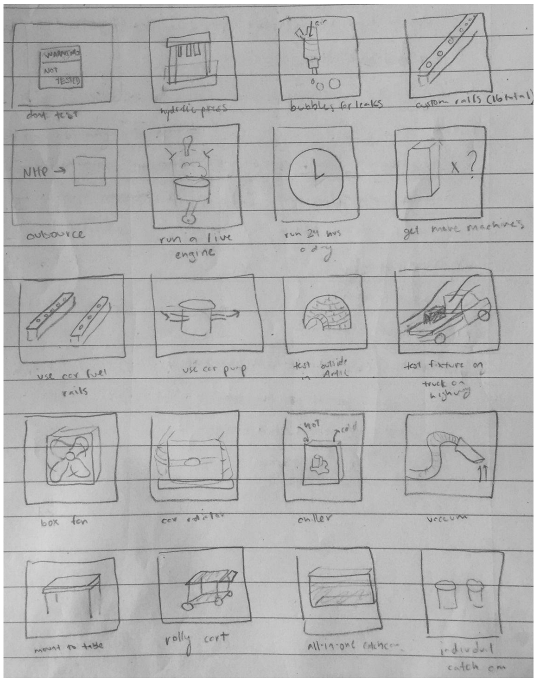
$$Given\ by\ Radiator\ Supplier:\ 169\ in^3$$

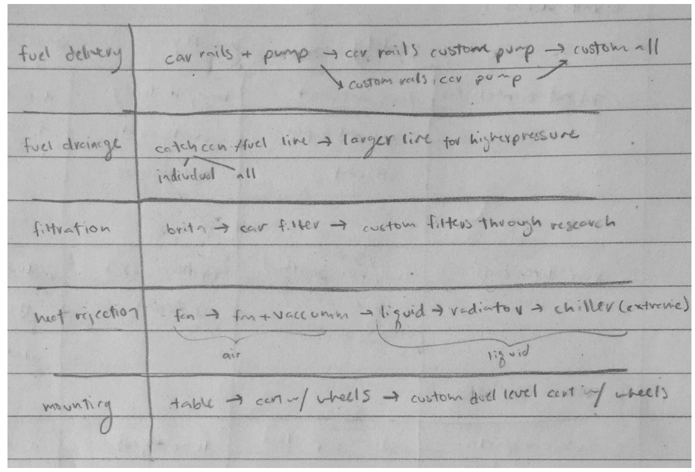
$$Total:\ 564\ in^3\ or\ 2.5\ Gallons$$

16 Appendix B

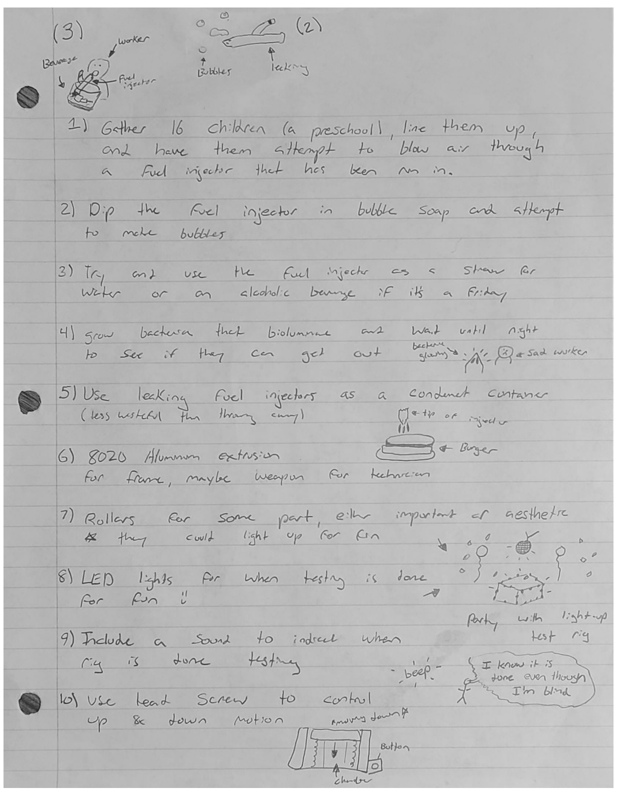
All concepts created during the concept generation process are provided below.







fuel delivery	car rails + pump → car rails custom pump → custom all; custom rails, car pump ↗
fuel drainage	catch can/fuel line → larger line for higher pressure; individual, all
filtration	brita → car filter → custom filters through research
heat rejection	fan → fan + vaccum → liquid → radiator → chiller (extreme) (air / liquid)
mounting	table → cart w/ wheels → custom duel level cart w/ wheels



1) Gather 16 children (a preschool), line them up, and have them attempt to blow air through a fuel injector that has been run in.

2) Dip the fuel injector in bubble soap and attempt to make bubbles

3) Try and use the fuel injector as a straw for water or an alcoholic beverage if it's a Friday

4) grow bacteria that bioluminesce and wait until night to see if they can get out

5) Use leaking fuel injectors as a condiment container (less wasteful than throwing away)

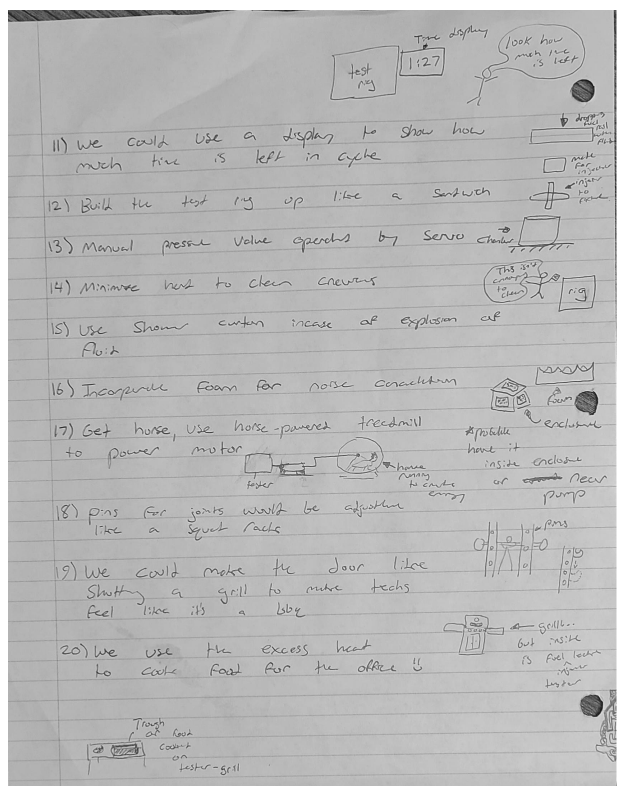
6) 8020 Aluminum extrusion for frame, maybe weapon for technician

7) Rollers for some part, either important or aesthetic as they could light up for fun

8) LED lights for when testing is done for fun !!

9) Include a sound to indicate when rig is done testing

10) Use lead screw to control up & down motion



11) We could use a display to show how much time is left in cycle

12) Build the test rig up like a sandwich

13) Manual pressure valve operated by servo

14) Minimize heat to clean crevices

15) Use shower curtain incase of explosion of fluid

16) Incorporate foam for noise cancellation

17) Get horse, use horse-powered treadmill to power motor

18) pins for joints would be adjustable like a squat rack

19) We could make the door like shutting a grill to make techs feel like it's a bbq

20) We use the excess heat to cook food for the office !!

1)

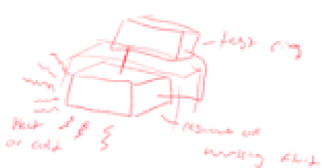
put injectors in, then lower room like a hood

2) Have a lazy Susan involved, both a person and the kitchen thing

3) Use a pager or one of those restaurant things that buzz when the table is ready to indicate the machine is done testing

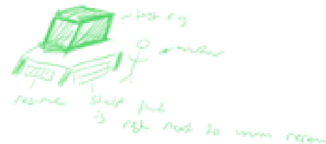
4) make joints like platforms

5) make reserve of working fluid act a radiator for room



6) Use two buttons to start test so both hands are in use not around test area

7) Create insulated pant enclosure to warm reserve to keep shelf of some test warm

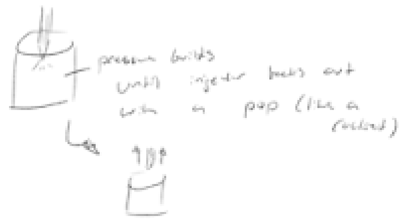


8) Create wall that you can watch the injectors spray

9) Aquarium, but with injectors

10) Use fuel injectors from run-in period to run a turbine to recapture energy

11) Use a leak to propell injector



12) Use see-through reservoir of working fluid and pipes so tech can watch fluid go !! (like washer/Dryer)

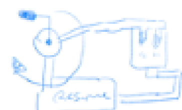
13) we could create a machine on a hinge, so you lay it out and then it sandwiches together

14) Use latches to clamp down structure to structure with fuel injector in enclosure

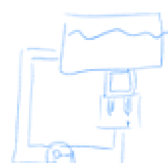
15) use gripping strips to clamp device together

16) integrate a weight machine into the test rig.

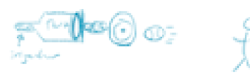
17) Use a human powered hand crank pump



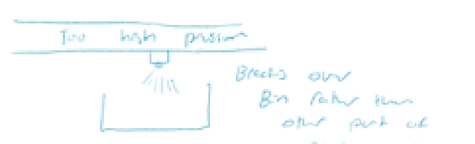
18) put the reservoir ontop and let gravity do work, pump just returns the working fluid



19) Use a baseball and target to create pressure;

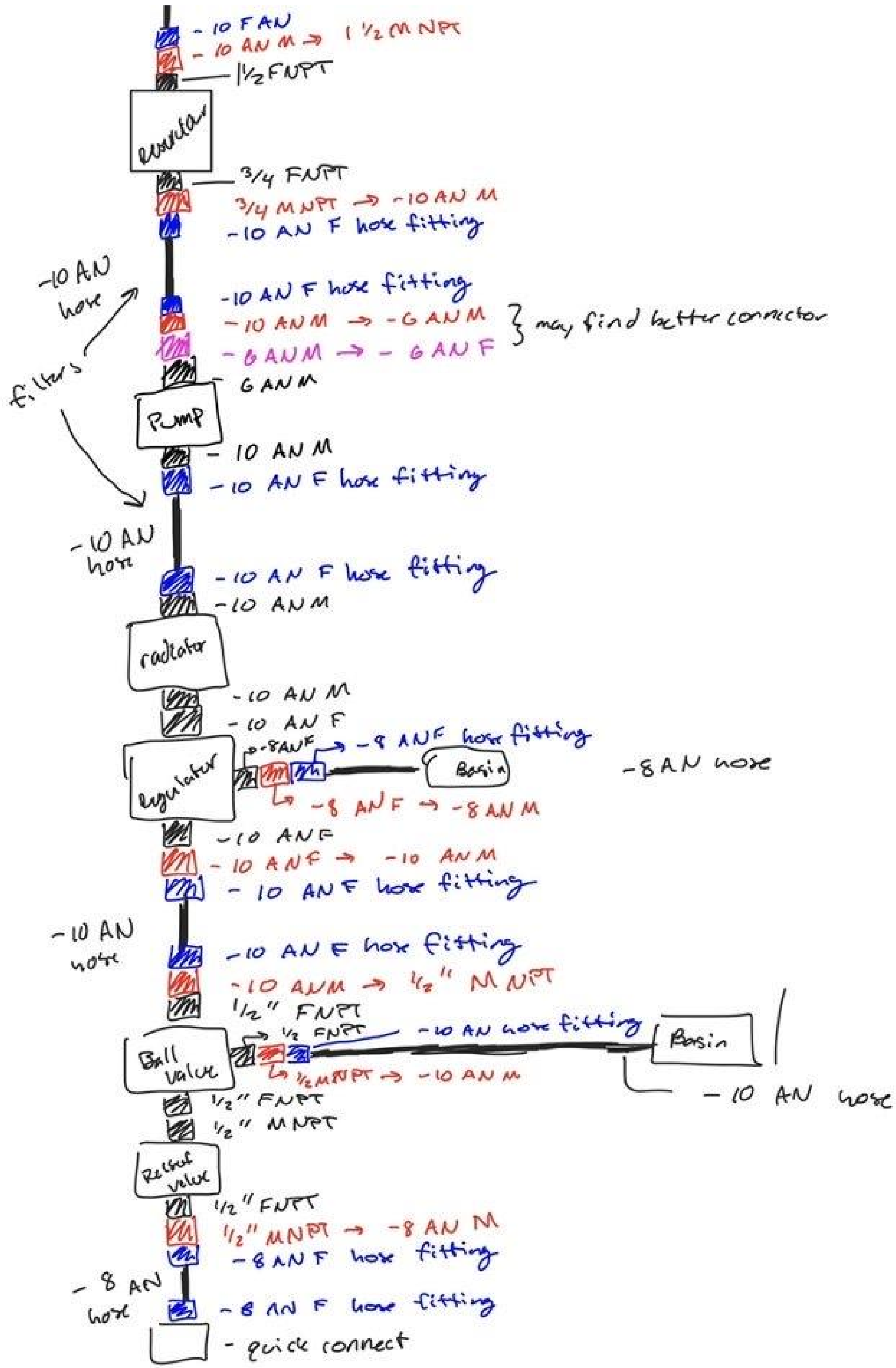


20) create weaker spot to break if pressure is too high



16 Appendix C

The selection of hoses, fittings, and adapters is shown below.



17 Author Bios

Kathryn Altes

Kathryn is a senior studying Mechanical Engineering. She grew up in Midland, MI. She chose Mechanical Engineering at the University of Michigan because it is one of the top ranked programs in the country. Kathryn is currently a catcher on the Michigan Club Softball Team. She also enjoys mountain biking, snowboarding, and going to the gym. She plans to graduate in three and a half years with a Bachelors in Fall 2022. This summer, she plans to work as a manufacturing intern at GM.

Katie Lemmen

Katie is a senior studying Mechanical Engineering with an interest in internal combustion engines. She grew up in New Era, MI and enjoys activities such as horseback riding, hiking, and off roading. Her interest in engineering came from joining a robotics team in high school. She is currently a Composites Lead on Michigan Baja Racing, although she spent time on the MRacing Formula SAE for two years. Outside of class and Baja, she is a four-year member of the University of Michigan Equestrian Team. Katie plans to graduate in May of 2022 with her bachelors and go into the workforce. She will start her career at Volvo Trucks North America as an Associate Cab Engineer.

Evan Millison

Evan is a senior majoring in mechanical engineering and minoring in economics. He grew up in Medford, New Jersey, but chose to study at the University of Michigan to pursue his interest in the automotive industry. During his sophomore year, he conducted research in collaboration with General Motors on smart materials and structures. Evan enjoys running, biking, and cheering for Philadelphia sports teams. Evan plans to graduate with his bachelor's degree in May of 2022. He will start his career as an Advanced Driver Assistance Systems (ADAS) Engineer at Subaru Research and Development.

Joe Williams

Joe is a senior majoring in mechanical engineering and minoring in material science and engineering. His major engineering interests revolve around materials, particularly fiber reinforced composite materials. He grew up in Stanton, MI and spends a lot of time listening to podcasts. He also is an Instructional Aide for the Center for Entrepreneurship and spent the fall 2021 semester as a co-op at Dana Inc. He plans to graduate in the fall of 2022, or potentially pursue a Masters in Material Science through the SUGS program at the University of Michigan.