NORTHERN
ARIZONA
UNIVERSITY

College of
Engineering, Forestry
& Natural Sciences

Project 10
Pipe Loss Experiment Redesign

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DISCLAIMER

EXECUTIVE SUMMARY

The 2018 capstone project is a complete redesign of a pipe flow experiment table that is used in the ME 495 lab at Northern Arizona University. The client for this project is Dr. Constantin Ciocanel. The system needs to be redesigned so that it yields more reasonable results so that the students can using it can take more knowledge from it and have a better understanding of the real-world concepts. The current table is also showing signs of age as certain components are wearing down and may not be as effective going forward. Keith, in MATLAB, developed a computer program to simulate a full system and predict expected results. The experiment is designed to show losses in the head of a flow when it goes through various fittings on a pipe system. The design is to have at least one elbow, T, and expansion/contraction joints. To obtain meaningful results, the team was able to find a pump that could achieve a Reynolds number from 10^4 to 10^5 through a minimum pipe diameter of ½ inch. Through several iterations of different layouts and materials being used, the team has come up with a final design that will be implemented to the best of the team's ability in the next semester. The design selected is similar to the old table but with improvements to the layout and efficiency of the flow, for example, a stronger pump is being used and the type of flow and pressure sensors will be more precise to allow for more accurate results. The proposed design meets all the requirements that were attainable by the team's means. The max Reynolds number the team achieved does not reach the requirement but is the best the team could do given other parameters. The client gave his approval to this when the team explained the dilemma. For prototyping, a full CAD model was developed and detailed to the fullest to the extent of the design so far, and the new pump will be ordered for the summer term so that the team can test the MATLAB program with a real system and prove the validity. The team will then take this information into the next semester when the construction process begins to have a base model. This will then be used to empirically obtain values that will be the goal of the experiment. A lab manual will then be created to complete the experiment and have it ready for use in the future.

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1 BACKGROUND

1.1 Introduction

Laboratory classes are crucial for helping students can get a physical meaning for topics that are taught in the more common lecture classes. They also give the instructors more opportunity to make meaningful teaching points for the subjects being introduced to the students. Experiments in a lab can quickly become outdated and not as much of an effective method for teaching students about complex topics. A team was put together in the capstone class to work together, and find a solution to this problem. This project tasks the team with completely redesigning an experimental pipe flow table from the ME 495 lab portion of the class. The client, Dr. Constantin Ciocanel desires a new experimental setup that will function with clear, and meaningful results. The team must design and construct a new table that is easily accessible to students and instructors alike. The team has been able to bring the team's own designs and concepts to the decision-making progress that will shape the desired experimental setup, based on what the client requires, and what will be most beneficial to the students and instructors that will be utilizing it for years to come.

1.2 Project Description

The team must redesign and construct an experimental table for the ME 495 lab at Northern Arizona University (NAU). The stakeholders of the project will be; NAU, the school will benefit from students having a better understanding of the learning material, the client, Dr Ciocanel, and the students at NAU, they will have another form of instruction on the topic which could lead to better understanding of the subject matter. The client wants a new table that will replace the older model. The experiment is for demonstrating how a fluid can experience pressure loss in a pipe, and how it affects the flow. The students are to measure pressure differences through different lengths, and fittings of pipe. They are measured across long lengths of pipe, through elbow and T-joints, as well as diameter reductions and expansions. The pressures are then used to find the major and minor head loss of the flow. There are to be three different forms of flow rate measurement for users so that they can perform head loss and velocity calculation in the analysis. A pump is to push water through the system and should be able to be regulated to achieve for specific Reynolds numbers and flow rates for different calculations and analysis. This new table will be able to educate students in a more effective manner than before, yielding more meaningful data and clearer results that can show that there is something happening within the flow as it travels through the pipes. The team will also be responsible for writing up a new lab manual for users to follow and give a set of analysis questions to test the understanding if the experiment. The possibility of automated measurement by use of data acquisition devices and a lab software will be explored later.

1.3 Original System

The current system in the ME 495 lab has been in use for about 15 years. This has caused numerous problems with the setup as well as making it more difficult to operate and take a teaching point from. Some of the pressure taps leak when trying to take measurements from a manometer. The small sections of the pipe have too small of a diameter and are over constricting the flow and is yielding inaccurate results. The pump cannot be variably controlled to change the flow rate and Reynolds numbers. The Reynolds number that the system operates at, does not show enough pressure drop over the longer length of pipe, so the head loss is very small, and does not lead to a satisfactory teaching point. Some of the pressure taps are located too close to the fittings, and as a result, the flow is not really developed again when the reading is taken, this leads to poor results in the lab discussion. The current table uses a 0.75 HP centrifugal pump operating at 0.5 hp. Copper piping and common ball valves are used to direct the flow through the table. There are three forms of flow rate transducers involved in the system, two are invasive to the flow and are taken manually by those who are performing the experiment. The third way is a non-invasive, ultrasonic flow rate transducer than can be attached to a length of pipe and read the flow rate from outside of the flow. All the measurements done in the lab are done manually by the users, there is no automated data collection.

2 REQUIREMENTS

As with any engineering design, the requirements for the design are the most important aspect of the system. Without understanding the customer and engineering requirements, the project will ultimately fail, as such, the design team has spent considerable amount of time determining the requirements to the experimental pipe loss design.

2.1 Customer Requirements (CRs)

To ensure that the design that is created is effective for the stakeholders and satisfies the overall goal of the client, A list of customer requirements was laid out for the team to base decisions from. If these requirements are followed, the design will be more effective and valuable to the stakeholders. The customer requirements given to us by the client are:

- **Reliability of Measurements:** this is the ability of the experiment to yield consistent and truthful results that reflect what is expected from the lab. This included the measurement devices as well as the structure itself to be a controlled system, such as pressure as being placed in sensible locations that will achieve accurate data.
- **Durability of Physical System:** The system will be required to withstand years of high flow rates and Reynolds numbers through the pipes, and measuring devices to last as well.
- **Variable control:** The flow need to be able to be altered in a simple way to achieve flow rates and thus, Reynolds number over a wide range.
- **Common types of fittings:** the system needs to have elbow, ‘T’, expansion, and contraction joints in different sections to show head loss across these types of fitting on a pipe system.
- **Three flow rate transducers:** For the students to measure the flow rate and perform head loss calculations, there needs to be three forms of flow rate measurement. Two are required to be invasive, and have one non-invasive measurement tool.
- **Labview integration:** This is a data acquisition system that will take data from the experiment and input into a software that can be used to analyze the results on the CPU unit. This is not a finalized requirement for the project, but is being considered to this point.

2.2 Engineering Requirements (ERs)

The customer requirements are not the only aspect of the design that are important, but an understanding of the engineering requirements is equally important as they dictate the feasibility and important aspects of the system. For the pipe loss experiment, the team identified the following engineering requirements.

- Voltage – 120 Volts RMS
- Operates within a set Reynolds Number Range – $10^4 – 10^6$
- Operates within a set Pressure Range - TBD
- Smallest Diameter Pipe Half Inch
- System has a Measurable Minimum Head Loss - TBD
- Cost - \$3000 or less

Each engineering requirement was selected based on discussion with the client and analysis of similar systems. Cost was included as an engineering requirement because a set value and relation to each customer requirement can be determined. The customer and engineering requirements are cross analyzed using a House of Quality which is found in the next section.

2.3 House of Quality (HoQ)

A House of Quality is a tool used by engineers to relate the customer requirements to the engineering requirements and to determine a ranking for each engineering requirement. The complete house of quality is located in 8.4 ~~8.3~~ Appendix D: Miscellaneous, Table D - 1 - House of Quality~~Table C - 1 - House of Quality~~. For the Pip Losses Experiment, the team considered the following customer requirements and weights:

- Reliability of Measurements - 5
- Durability of the Physical System - 4
- Life Span of at least 10 Years - 2
- Variable Flow Rate Control - 5
- One Contraction Joint - 5
- One Expansion Joint - 5
- One Elbow Joint - 5
- One Tee Joint - 5
- Three Volumetric Flow Rate Sensors - 5
- Lab View Integration – 2

The weights where determined by discussing what the client wants most from the design, creating a set of weights and then presenting the weights to the client for his approval. The weights scored at a five are non-negotiable items that the design must meet as per the client. Any weight below a five are simply desires of the client for what he would like to have the design to accomplish. The engineering requirements determined by the team through research and discussion about the client requirements and finally approved by the client, with the target ranges and tolerances are in Table 1 - Engineering Requirements.

Table 1 - Engineering Requirements

Engineering Requirements	Target Range	Tolerances
Voltage	120 Volt RMS	± 10 volts
Operates within set Reynolds Number Range	$10^4 – 10^6$	± 100
Operates within set Pressure Range	5-50 kPa	± 5 kPa
Smallest Diameter Pipe ½ in	½ inch	± 0
System has a Measurable Minimum Head Loss	10 kPa	± 2 kPa
Cost	$3000	± $200

From the QFD, the team could determine the following ranking of engineering requirements:

1. The system has a measurable minimum head loss.
2. The system operates within a set pressure range.
3. The system stays within budget.

4. The system operates within a set Reynolds number range.
5. The smallest diameter pipe is half an inch.
6. The system operates of standard 120 Volts RMS power.

The rankings for the engineering requires show that the primary goal for the design, as given by the client, is also the primary engineering requirement for the design and has been approved by the client.

2.4 Testing Procedures (TPs)

To ensure that all engineering requirements are met for the design, the team will be completing a comprehensive testing procedure for each individual requirement. Several of the requirements are strict guidelines for the physical properties of the materials purchased and the pump selection, as such those tests will simply be a pass or fail, either it meets the requirement or does not. The remaining requirements will require the team to develop a testing procedure to ensure that the requirement is met.

2.4.1 Pass – Fail Tests

Pass or fail tests are a simple test to use to enforce hard rules or guidelines to a requirement within the project. There are several engineering requirements that facilitate a simple pass or fail test for the design, these requirements are: 1. Voltage of 120 RMS, 2. Smallest diameter pipe is half an inch, and 3. total cost is below \$3000 + \$200. To ensure that these requirements are met, the entire design will be broken down into individual components and compared against the three pass-or-fail tests. If the component fails, the component will be redesigned until it passes all tests, otherwise the component is designated as a successful component. For the cost test, the cost of each component will be tabulated and then the entire cost will be the summation of each components cost. If the total cost exceeds the \$3200 limit, then each component will be re-analyzed, starting from the highest cost component to the lowest cost, and possible redesigns will be determined evaluated in sequence until the cost demand has been met.

2.4.2 Flow Energy Tests

The remaining engineering requirements that are not simple enough for a pass-or-fail will be tested using the fluid flow energy balance equation. The energy balance equation is as follows: $\left(\frac{P_1}{\rho}-\frac{P_2}{\rho}\right)+\left(\alpha_1\frac{V_1^2}{2}-\alpha_2\frac{V_2^2}{2}\right)+(gz_1-gz_2)=h_t-h_p$, where P is the pressure, V is the velocity, Z is the height from a reference point, α is the kinematic energy coefficient ($\alpha\approx 1$ for turbulent flow and $\alpha=2$ for laminar flow), h_t is the total head loss, and h_p is the head from turbo machinery. The energy balance equation for returns the energy of the fluid, as known as the head of the flow, in two common units, either $\frac{l^2}{t^2}$ (units of velocity squared, or energy per unit mass) or l (units of length), the team has used units of length for every other energy balance calculation and thus will be continued. With the energy balance equation, the pressure and velocity of the flow can be determined at any point within the flow, which, with the properties of the fluid at room temperate and the physical dimensions of the pipe network. The Reynolds Number, $Re=\frac{\overline{V}*D}{\nu}$, where $\overline{V}$ is average velocity of the flow, D is the diameter of the pipe, and ν is the kinematic viscosity of the flow, can be determined.

To use then energy balance equation for a fluid flow, the pressures, velocity, and the height is required. To determine these values, three processes will be used. First, for height, if all points of measurement are at the same height then the change in height is equal to zero, thus the Z terms are not needed. For the pressure, the pressure will be measured using a digital pressure transducer that will be connected to the pipe system at multiple points to be able to measure the pressure at that point. With the pressures at the two points and an approximation for the head loss, it is possible to determine the velocity of the flow. With the velocity of the flow, the average Reynolds number, and head loss can be determined.

Since, having an estimate of the head loss is needed to determine the velocity of the flow, it is often better to start with a velocity of the flow and get the head loss, pressures, and Reynolds that way. To do this, a flow rate is specified, which is a function of flow velocity, and cross-sectional area, more specifically $Q = \frac{V}{A}$ where Q is the flow rate, V is the velocity, and A is the cross-sectional area. A simplified derivation of the energy balance equation as a function of flow rate is provided in section 5.5.1 Design Simulation and Analysis – Keith Caton. This equation will be used to determine the pressure and head loss across each section of the pipe network. With the head loss, pressures, and Reynolds number known, each property will be evaluated against the target range. If the total head loss, pressures, and Reynolds number within the system are within the bounds desired, then the design meets the customer requirements, if not, the design will be re-evaluated and changed until the requirements are met or the physical limits are determined.

3 EXISTING DESIGNS

As with any engineering project, an understanding of what has already been developed is just as important as understanding what the design must do. For that, the team researched current designs to determine advantages and disadvantages with the current systems and to establish a base line. The results of that research can be found in this chapter.

3.1 Design Research

The team researched four other universities designs for similar experiments. The four universities researched are, University Warwick, Ohio Northern University, University of Vermont, and UC Santa Barbara. An evaluation and comparison of these universities experiment to Northern Arizona University's current experiment is in the follow sections.

3.1.1 University of Warwick's Head Loss Experiment

The University of Warwick preforms a similar experiment to what is being required for Northern Arizona University. Warwick's experiment only tests straight pipe head loss and not head loss caused by pipe fittings or joints [1]. The process for determining the head loss over the straight pipe section of the experiment is the same process that the current experiment the ME 495 students preform which uses pressure tap located at each end of the test section to record the difference in pressure across the test section [1]. The process of recording the differential pressure across the system is the same process that the design team is planning on using for the new experiment, thus the Warwick experiment still provides valuable insight into the process of collecting and recording the pressure difference.

To perform the experiment, each student is required to review their text books and class notes about pipe flow and head loss and preform a series of calculations to review the governing equations for the practical part of the experiment [1]. The equations include the calculation for Reynolds Number, average velocity from volumetric and mass flow rate and from the Reynolds Number, straight pipe friction coefficient, mass flow rate, and cross-sectional area of the pipe [1]. After completing all preliminary calculations, the students perform the experiment over two different lengths, 17 millimeters and 15 millimeters, and roughness of the pipe, smooth for the 17 millimeters and rough for the 15 millimeters [1]. The students collect five sets of differential pressure readings for the two pipe segments and then determine the change in velocity, the Reynolds number and the friction coefficient [1]. Next, the change in pressure is plotted against the change in the velocity on a log plot and the friction coefficient is plotted against the Reynolds number on a log plot as well [1]. Finally, the students are required to write a report of their findings from the experiment and prove the head loss from the system is a function of the change in pressure and not from a change in velocity which cannot happen for an incompressible flow [1].

Warwick's experiment includes several items that Northern Arizona University's new experiment is also required to incorporate, mainly the head loss over a straight pipe and data analysis to prove the head loss in a function of the change in pressure. The new design for ME 495 will include, in addition to the straight pipe head loss, head loss over joints and fittings and is primarily focused on replicating the Moody chart and validating results.

3.1.2 Ohio Northern University's Experiment Proposal

Ohio Northern University preformed the same process that is currently being performed by the design team to develop an experiment to determine and validate the head loss of a pipe flow system [2]. A senior design project was created to develop a head loss experiment, the results of which was analyzed by the design team. The purposed experiment is very similar to the current and selected design for ME 495 in which the pump, reservoir and filter are located on the ender side of the experiment table and the test sections located on the top of the table [2]. The key difference is that Ohio Northern University's proposed design only determines the head loss of the flow traveling through a gate valve and not any form of an elbow, contraction, or expansion joints or fittings [2]. The tests of straight line pipe flow head loss and head loss over the gate value is like the process being considered by the design team.

Ohio's proposed design includes three pipe segments with pressure taps located at each end of the segment [2]. The first segment is a simple smooth three feet length of half an inch piping, the second is the same length and diameter as the first but the pipe interior has been roughened to increase head loss [2]. The final section is also three feet long and half an inch diameter but includes a gate valve located half way down the length of the pipe to determine the head loss over a simple fitting like a gate valve [2]. The simplicity of the design as well as initial designs considered using a gravity feed reservoir or using building supplied water but both of those approaches proved to be unfeasible for the requirements of the client [2]. Both designs considered are also possible for the new ME 495 but Ohio's analysis provides insight into the feasibility and potential problems with using similar designs such as the lack of consistency with supplied water and the size and height requirements of a gravity fed reservoir [2]. The experiment requires the students to validate their results using many different methods, each method for a different aspect of the system [2]. For example, to validate the flow rate sensor, the students are required to set the flow rate at a base rate and then record the time needed to fill a specified volume amount, this process is repeated for several different flow rates and the percent error is calculated to provide a correcting factor [2].

Ohio Northern University's proposed experiment is a prime example of how to empirically determine head loss over a series of different pipe flow segments. The proposal provided the team with abundant information and design ideas that are used to help narrow down the design and provide the best design for the client and Northern Arizona University.

3.1.3 University of Vermont's Head Loss Experiment

The University of Vermont has an experiment to determine the head loss of a fluid flow over different joint and fitting types [3]. The key difference between the Vermont's experiment and Northern Arizona University's experiment is that, Vermont's experiment uses air as the working fluid while the current and considered design uses water [3]. A simple system of a long straight pipe made up of multiple segments is used to perform the experiment, where the segment located half way down the pipe is replaced with different types of elbows to determine the head loss across the joint [3].

The students are given 20-30 minutes to record measurements including the stagnation, static, and dynamic pressures of different points of the pipe system [3]. The use of Pitot-Static tubes is used to generate a velocity profile of the flow for one of the segments, which is then used to determine an average velocity which is used for the rest of the experiment [3]. With the average velocity and static pressure measurement tools, the student fit the joint to be tested and record the pressure loss over the joint [3]. After recording the pressure loss, the head loss over the joint is determined and then the loss coefficient is then determined from the head loss [3]. Finally, the head loss and loss coefficient are validated using values from the class text book [3].

3.1.4 US Santa Barbara' Head Loss Experiment

At US Santa Barbara, mechanical engineer students undertake a several-week-long experiment to determine the head loss over a simple pipe flow system. The experiment requires the students to build a system to calibrate the sensors that are used, validate the calibration, build a simple pipe system that can vary pipe diameters and fittings, and record the pressure losses over the system. Using the pressure loss over different sections of the system, and information about the head loss coefficients, either in the form of a minor loss "K" value or a roughness to determine the friction coefficient from a Moody diagram. Finally, the students must replicate a section of the Moody Diagram and compare the loss coefficients vs length of pipe over the diameter to validate the results from the class text book.

The experiment requires the use of three different sensors, two flow rate sensors and one differential pressure sensor. The flow rate sensors used are an Omega paddlewheel flowmeter, which is an invasive sensor that has a cut in and cut out flow rate that outside of those boundaries will produce erratic and unreliable results. The students are tasked with determining these two boundaries and then collecting data points within the boundaries to determine a relationship. The functional relationship is left to the students to determine, but they are given hints that a 2nd order polynomial and higher as well as power function are good candidates to consider. Secondly, an Orifice plate flowmeter is used to measure the pressure drop across the orifice plate as a function of the flow are, which is then used to determine the discharge coefficient. The pressure sensor used is the Validyne differential pressure transducer and the student undergo a similar process to calibrating as the Omega paddlewheel flowmeter. The main difference is the relationship is expected to linear or 2nd order polynomial, and if the linear fit is a good fit, left to the students to determine what a good fit is, then they allowed to use the linear best fit for the remainder of the lab. After the sensors have been calibrated, the students build a test system and begin to determine head losses.

To test head loss over straight pipes, the students must prepare three six to eight feet long sections of pipes at three different diameters. Water is pumped through each section of straight pipe and the pressure difference over the section and the flow rate of the liquid is measured. Using the two measurements, the major head loss is determined for several Reynolds numbers and then plotted against a Moody diagram. A similar approach is handled for minor losses. A single diameter pipe is chosen and then multiple elbow and tee joints are attached to the system and the minor head loss for each fitting is determined using the flow rate and pressure difference across the fitting. Finally, the students create a complete pipe system using a Wheatstone bridge to measure the pressure, and head loss difference, between two pipe segments that are setup in the exact same way but will vary with height. The students then vary the height of one of the pipe segments and observe the change is head loss across the two segments. For each task within the experiment, the students collect data points that are used to validate the data.

Once all experiments are completed, the students produce a report that includes the pressure transducer best fit line, the paddlewheel flowmeter best fit line, and the relations between the flow rate and the pressure difference over the Orifice-plate flow meter. Additionally, the report includes the minor and major head losses as a replication of the Moody chart, then minor loss “K” value vs the length of pipe over the diameter of pipe, and the lost coefficient and the length of pipe over the diameter of the Wheat bridge technique. All results are compared against values from the text book to determine validity.

Overall the experiment does a good job of describing the head losses over a pipe system that utilizes all three terms to Bernoulli’s equation, pressure, velocity, and vertical position. The design(s) being considered by the capstone team includes the pressure and velocity terms of Bernoulli’s equation but does not include any differences in height, which is something the team should investigate. The major down fall to the experiment is that the students must build the experiment each time and then disassemble it which takes considerable amounts of time and is likely one of the reasons why the experiment is preformed over multiple weeks. Additionally, the NAU design is currently planning on using three flow rate sensors, one of which is non-invasive which the UC Santa Barbara experiment does not have, which increase experiment run time. The ability to determine head loss uses multiple processes to determine, which provides the students with the experience of multiple approaches to determine the same parameter. This ability to use different methods is greatly beneficial to the students and something the NAU design should consider. Overall, the UC Santa Barbara design is a good example that has several benefits but also several down falls which could be improved upon with the NAU design.

3.2 System Level

As the project is based around improving the design and functionality of one of the old ME 495 experiments, it is imperative to gather as much knowledge as possible. Investigating what other schools are doing in this case the team can gain a better understanding of what works and what doesn’t. Below are a few designs from schools and other companies that show some advantages and disadvantage of certain designs. Figure

1 shows a complicated maze of pipes and fittings that will yield various results. The increased amounts of pipes result in a greater range of values, but due to the budget, the team need to stay with as few of pipes as possible while reaching the same results. What can be taken from this design would be that it is unnecessary to have that many different pipes. The team can achieve the same results from lesser amounts of pipes if the team adjust the diameters and flow rate. This design is also meant to be displayed and used standing up. Due to the device being set on a table the team can achieve a more uniform flow rate than this design.

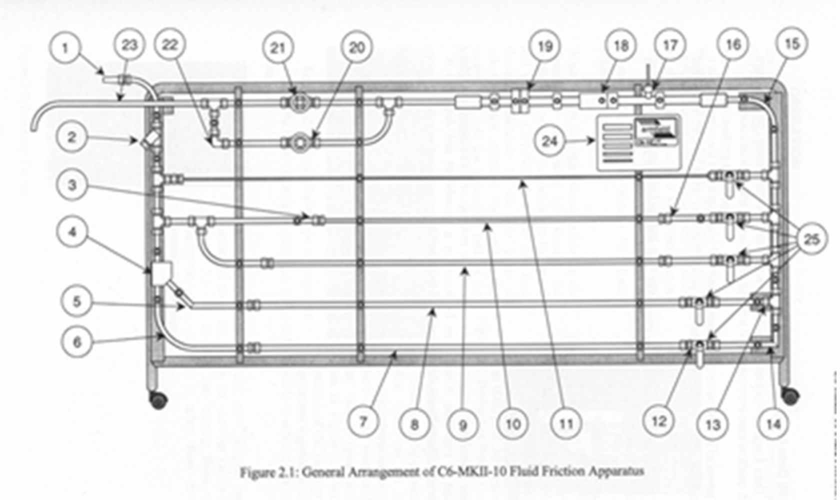


Figure 1 - Commercially Available Pipe Flow Experiment - Jfccivilengineer.com

A second design is evaluated to see what can be utilized within the own design or what the team should not include. Figure 1 - Commercially Available Pipe Flow Experiment - Jfccivilengineer.com~~Figure 1 - Commercially Available Pipe Flow Experiment - Jfccivilengineer.com~~ sits upward on wheels, giving the flow an inconsistent measurement along the vertical pipe sections. What this device lacks are T-joints that the team require to have in the design. What the team can take away from this design would be that the team are on the right track with the design having the dimensions that the team do. This table is too big and does not fit within the allotted dimensions. Figure 3 can also be used as a basis for the so that the team know that to improve upon. There is already a very similar design as a separate experiment in the ME495 lab. The team must use this to better the own design so there will be no need for both experiments to be present. One way to do that would be to make it easier to use and for the results to be significantly better. Due to the simplicity of Figure 1 - Commercially Available Pipe Flow Experiment - Jfccivilengineer.com~~Figure 1 - Commercially Available Pipe Flow Experiment - Jfccivilengineer.com~~ and Figure 2 - Commercially Available Pipe Flow Experiment - Lerneasy.info~~Figure 2 - Commercially Available Pipe Flow Experiment - Lerneasy.info~~, the team cannot take much inspiration for them. However, it does show us that the team are on the right path to reach the goals.

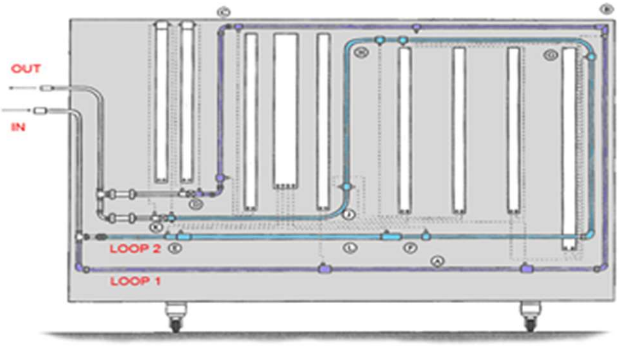


Figure 2 - Commercially Available Pipe Flow Experiment - Lerneasy.info

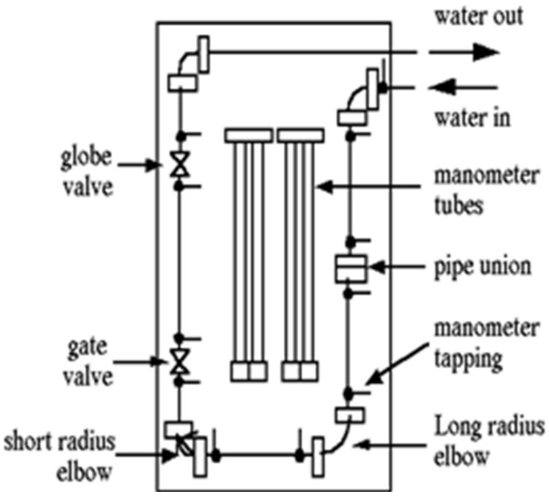


Figure 3 - Commercially Available Pipe Flow Experiment - Www2.latech.edu

Figure 3 - Commercially Available Pipe Flow Experiment - Www2.latech.edu~~Figure 3 - Commercially Available Pipe Flow Experiment - Www2.latech.edu~~ shows a very similar design and functionality as to what the team should strive for. There are a multitude of elbow and T-joints, as well as an easy to read manometer. The design and application will improve on this by having more than just as single way to measure the flow rate. The team will have better sensors and sturdier materials for a long-lasted experiment. This design and how it functions will be a general basis for how the team design and build the finished project.

The end goal is to make a simple design that still gives us the results of a more complicated design. The team can utilize all these designs for us to achieve the goals.

Figure 4 - Commercially Available Pipe Flow Experiment

3.3 Functional Decomposition

The purpose of the experiment redesign project is to create a better-functioning pipe flow system for experiments. The overall function of the pipe flow experiment apparatus is to teach about pipe losses. This function can be generally described in a Black Box Model like in Figure 5 - Pipe Flow Black Box Model. The main material flows required for the function of the apparatus are the human interactions of the students and the instructor, and the water within the system that would occasionally be replaced between experiments. The main energy flows will be the electrical energy from an outlet to power the pump and the human energy to move the measurement components and data collection supplies. Energy will be dissipated due to losses and friction to export heat. The main signal flows will be the starting and stopping of the apparatus, the visuals of the measurements, and the indications that the apparatus is operating correctly through noise and water flow visuals.

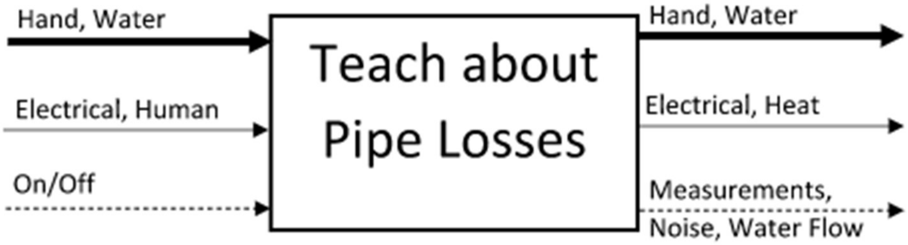


Figure 5 - Pipe Flow Black Box Model

To further analyze the flows required to make the apparatus function, a Functional Model was created and the result is shown in Figure 6 - Pipe Flow Functional Model. There are two main areas of functional flow in the experiment redesign: the physical pipe flow apparatus and the experimental procedures and lessons; both functional flows are required for the success of the apparatus. Just like in the Black Box Model, the human interaction, water, electrical energy, human energy, and starting the system are inputs and the human interaction, water, electrical energy, heat, measurements, noise, and water flow visuals are exported. There are other inputs that take place within the apparatus. They are sensors, data collection instruments, and report. Additional exports include the sensors, pressure measurements, flow rate measurements, and report. These extra inputs and outputs are part of the apparatus and they themselves flow throughout the Functional Model as well.

The Functional Model is essential for the understanding of the experiment redesign apparatus because it shows all the required components that make the experiment function correctly. The Functional Model shows the importance of certain components that flow through more junctions than others. For example, the data collection flow goes through the most junctions and interactions between other components so it is the most important component for the function of the experiment. This is understandable because the data collection can take the form of multiple measurements and is required for the report and the demonstration of the students' understanding. Another important component of the Functional Model is the flow of the water. The water is required to make the experiment yield results and it stays within the system to keep it running successfully. From the Functional Model, the experiment redesign could be analyzed into systems and subsystem levels for sorting design specifications.

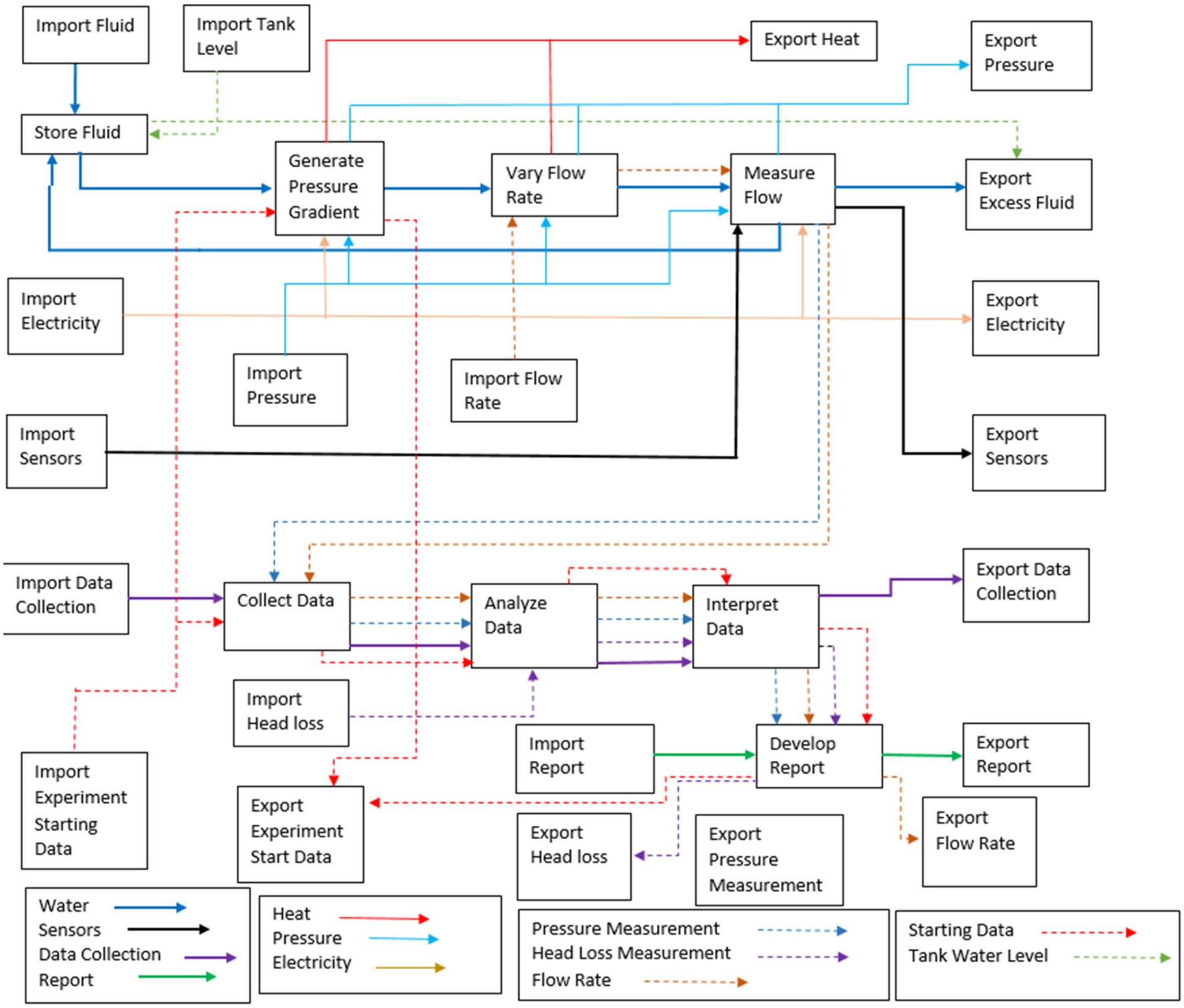


Figure 6 - Pipe Flow Functional Model

3.4 Subsystem Level

Some of the subsystems include the varying volumetric flow rate pump, and step up and step-down sections of the whole system. Because of the simplicity of the project there are not many separate subsystems that could be included. The most important subsystem would be the varying volumetric flow rate pump. This pump will be used to change the flow of water, giving us different flow rates for us to reach the right Reynold's number and head loss values that the team are looking for.

The step up and step-down sections of the system are important for us to get the values the team need. The step-up section acts as a link from a smaller diameter pipe to a larger one. The same goes for a step-down section, except in the reverse. These changes of diameters increase or decrease the flow rate allowing us to gain varying head loss across those sections. From various other experiments and the own calculations, the team can decide which the best diameter change is needed.

Each section of this design whether it be the pipes, joints, pumps, or steps are all being utilized to achieve the proper results that the client wishes. For the Pugh chart specifically, the systems analyzed were pipe material, pipe system orientation, pipe roughness change, addition of labels to the pipe system, pipe diameter change, and flow rate changes.

4 DESIGNS CONSIDERED

For the Pipe Losses Experiment the design space is already well defined, so the designs considered are focused on materials, fitting types, joints types, and sensor systems with a final section for each member's individual overhead sketches of the table layout. For each area, the team conducted an analysis to gather all needed information to narrow down each item and create a final list for additional analysis. A breakdown of each section is detailed below in the order stated.

4.1 Materials

Pipes came in many difference materials that are designed to meet different goals for different systems. The boundary for the materials are ones that are valid for fluid pipe flow. There are two major properties for materials that are considered. First, how corrosive the material is. To meet the life expectancy from the client, the materials need to be able to resist corrosion from the working fluid. Secondly, the roughness of the pipe is important as it directly affects the head loss over the system which is one of the major requirements for the design. The material selection is for the pipes that will facilitate transporting the fluid and the frame used to hold the system. The team considered seven pipe materials that are commonly used to transport fluids and are as follows:

1. Aluminum
2. Concrete
3. Copper
4. Clay
5. Glass
6. Plastic
7. Steel

A breakdown of each material is found in the following sections.

4.1.1 Aluminum

Aluminum piping has become an attractive alternative to copper because of the increase price of copper over the last ten years along with the ease of use and corrosive resistance provided [4]. The corrosion resistance is of desire to the team because of the request life span of the project which a function of the corrosion of the pipes used. For fresh water, Aluminum has excellent corrosion resistance and usually only faces corrosion in the form of pitting on the wetted surface [4]. Water is the current fluid material that the design will use and thus the resistance to water corrosion is of great benefit.

Aluminum's corrosion resistance is a product of the how highly corrosive pure Aluminum is [4]. As Aluminum is exposed to a fluid, the outer surface of the material rapidly develops an oxidized layer that creates a protective layer for the remaining material [4]. The use of water in the system would ensure the creation of the protective oxidized layer and increase the life span of the Aluminum piping. With the creation of an oxidized surface, the corrosion of water is usually in the form of pitting on the surface [4]. The pitting created could be advantageous to the design as one of the major requirements is the requirement of a significant and measurable head loss over the system which the pitting could increase the overall head loss of the piping. The effect of the pitting to the head loss is still yet to be determined.

One of the main disadvantages of Aluminum is the inability to weld the material and thus the material is more difficult to work with. For piping, an Aluminum, Magnesium, and Manganese alloy has two characteristic that make it particularly attractive. First is the ability for the material to be welded, which would allow for stronger and tighter fittings within the design to prevent leaks and increase life span [4]. Second is the increase corrosion resistance that the alloy provides, which, again will increase the life span of the design and decrease the need for replacement pipes [4]. Aluminum alloys 535 and B535 are the main candidates for Aluminum, Magnesium, and Manganese alloys for the design [4] but initial research shows that the alloys are not cost efficient.

Aluminum drawn tubing has a roughness of approximately 0.0015 millimeters, which is on the lower end of the spectrum for pipe roughness [5]. The roughness is important for creating a signification amount of head loss over the system which is a requirement for the entire design. Finally, Aluminum's density is lower than other metals and thus will allow for a lighter system [6]. The requirement of weight is not important but being able to move the system is and thus Aluminum would increase the mobility.

Aside from pipe materials, the table and frame for pipe system also must be redesigned as well. Aluminum has many characteristics that are desired for building a frame the system. The main disadvantage is the requirement of special alloys to weld the material. Aluminum is also an effective heat diffusing material, high thermal conductivity value, but heat of the pipe system is not a major concern for the design [6]. As for the remaining functions, the pump could be made with aluminum, but the remaining functions are not affected by the material.

4.1.2 Clay

Clay piping is common for sewage and highly corrosive fluids because the use Vitrified Clay Pipe is natively inert [7]. Clay piping's native resistance to corrosion will allow for extended periods of fluid flow with no measurable degradation of the material. Additionally, clay is under the ceramic material category, and thus has the advantages and disadvantages of ceramics [6]. The resistance to heat is not important to the design but the stiffness would reduce changes to system from thermal sources or forces [6]. Unfortunately, ceramics have a major disadvantage in that ceramics do not show signs of failure but instead fail catastrophically and thus expresses a safety concern to the users [6]. Finally, clay piping as a large roughness range from 0.7 – 9.0 millimeters [8]. The possible large roughness for clay does make the material attractive for having a large amount of head loss over the system.

Clay has been used as a building material and could be used to build the frame and support system to for the design. The stiffness and strength of ceramics are attractive but, again, the short comings of ceramics and sudden failures make the material difficult to work with [6]. The remaining functions of the system are not affected using clay as a pipe material or building material.

4.1.3 Concrete

The use of concrete pipes is common practice all over the developed world and it has become a staple for construction and building. Concrete offers many advantages; the main advantage is the availability due to the simplicity of the production process. However, while concrete is a readily available material, it is not a practical material for small scale piping. Concrete piping is usually used in the transportation of large amounts of a fluid in civil style applications. The ANSI/AWWA C301 specification covers pipe diameters from 16 inches up to 60 inches, which is well outside of the range of pipe sizes for the project design space [9].

Concrete could be used to build the table and frame for the system. While a frame built with concrete would be very strong, it would also be very heavy and difficult to build. The remaining functions are not affected using concrete.

4.1.4 Copper

Copper is currently the most common material used for fluid pipes and what the current design uses. There are many reasons for the use of copper pipes but one of the main is copper's corrosion resistance [10]. Like Aluminum, Copper produces a protective film over the outer surface which allows for the high level of corrosion resistance [10]. Copper has many of the same qualities as Aluminum with a major difference being Copper pipes are soldered at the joints while Aluminum is threaded or welded (if weldable Aluminum). Additionally, the pipe roughness for drawn copper is the same for Aluminum at approximately

0.0015 millimeters [5].

Copper is also a great material, high thermal conductivity value, for transferring heat and will allow for the heat generated in the system to be dispersed easily [6]. Copper wiring is often used for electronics and is likely to be the medium use for the wires needed for the sensor system. While building the table and frame out of copper is possible, it is impractical and likely to be costly. The remaining functions are not affected using copper as the pipe material.

4.1.5 Glass

Glass piping is being considered for a potential flow visualization section of the system. While flow visualization is not a requirement from the client, the team is preforming some preliminary research to evaluate how difficult it would be to implement in the system. The use of glass tubing would make it possible to use flow visualization techniques, but glass does prove to be a challenge to work with. First, glass is of the ceramic material type and thus has the benefits of ceramics (heat resistance, high stiffness, etc.) but also the major down falls of ceramics (brittle, sudden catastrophic failure, etc.) [6]. Glass could still be a valuable material for flow visualization, but additional care would be needed for use.

Glass is considered highly corrosive resistant, such that many believe that glass would resist weather and corrosion for many of years [11]. The corrosion resistance of glass, as well as the ease of cleaning, does make glass a particularly attractive option for fluid flow, but do to the weaknesses of ceramic, only low speed flows are viable. Secondly, the roughness value for glass is like that of drawn tubing at approximately 0.0015 millimeters [12].

The frame and support structure for the design could also be constructed from glass, but the remaining functions for the are otherwise not affected using glass piping.

4.1.6 Plastic

There are many different types of plastics and many are used for fluid piping systems. Plastics are a polymer, or a repeating chain of a simple molecule, and are one of the most common materials available today [6]. Most plastics have a difficult time decomposing which is partly because plastics have a high corrosion resistance [13]. Again, the material corrosion resistance is important to increase the life span of the system but plastics provides other problems. Plastics, more commonly polymers are susceptible to material changes from even small heat sources [6]. Heat sources can make a ductile plastic into a brittle material that can begin to exhibit ceramic like properties, commonly losing the ability to express strain and warn of failures [6]. There are methods to deter the restructuring of plastics by reducing the heat transfer to the system.

Plastic pipe systems have similar roughness to values to that of drawn metal piping of around 0.0015 millimeters [12], or a very smooth surface which will reduce the head loss of flow through the system. Plastic does have an advantage over metal materials because it is easier to work with. Plastic pipes are often able to be cut with shears and fittings usually just use an epoxy so make a fluid tight seal. The frame and support structure could be made from plastic but the ductility of the material would likely make it difficult to create a stable, long lasting, structure. The sensors and sensor reading points are likely to use plastics are parts of the devices and will be used as parts of the wiring used throughout the system. The remaining functions of the systems are not affected using plastic.

4.1.7 Iron/Steel

Considered to be one of the most common building materials in the world, iron, and it counterpart steel, are used in almost every major construction project in the modern world. There are many reasons for how common steel is, the main one is the strength of the material [6]. Steel is considered one of the strongest materials in the world that is in abundant supply would be able to handle the forces applied by the pipe system. Additionally, steel is weldable, thus water tight fittings are possible with relative ease (relative to the other materials analyzed) [6]. There is one major drawn back to steel, and that is, steel is highly corrosion in the form of oxidation [6]. Oxygen and steel bound easily to form an iron oxide that causes the material to lose most of its strength and durability [6]. There are steel alloys that greatly improve the corrosion resistance, such as a steel and chromium alloy, also known as stainless steel, but those alloys often increase the cost of the steel and reduce the machinability [6]. Steel piping also does not have an increase in pipe roughness to other drawn metals unless the steel is casted or galvanized [5]. The galvanizing of steel would increase the corrosive resistance but at an increase to the cost and potential reduced machinability [6].

Steel could be used for the support structure of the system. The support structure does not facilitate the flow of the working fluid; thus, it is not subjected to the same corrosive environment. Additionally, the strength of the steel would help to ensure a stable and long-lasting design. The rest of the functions for the design are not affected using steel as a building or piping material.

4.2 Pipe Fittings

The project client is requiring the pipe system have a minimum number and type of joints but no bounds on the maximum number. For this, the team is required to determine the most efficient configuration for the overall pipe system. The minimum fittings required are as follows:

1. One T-Joint
2. One Elbow Joint
3. One Step-up (Expansion) Joint
4. One Step-down (Contraction) Joint

The client left each joint as generic version leaving the selection of a specific type to the design team to determine what works best for the system. For the fittings, the major determining factor is the head loss coefficient of the fitting, with the ability to incorporate the fitting into the overall layout a secondary factor. A breakdown of each fitting type is as follows with a breakdown of each general type of pipe fitting and its corresponding head loss coefficient located in Appendix A, table 1.

4.2.1 T-Joints

There are two types of T-Joints, branching and dividing line that differ in the way the flow is separated into multiple streams [5]. The difference in tee joints is just by the way it separates the flow, either is a “T” style or a “Y” style which varies the head loss coefficient for minor loss over the joint [5]. The major difference is that they the fittings change the layout of the system, which changes the overall design of the system and each type must be considered. Additionally, the material used will determine the connection type for the function, either press fit, or a threaded attachment both with a sealant. The use of the a threaded or press fit also changes the head loss coefficient for the joint [5].

4.2.2 Elbow Joints

Like tee joints, different elbow joints determine the head loss coefficient used for each fitting [5]. Elbow joints do not have the same geometry differences of tee joints because the elbow joints, usually, come in 90 or 45-degree direction changes to the flow with either a long bend or a short bend [5]. Since head loss one of the major components of the design, each different elbow’s head loss coefficient will be a determining factor for which one is used but each type could be used to demonstrate the differences for each elbow.

4.2.3 Step-up and Step-down Joints

The last joints that are required for the design are expansion and contraction joints. As with all minor losses, the minor loss coefficient is the main factor for determining the optimal fitting to use for the system. Unlike the other fitting types, the minor loss coefficient is not a set value for the specific fitting but is a function of the smaller area vs the large area and how gradual the change in area is in the form of the angle of the gradient [5]. A smaller angle for the gradient results in a smaller minor loss coefficient, as well as a higher ratio to the areas (one being the highest value) results in a smaller minor loss coefficient [5]. The area ratio and the angle of change will both have to be analyzed to determine the most efficient combination of joints.

4.3 Sensor Types

As per the client's requirements, the system must be able to handle two sensor types, first, three different flow rate sensors, and secondly, a differential pressure sensor. The three different flow rate sensors are design to demonstrate three different techniques to measure flow rate through a pipe. Two of the flow rate sensors are to be invasive sensors that fit within the pipe system and record the flow rate by directly measuring the flow across the system. Invasive flow rate sensors act like pipe joints and fittings and create a minor head loss across the sensor, this head loss is usually far greater than that of simple pipe joints like the elbow [5]. The second type must be a noninvasive sensor that can be moved around the pipe system to determine the flow rate that specific section of the pipe. The client recommended the investigation of ultrasonic flow rate sensors like the current sensor used with the old design. Flow rate sensor research is still on going, but the cost of many sensors has become an issue which the client as provided a solution which will be elaborated upon within the budget section.

The pressure sensor to use is still under research but the current design uses a digital differential pressure sensor. The current sensor, while the client does now the rational for the sensors selection, is not sensitive enough for certain sections of the current system, which makes collecting data from the current system difficult. There are two approaches for determining an optimal sensor, first is to set a pressure range for the system and find sensors that operate within the set pressure range, or to choose a range of sensors that operate within a set pressure range and design the system to operate within that pressure range. The latter method is the method selected by the team and approved by the client, this method will give the team a base range for the design simulations.

4.4 Layouts Considered

While the materials and the fittings can be compared analytically, the layout of the system is a conceptual system that must be analyzed. To do this, each team member was tasked with producing a sketch of the overall layout of the system which includes the fittings, the joints, values and sensor locations. Each member's sketch was then presented to the rest of the team in a gallery method and each sketch was examined in detail by the entire team one by one to determine positives and negatives to each. All designs can be found in Appendix 8.1 .

4.4.1 Design 1

Design 1, located at Figure A - 1 - Concept 1is a simple straight path system that has all the needed joints and fittings in a straight line. This design is very simple, a straight path removes the requirement of values to divert the flow to different sections to test different components of the system. Additionally, if values are not used in the pipe system, mass balance calculations to determine the flow rate through each segment to determine the velocity in each section which is required to determine the head loss over the fittings. The design has the disadvantages of being a straight system, that is either very long, a purely straight system, or is very wide with many elbow joints to allow each section to facilitate each needed component. The loss of needing values also removes a potential learning opportunity of the head loss over different types of values.

4.4.2 Design 2

The second design is based on the current system that is used by the ME 495 lab, and because of this, it is an improvement to the current design instead of a complete redesign. The design, uses a long straight pipe to allow for straight pipe head loss determination, which then feeds into a section of pipe that has multiple tee-joints with values to redirect the flow to the individual sections of the system where the different joints and fittings head loss will be determined. The design has the advantages of being a compact design that could possible reuse the current frame and table top of the old design which was desired by Dr. Mazumdar to have a more compact design. Additionally, the values allowed for the need for mass balance evaluation of the flow over different segments unnecessary because the entire flow could be redirected to only a single segment, but if desired the flow could be directed to two segments and mass balance could be performed. The use of multiple valves, and two long sections of multiple tee-joints does increase the complexity system and has the potential to recreate the problems that the current design has, refer to the background section for information about the problems with the current design.

4.4.3 Designs 3 and 4

Designs three and four are both very similar so they have been grouped together. Both designs feature a system where the flow starts with a long straight section that then feeds into an elbow joint, which feeds into a tee-joint that separates the flow into to two segments which then converge into a single outlet from a second tee-joint. The designs differ in the layout of the two segments.

The third design features values and that allow the direction of the flow to be controlled, between a section with a pitot-static tube to determine flow rate followed by an expansion and contraction fitting over a small section of straight pipe. The second segment contains a series of different 90-degree elbow joints that allow for the head loss from different joint types to be analyzed. The third design is the most complex design of the four, requiring many values, elbow joints and tee joints, and will take up a large amount of space to ensure the flow has returned to a fully developed flow after each joint type.

The fourth design, also has two segments for the flow but with man differences. The first segment is another straight-line pipe to determine the loss of flow over a section with a different diameter or material. The second section includes two 90-degree elbow joints, one a long transition, the other a very sharp transition. In between the two joints is a 90-degree expansion and contraction joint. The two segments rejoin at a final tee-joint before returning to the fluid reservoir. The design is simpler than design two and three but not as simple as design one, and requires the use of mass balance to determine the flow rate through to two segments of the system. Additionally, the design removes some of the educational opportunities for the students which inhibits the primary goal of the design.

4.5 Component Designs Considered

For the individual component of the design, the team took part in the 6-3-5 method for three components. The components of the system that are analyzed are how to have a minimum measurable head loss, how to measure the flow rate of the working fluid, and how to vary the flow rate of the semester. The varying flow rate component of the system was considered twice because of the how important to the component is, the ability to vary the flow rate is fundamental to the design and trying to extract as many ideas as possible to determine the best possible solution.

5 DESIGN SELECTED – First Semester

As with all engineering problems, one of the early steps to generate as many designs a possible no matter what the circumstance or feasibility of the design. After designs have been generated, the team must be able to narrow down the designs to designs that meet the criteria and requirements of the client and what is engineeringly feasible. The process or narrowing down the designs is the process of design selection which has many different methods that all have their own advantages and disadvantages. The team decided to use two methods for selecting the best concepts, first a Pugh Chart which compares all designs to a set datum, and secondly a Decision Matrix, which compares all designs to each other with weighted categories. The Pugh chart was used to determine the best overall layout design created by the team and was compared against one of the designs from the research the team preformed, while the Decision Matrix was used to compare the individual components of the design. A special note for the joints and fitting design selection, since the primary goal of the design is to teach about head loss, the design will attempt to include all possible joint and fitting types as to demonstrate the differences in each type. With the desire to provide as many different opportunities to the students means that each joint and fitting are considered equal and will, instead, be determined as the layout of the system is finalized. It must be stressed that the selected design and components are preliminary and subject to major changes as the design process progresses.

The selected over all layout is design 3. Design three featured every aspect of what is desired for the design, mainly the ability to educate and demonstrate head loss of a pipe flow system. The material selection is currently split between two different materials, first is plastic piping for the availability and cheaper cost, and second copper piping for the increased strength and reliability of the material.

5.1 Rationale for Design Selection

The team came to the selections using simple MatLab calculations, a Decision Matrix and a Pugh chart. The Decision Matrix and Pugh chart are in Appendix 8.1. The team started with material selection to determine which material would be the best choice for the final design and to provide additional information when selecting a design.

For the material selection, the team used a Decision Matrix to compare all the researched materials to each other to find the best material. The categories for the materials with their corresponding weights are:

- Cost – 3
- Corrosion Resistance – 5
- Roughness – 5
- Strength – 4
- Sizes Available – 5
- Ease of Fitting – 4
- Life Span – 3

The weights for each category where determined by the comparing the QFD to what the client and the team felt where the most important characteristics about the material. The corrosion resistance of the pipe, the roughness and the available sizes are the three most important criteria for the material for different reasons. The corrosion resistance is needed to ensure the experiment is safe and long lasting for the college of engineering. Second, the roughness is a weight of five because the roughness of the pipe is directly proportional to the head loss of the system, which is the primary goal of the design. Finally, the sizes available was originally scored very low, but upon researching pipe materials it became apparent that not all materials operate within the size restrictions for the system, because of this, the sizes available category was evaluated to a weight of five. From this analysis, the two highest materials are Copper and Plastics pipes. Copper came in with a score of 95, while Plastic pipes have a score of 97. Plastic pipes beat out

Copper piping only because of the cost of coper pipes being higher than the plastic. The strength and life span of the plastic piping is an area that the team will have to conduct additional analysis of because of the potential forces the fluid could apply to the system. To ensure that if plastic does not meet the standards needed for the system, copper will also be analyzed in parallel to the plastic pipes to allow for a simple transition should plastic not be up to the standards needed. Next the team analyzed each design using a Pugh Chart.

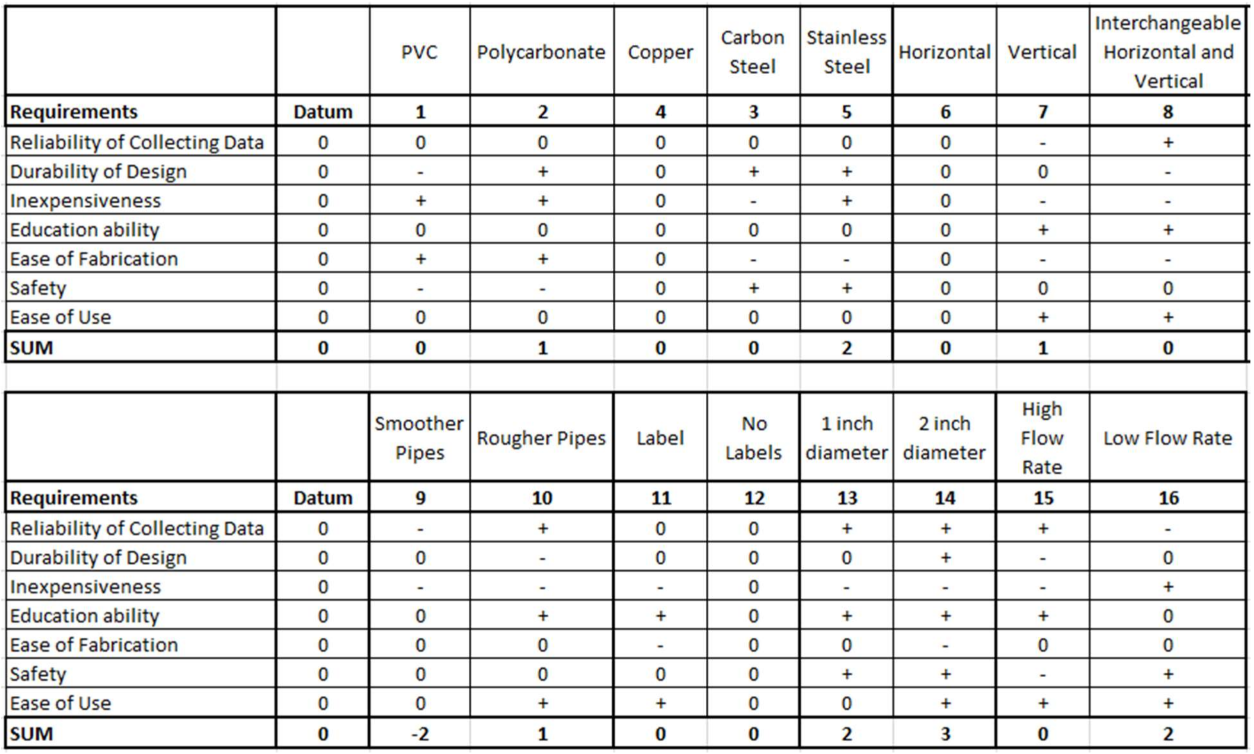
A Pugh Chart is used to determine the overall design used the following requirements to determine the best design.

1. Reliability of Measurements
2. Durability of Physical System
3. Three Forms of Flow Rate Measurements
4. Minimum Pipe of Diameter of 1/2 inch
5. All necessary fittings and joints types used
6. Ease of use
7. Ease of Assembly
8. Variable Flow Rate

Each concept was compared to Ohio Northern University's design as the benchmark, which was the closest system to the desired design the team could find. The Ohio design is a system for determining the head loss over three segments of straight pipe, one with a ball valve, with smooth and course pipes [2]. The desired goal for the Ohio experiment is to teach about head loss, which is the same primary goal for the new design for ME 495. As stated in the background section, the lack of joints and fittings other than a single valve be deviate from the client's requirements but the principle remains the same. The Pugh chart demonstrated three possible designs that are all within one point to each other, design 1, design 3, and design 4, with design 3 one point higher than design 1 and 4. The deciding factor between these three designed is the inclusion of a variable flow rate system within design 3, while designs 1 and 4 did not include this feature. Design 2, was the worst design because of the complexity of the assembly, the long series of tee-joints at the ends and need for several valves, the lack of a contraction or expansion joint, the lack of three forms of flow rate measurements and the use of plastic piping reduced the durability of the physical system. Design one and four were not chosen because of the lack of a variable flow rate or control system for variable flow rate, since this is one of the main requirements from the client, both designs were marked as inadequate. Design 2, being able to meet all the requirements of the client is thus the chosen preliminary design for the pipe system layout.

The Pugh chart show in Table 2 - Pipe Experiment Pugh Chart is separated into six main sections: pipe material, pipe system orientation, pipe roughness change, addition of labels to the pipe system, pipe diameter change, and flow rate changes. The datum set for the Pugh chart was based on the original design that needs to be improved. The original design has copper pipes, is oriented horizontally, has smooth pipes, does not have educational labels, has ¾ inch diameter pipes mainly, and has a variable flow rate but not by the pump. The first criteria analyzed in the Pugh chart was pipe material. Actual complete designs were not considered for the Pugh chart since there are many permutations that the pipes can be combined, however there are certain general characteristics of the apparatus that need to be considered individually to yield a cohesive result of the best attributes.

Table 2 - Pipe Experiment Pugh Charts



		PVC	Polycarbonate	Copper	Carbon Steel	Stainless Steel	Horizontal	Vertical	Interchangeable Horizontal and Vertical
Requirements	**Datum**	**1**	**2**	**4**	**3**	**5**	**6**	**7**	**8**
Reliability of Collecting Data	0	0	0	0	0	0	0	-	+
Durability of Design	0	-	+	0	+	+	0	0	-
Inexpensiveness	0	+	+	0	-	+	0	-	-
Education ability	0	0	0	0	0	0	0	+	+
Ease of Fabrication	0	+	+	0	-	-	0	-	-
Safety	0	-	-	0	+	+	0	0	0
Ease of Use	0	0	0	0	0	0	0	+	+
SUM	**0**	**0**	**1**	**0**	**0**	**2**	**0**	**1**	**0**

		Smoother Pipes	Rougher Pipes	Label	No Labels	1 inch diameter	2 inch diameter	High Flow Rate	Low Flow Rate
Requirements	**Datum**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Reliability of Collecting Data	0	-	+	0	0	+	+	+	-
Durability of Design	0	0	-	0	0	0	+	-	0
Inexpensiveness	0	-	-	-	0	-	-	-	+
Education ability	0	0	+	+	0	+	+	+	0
Ease of Fabrication	0	0	0	-	0	0	-	0	0
Safety	0	0	0	0	0	+	+	-	+
Ease of Use	0	0	+	+	0	0	+	+	+
SUM	**0**	**-2**	**1**	**0**	**0**	**2**	**3**	**0**	**2**

The five main materials chosen were PVC, Polycarbonate, Carbon Steel, Stainless Steel, and Copper. PVC and Polycarbonate had somewhat weaker yield strengths of 7,640 psi [14] and 13,000 [15] psi respectfully compared to the 10,152.6 psi for copper [16]. Carbon steel and stainless steel both had stronger yield strengths of 60,200 psi [17] and 31,200 psi [18] respectfully. The polycarbonate and stainless-steel pipes had positive results from the Pugh chart. Both materials were cheaper than the copper prices and had higher yield strengths. Stainless steel scored higher than polycarbonate because the modulus of elasticity for steel was 29,000,000 psi [17] whereas the modulus of elasticity for polycarbonate was 350,000 psi [19]. Stainless steel would be able to withstand more pressure than the polycarbonate and thus be safer to use. Carbon steel had the same modulus of elasticity of stainless steel and a higher yield strength, however carbon steel was less corrosion-resistant and more expensive than stainless steel. The two materials that will be considered in the decision matrix are polycarbonate and stainless steel.

The next criteria analyzed in the Pugh chart was pipe system orientation. The three orientations considered were Horizontal, Vertical, and Interchangeable Horizontal and Vertical. The original pipe design was horizontal and due to that, some locations on the display were hard to see and apparatus was difficult to transport. By considering a vertical design, the apparatus would be easier to see and present for education ability and be able to transport easy enough for one person to move it. Also, by having a vertical apparatus, the effects of gravity on the flow through the system could be studied for more applications to education. The possibility of an interchangeable horizontal and vertical apparatus was also considered for a flexible experiment that includes the ability of transportation and education ability as well as the sturdiness of being a horizontal table. The interchangeable system orientation would be a great way to combine both other possibilities, however the drawbacks include the fact that it would be more complex to manufacture, it would cost more to obtain the specialized mechanical parts for the orientation, and the apparatus would be subject to more wear and fatigue due to movable parts that may fail. The vertical and interchangeable orientation will both be considered in the decision matrix.

The next criteria analyzed in the Pugh chart was the roughness change. The inner roughness of the pipes could either be smoother, rougher, or be kept with the original roughness. By making the pipes smoother, purchasing the pipes would be costlier due to the added specifications and collecting data would be harder because the Reynolds number value would change less through the pipes. By making the pipes rougher, purchasing would still be costlier due to the added specifications and the pipes would be subject to more corrosive effects like water erosion to impact the pipe durability. If the pipes were kept with the standard roughness, the prices would stay the same for each material and the roughness would stay close to the estimated values for less error in experimental calculations. The standard and rougher pipe roughness will be considered in the decision matrix.

The next criteria considered was the addition of informative labels on the design. This possibility was considered due to their use in the HM 150.11 apparatus design from the Grunt Hamburg pipe systems. By having labels around the fittings, dimensions, and important comprehension aspects of the experiment, students would be able to have higher education ability when performing an experiment. The only drawback of adding labels was the complexity of manufacturing the labels and the cost to go along with the manufacturing. According to the Pugh chart, adding labels to the apparatus would provide a net neutral outcome compared to not adding labels, however the labeled design will be considered in the decision matrix along with the not labeled design.

The next criteria considered was the main pipe diameter change. The main pipe diameter was the diameter chosen from the manufacturer and the diameter that would be used in experimental calculations. The inner diameter will impact the Reynolds number range, the strain that the pump will endure to push water through the pipe, and the pressure that the pipe material will endure. The diameters considered in the redesigned apparatus were a 1 inch and a 2-inch diameter pipe. Both pipes would cost more than the original ¾ inch design, be safer to use because the endured pipe pressure and pump strains would be less, and have more reliable data collected from them. The 2-inch diameter pipe would be better than the 1-inch pipe because it would be more durable and easier to use since the pipes were thicker. Both diameters will be considered in the decision matrix.

The last criteria considered was having a high flow rate or a low flow rate as the main speed used for the experiment. Both flow rates would be able to yield the desired Reynolds number range of 10^4 to 10^6 depending on the diameters used in the apparatus. According to the Pugh chart results, the apparatus would function better with a low flow rate because it would be safer to operate the pump at lower flow speeds, and the pump used can have a lower max speed and thus cost less. The low flow rate for the experiment would be considered in the decision matrix.

5.2 Design Description

The final design is ultimately an iteration of the old design. The client rejected most of the designs presented by the team and then requested that the old design be updated to include all the desired fixes and changes. As such, the layout of the original design, the three different segments from a long inlet segment, with the two middle segments featuring the contraction and extraction requirements.

5.3 Prototyping

For the prototype requirement that team has agreed upon using the old design as a test bed for the future design. The client has agreed to replace the broken pump with the pump purchased by the team, this process will take place over the 2018 summer, as such the team will be meeting over the summer to perform the analysis and experiment.

The analysis will consist of multiple parts. First, the team will execute the old experiment in the entirety. During which, the team will record any areas of the experiment that have problems and difficulties, while also noting what the old design performs well. Secondly, the team will validate the mathematical models developed for the new design. The models will be adapted to model the old design and then results will be calculated using the models, then validated with the measured values from the old design. If the calculated values are within ten percent of the measured values then the model will be considered accurate, if within one percent, the model will be considered valid and can be used to future design iterations. If the model is outside of those bounds, the model will be reworked and retested until the model values are at least less that ten percent error. If unable to get the model within the ten percent, the error within the old design would have to be considered. Additional work to validate the model would then be required and will possibly require using one of the flow tables in the lab.

The second part of the analysis will include breaking down the old model and attaching new devices to the system. The primary desire for the analysis is to test the validity of using the quick disconnect taps for the differential pressure manometer. The connection of the quick disconnects is the most desired test, as the current pressure taps are prone to break free of the mounts. To determine the best method to fit, the team will attempt many different fitting types that will depend on the material of the quick disconnect and how to bound that to the copper pipe. Finally, the team will take these results to iterate the design to ensure that all the requirements are left and that the new design does not replicate the problems with the old design.

5.4 Design Model

The model for the design is developed using Solidworks 3D Modeling software. Solidworks provides a detailed tool to provide the needed information to accurately model the system. The design is broken into two sections, the upper pipe section and the lower structural and ancillary component, the pump and reservoir.

5.4.1 Upper Section

The upper pipe section is just the model of the pipe network and does not include the table top. This section was designated because it is where the students will be preforming most of the experiment and interacting with the design. The assembly is made up of several different parts that include,

- Straight Lengths of Pipes
- Elbows
- Tee Joints
- Contraction and Expansion Joints
- Pitot Static Tube Mount
- Ball Assembly
    - Internal Ball Valve
    - External Ball Valve Housing
    - Valve Grip

The complete assembly is located in **Error! Reference source not found.**~~8.4 ~~**Error! Reference source not found.** **Error! Reference source not found.**~~Figure D - 1 Upper Section Assembly~~. As stated above, the upper assembly is broken into three segments, with an entry segment and exit segment. The entry segment features a ball valve, a long straight length of piping, used to determine the head loss over a long length of pipe, and an elbow to redirect the flow into the tee joint that separates the flow into the different segments. The first segment features an expansion into a long straight length of pipe, designed to measure head loss over a larger diameter pipe, into a contraction, through a valve, to control the flow entering that segment, and then redirected using an elbow into the exit segment. The first segment is designed to test how an expansion will affect the head loss of the pipe system, mainly that diameter is raised to negative fifth power, so a small change is diameter causes a large change in head loss. The second segment is designed to further reinforce this idea that diameter is the most sensitive parameter for pipe head loss, as this segment features a contraction joint into a small diameter pipe, which then returns to the standard pipe size in an expansion joint before entering the exit segment. A valve located immediately after then expansion joint is designed to restrict the flow through the system when not needed. The final segment is designed to measure the head loss over two different common pipe flow devices. First, there will be a pitot static tube that will be inserted into the flow that will be used to determine the flow rate of the velocity, Pitot-Static tubes a very common and simple tool used to determine the velocity of the flow by comparing the stagnation pressure to the static pressure of the flow using $p_{stag} - p_{static} = \frac{1}{2}\rho V^2$ [5], where velocity can be solved for giving the following: $V =$

$\sqrt{2\rho(p_{stag} - p_{static})}$. Using the solved for velocity, the flow can be determined using $Q = VA$, where V is the velocity, and A is the cross-sectional area. Additionally, the head loss across a ball valve will be determined. The ball valve is placed able to both restrict the flow through that segment and to get an accurate pressure measurement from the taps. Finally, the segment also includes an elbow to redirect the flow into the segment and then enters the exit segment.

Total size of the assembly is slightly larger than the total size desired for the table. The assembly is approximately five feet by ten feet, which is the maximum size for the table that is desired. Since the assembly needs to be slightly smaller than the table this size needs to be cut down. First impressions are to cut down the short length of pipe that connects the entrance segments to the three experimental segments, this would reduce the width of the system. Additionally, cutting down the lengths of each segment will reduce the length of the pipe system. Each of these comes with advantages and disadvantages. Frist, the disadvantages, the major disadvantage is the reduction of length to ensure that the flow as returned to a fully developed flow before the next pressure tap. The advantages are great, first the head loss over the entire system will decrease, this will improve the flow rate which is a requirement that the client is requesting. The current flow rates produce Reynolds numbers that are smaller than what the client is requesting and is requiring that the system be iterated to produce higher flow rates. Second, the cost of the entire design would be reduced. While the current cost of the design is within the desired budget, and reductions to the cost are valuable and pursued. The individual lengths of each pipe section are located in the drawings in Appendix C – CAD Model**Error! Reference source not found.**.

5.4.2 Lower Section

The lower section consists of just a few major components. First is the reservoir for the system, which will act as a holder to ensure that there is enough fluid to prime the system and act a filling and draining point. The next major component is the pump which will provide the flow rate and increase to pressure of the working fluid to push it through the system. Finally, the table and all connecting pipes are part of the lower section. The table and frame are purely structural and provide no other functions. There are connection pipes from the reservoir to the pump, then the to the entrance and exit segments of the upper section to complete the pipe network. A completed model is located in Appendix C – CAD Model**Error! Reference source not found.**.

5.5 Analytical Reports

Each member of the team was tasked with analyzing a different element of the design and how it will improve or hinder the project. The members were tasked with the following, Keith preformed an energy balance of the entire system to determine the validity of a selected pump. Michael preformed research on pumps and control systems to determine which would work best for the design. Mark preformed research on sensors and data acquisition systems to determine what would be the best method(s) to perform the experiment once the design is finished. Finally, Cole preformed material stress and strain analysis, and researched pressure tapping systems and how to connect the sensors to the pipe system. The results of these analysis are to follow.

5.5.1 Design Simulation and Analysis – Keith Caton

Since the experiment requires the ability to measure and record the change in head over several different pipe lengths and fittings, the system requires that a measurable head loss is needed, but that the pump selected can provide sufficient energy to the flow to push the fluid through the system. As such, the pressure at each critical point of the system is needed. A critical point is a point after a long section of pipe, or immediately before and immediately after a fitting within the pipe system, as it is these points that students will collecting data but also the points where the flow is going to experience the greatest head loss. Fortunately, the energy flow of a fluid, $\left(\frac{P_1}{\rho} + \alpha_1 \frac{V_1^2}{2} + gz_1\right) - \left(\frac{P_2}{\rho} + \alpha_2 \frac{V_2^2}{2} + gz_2\right) = h_t - h_p$, is well defined and a simple equation for a two-point analysis and will be the governing equation for the entire analysis [5].

5.5.1.1 Assumptions

As with most fluid analysis, the assumptions made dictate the analysis that will be performed and what the governing equations will be. For the analysis of the head loss of the system the following assumptions will be made:

1. The flow will be an incompressible flow at all points throughout the system.
2. The fluid temperature will be the same as room temperature at all points within the system, and room temperature will be $25°\mathrm{C}$.
3. All critical points will assume the flow is fully developed.
4. All flow throughout the system will be turbulent flow, thus $\alpha \approx 1$ for the energy balance equation [5].
5. The friction factor for straight pipe analysis will follows the Bruus Correlation as follows: $f = \frac{0.25}{log_{10}(\frac{\epsilon}{3.7*d}+\frac{5.74}{Re^{0.9}})^2}$ [5].
6. The flow at branching points within the system will be completely directed to one branch (the alternate routes will have valves that stops all flow).
7. Acceleration due to gravity will be assumed constant and equal to $9.81\ \frac{m}{s^2}$ or $32.2\ \frac{ft}{s^2}$.

These assumptions allow the energy balance equation for a fluid flow to be solved matching the operating conditions within the thermo-fluids lab. The assumptions are not without penalty. Assumption 3 states that the flow will be fully developed at all points, which is not true for the actual system. As the flow moves through fittings, the flow characteristics can change greatly in the region of the system immediately after the fitting. As such, the energy balance, even without these assumptions, is only a loose approximation of the flow characteristics [5], thus the system is expected to behave differently that from the analysis preformed.

5.5.1.2 Analysis Plan

To determine the energy over the entire system and the head loss between each critical point, and the operating point of the system, a complete simulation of the design will be needed. Before the simulation can be even be performed a layout of the pipe system and identification of the critical points. Once the layout has been chosen and critical points designated from the criteria stated above, the inputs for the simulation are needed as it will determine the algorithm that will be used to build the simulation. The inputs for the simulations are as follows:

1. The pump curve of the selected pump.
2. The length of each straight pipe section.
3. The diameter of each pipe (Only diameters that differ).
4. The approximate roughness of the pipe material (a single material will be used for all pipes).
5. The head loss coefficients for each fitting type that is used.
6. Fluid properties at $25°\mathrm{C}$:
    a. Density
    b. Kinematic viscosity

With the expected inputs for the simulation defined, the viable outputs for the system can be determined. For the simulation, three outputs are desired, 1) the pressure at each critical point, 2) the head loss over each combination of immediate critical points, 3) the average Reynolds Number for the flow. Finally, with the expected inputs and desired outputs, the actual algorithm needed to determine the desired outputs from the expected inputs is needed.

5.5.1.3 Analysis

For the analysis of the selected design the ability to change the inputs at will and return the results of the simulation is one of the most important aspects of the simulation. As such, a computer program is needed to build the simulation in and then perform the simulation and output the results in a way that is easy to read. The selected platform for the simulation is MatLab R2017b which is provided to all Northern Arizona University students for academic school work and research.

The first task of the analysis is to simply identify the critical points within the design. As stated above, a critical point is a point after a long section of pipe and/or immediately before and immediately after a fitting. A breakdown of the critical points and complete designation of the dimensions of the design can be found in Appendix C – CAD Model, Figure C - 3 - Upper Segment Pipe Lengths. Next, the governing equation for energy balance within a fluid system must be derived into a form that uses the inputs desired.

5.5.1.3.1 Energy Balance

To build the simulation, the governing equation of energy analysis needs to be evaluated to determine how each input can affect each individual term with the energy balance equation. The terms on the left side of the equation represent the useful energy stored within the fluid its-self. That is, the energy from a difference in pressure, velocity (kinetic energy), and vertical position (potential energy), which can be extracted or injected into the fluid. The right side of the equation, represents the energy loss from irreversibility's (h_t), and the energy injected or extracted from the system by turbomachinery (h_p), such as a pump or turbine. To assist in the analysis, the energy balance equation is rewritten to group up each like term, $\left(\frac{P_1}{\rho}-\frac{P_2}{\rho}\right)+\left(\alpha_1\frac{V_1^2}{2}-\alpha_2\frac{V_2^2}{2}\right)+(gz_1-gz_2)=h_t-h_p$, to allow for the energy from pressure, the kinetic energy and the potential energy of each critical point to be analyzed directly. As stated in section 5.5.1.1 Assumptions, the α term within the kinetic velocity term of the energy balance equation, will be assumed to be approximately equal to one, or that the flow will be fully turbulent throughout the entire system. Using this equation and equations for mass flow rate, the author was able to simplify the energy balance equation into a set of equations that can used for each segment of the system. These simplified equations prove all the needed tools to analyze the system and determine the theoretical results of different proposed pumps.

For brevity, the implication of the generalized energy balance is left to the reader, which results in the following equations. After simplifying the energy balance equation for the use of this design, the equation becomes $P_2 = P_1 - \rho * \left(\frac{8*Q^2}{\pi^2*D^4} * \left(\sum_{j=1}^{g} K_j + \frac{f}{D} * \sum_{i=1}^{n} L_i\right)\right)$, which will allow the simulation to determine the pressure at the majority of critical points as a function of the expected inputs. Applying the same process to the general energy balance equation to form an equation that is a function of the inputs for the simulation, the equation becomes $\left(\frac{P_1}{\rho}-\frac{P_2}{\rho}\right)+\frac{8*Q^2}{\pi^2}*\left(\frac{\alpha_1}{D_1^4}-\frac{\alpha_2}{D_2^4}\right)+(gz_1-gz_2)=\frac{8*Q^2}{\pi^2}*\left(\sum_{j=1}^{g}\frac{K_j}{D_j^4}+f*\sum_{i=1}^{n}\frac{L_i}{D_i^5}\right)-h_p$. The final form of the energy balance equation as a function of flow rate, geometry, and loss coefficients will be used for the sections of the pipe system that do not follow the requirements to use the simplified energy balance equation. With the two governing equations for the entire simulation derived in terms of the inputs to the simulation, the actual simulation can be build and executed to determine the performance and validity of different pumps.

5.5.1.3.2 Additional Needed Properties

While the energy equation is the governing equation, the lengths, diameters, material information, fluid information and pump information are also needed. As for the pump, the team decided upon the GOULDS WATER TECHNOLOGY, Open Dripproof Centrifugal Pump. Model Number: 1MC1G1A0 as a good starting point as it has a decent head and flor rate when compared to other pumps [20]. Finally, the material information and fluid information are all retrieved from Fox and McDonalds Introduction to

Fluid Mechanics 9th edition [5].

5.5.1.3.3 Simulation

For the actual simulation, the system is broken into five segments, the three different runs for students to use to testing, and the entrance and exit segments. The entrance segment includes the pump and the height change from the tank to the top of table, while the exit segment returns the flow to the tank and has a height change from the top of the table to the tank. To ensure that the pump operating at the given specifications will be able to handle the flow of the fluid through each segment of the system, the final critical point is a point immediately before exiting into the tank. This is to ensure that there is a favorable pressure gradient, from high to low, throughout the entire pipe system, because an unfavorable pressure gradient will cause the pump to have to operate outside of recommended ranges. To perform the simulation, a MatLab script is develop, located in 8.2 Appendix B: Analytical Reports section 8.2.1.1 Simulation Code, that takes in all design parameters, pump information and fluid information and then determines the pressure at each critical point and the head loss between immediate critical points. The head loss is then plotted against the pump curve and the point of intersection is calculated. This point of intersection is the operating point of the system and is a function of the flow rate. The solution for the operating point is an iterative solution because of the flow rate squared terms and the overall complexity of the total head loss over the system.

5.5.1.4 Results

The analysis shows that the operating point for the three segments for the selected pump are lower than expected. The first segment has an operating flow rate of 56.61 gpm, with a Reynolds number of $2 * 10^5$ and $1 * 10^5$, there are two Reynolds number of an expansion in the segment. For the second segment, the flow rate is 44.81 gpm, with a Reynolds number of $1.58 * 10^5$ and $2.11 * 10^5$, similar to segment one, there is a contraction in the segment, thus two Reynolds numbers. The third segment has a flow rate of 48.92 gpm, and a Reynolds number of $1.73 * 10^5$. Additional result information provided in 8.2 Appendix B: . While the flow rates being achieved are acceptable, the Reynolds are lowered than desired. To increase the Reynolds number, either the head loss in the system or the pump has to be changed to a more powerful one. The team is investigating both options to attempt to maximize the Reynolds number as per the client's request.

5.5.2 Material Analysis – Cole Neilson

For the senior design project, my team was tasked with redesigning from the ground up, a new experiment table that measures pressure drop over various lengths and fittings of pipe to calculate head loss. The current table in the ME-495 lab is outdated and is not providing meaningful or reliable results for the instructors to use as teaching points to the class. The results that are obtained from the lab do not do a satisfactory job of displaying the concepts that are meant to be taught by not covering a broad enough range of measurements for students to visualize. For the design to yield proper measurements, it must have appropriate layouts and materials to function properly. The layout of the pipes must be practical and easy to work with a s student or lab instructor. The material of the pipes must be robust, and durable for many years while being worked with nearly every day. In some measurement systems of pipes, there is not enough distance allowed after a disruptive fitting to allow for the flow to become fully developed once again. This will lead to incorrect measurements and misleading conclusions from the experiment. In my analysis, I will perform quick stress san analysis to verify that the pipes being used will be viable for the operating conditions, an analysis of entrance length for pipes to be able to design the experiment in a way that can provide reliable results. I will also look at the material being used and examine the best ways to apply pressure taps to the system and how to join up all the parts to create a well-functioning, and durable system.

5.5.2.1 Material Selection

The material of the pipe is generally, the most crucial aspect of my technical analysis. This will dictate the form of fitting that will be applied to put all this piping together, and how the pressure taps will be implemented onto the line. The pipe material will also have major cost implications on the design.

In early considerations for the design, the material that was regarded as best for us was a poly-vinyl Carbonate (PVC). It was the cheapest of all the easily accessible piping materials, easy to buy in bulk and can be simply press fit together along with a PVC cement. PVC is a smooth surface pipe that will have low friction factors, this made achieving higher Reynolds numbers difficult. Another problem with using PVC pipe is the process of connecting pressure taps that are simple and practical for students and teachers alike. Pressure taps would require more parts and fittings for every tap location. For every extra fitting that is needed for the pipe system and pressure taps, there is more chance for failure over time using numerous students using the table over the years. This same issue will be especially present when connecting the pipes to the pump and water storage tank. The connection will be more difficult than planned and may not be as long lasting as the team desire. The three flow rate sensors will also be difficult to implement to a system that is using PVC pipes as well. This forced me to reconsider my approach to the material being used and explore other options that will be more viable to the experiment apparatus. The client then pushed us to choose a more robust material that will better handle the constant abuse that will dealt to it when the experiment is run. It was decided that copper piping is the material the team will use moving forward. The smoothness of copper piping is close to that of PVC, so the team will be able to keep the calculations that the team has previously conducted when concerning Reynolds numbers and friction factors [12]. Copper is also sturdy enough to last for extended periods of time when under use by the students and instructors. The downside of copper is that it is among the most expensive materials to use for piping, so this will take large portion of the budget already.

5.5.2.2 Stress on Fittings

The next aspect to analyze was the ability of the pipe fittings to withstand the forces that are introduced by the flow. The team will be assuming press fittings for the system and use a concrete like paste to seal the pipes together and make sure that there is no pressure or fluid leaks. The concrete is known to be stronger than the metal itself after sealing, so the yield strength will be that of the copper itself. The equations used for a 90° elbow are:

$$R_x = m\ v\ (1 - \cos\beta) \tag{1}$$

$$R_y = m\ v\ \sin\beta \tag{2}$$

R = force (N)

m = mass flow (kg/s)

v = velocity (m/s)

β = bend angle (°)

Using these equations gives a resulting force in the x and y directions of the elbow [21]. The yield strength of copper is minimum 40 MPa. The forces and resulting stresses are about 4 MPA, far below the yield strength of copper which assures us that there will be no problem with the system if there is proper assembly and precautions taken.

Pressure Taps

To perform the experiment and be able to take pressure drop readings, there will have to be pressure taps installed strategically along the pipe system. To have a manometer be able to connect and read data from the line, the team must tap the pipes and install a way of connection. This can be achieved by use of T joints with a threaded exit port and attaching a pressure gauge to the line. Although, this will lead to the loss of head and affect the flow though the fitting. A better approach to this issue would be cut a hole into the pipe to tap through to the line. The team will then add a press valve to the tap. This allows for most differential pressure gauges to be connected to the pipe and will be simpler for the students working with the experiment to quickly remove the manometer and apply it to another section of the pipe. This will be a difficult process to carry out when it comes manufacturing the system, but it is the most efficient when it comes to the actual process of performing the experiment as a student or instructor.

Figure 7 - Exampled of Pressure Taps

5.5.2.3 Flow Development

One big issue with the current system in the lab is that the pressure taps are not located far enough from the fitting to facilitate the pressure measurement of a fully developed flow. The reading is currently unreliable and may not be giving true information regarding pressure drop over a fitting or bend. The flow needs more space after so that it can develop and give accurate measurements. Calculations were done to find the optimal distances to achieve fully developed flow after fittings. For the equations, I assumed a Reynolds number of 9.4x10^4, and a constant entrance length for all types of fittings and inlets.

$$El = l_e / d \tag{3}$$

$$El_{turbulent} = 4.4\ Re^{1/6} \tag{4}$$

Table 3 - Entrance Lengths for Various Diameters

Diameter of pipe (in)	Length Needed (in)
0.5	14.83465064
0.75	22.25197596
1	29.66930128
1.25	37.08662661
1.5	44.50395193
1.75	51.92127725
2	59.33860257
2.25	66.75592789
2.5	74.17325321

The entrance lengths require are quite high for the Reynolds numbers that the team will be attempting to achieve in this experiment. The standard diameter used will be about 1.5 inches which means the team will have to have 44 inches after each fitting before the team can accurately measure the pressure at a fully developed flow. This is a big problem because the team simply don't have the ability to make the experiment this big and remain within all the customer requirements. Further Research is being done to find appropriate lengths

5.5.2.4 Results

This research was done to find the validity of choosing the pipe material and how it will be put together and implemented with the rest of the components of the system. The chosen material will be copper pipe which should allow for easy assembly and provide a robust system that will be able to withstand the constant stress of laboratory classes for years to come. The team will use air press valves that can be easily connected to the manometer chosen in another analysis report. If the other report decides on another form of pressure measurement, then the team will have to adjust accordingly. The pressure tap location was a bot of concern for the client before research had begun. The Numbers generated by my algorithm are troublesome in that they would require a much larger system and cost much more than originally planned, I will work with the client in the future to find a solution that works for both parties and accomplishes the overall goal of the project by yielding reliable and accurate results for the students so that they may actually understand the real concepts at work. The real goal of the project would be to provide a crucial medium for students to use and obtain a better grasp on the concepts taught in other classes, and these aspects will ensure a stable and easy to use system to facilitate the most learning possible.

5.5.3 Sensor Selection – Mark Frankenberg

The Capstone project consists of redesigning an out of date and ineffective lab experiment for the Thermal Sciences (ME 495) lab. This consists of measuring pressure drops over various designs of pipe, including straight runs, elbow and T joints, as well as an increase and decrease of diameters. From this overall setup the team can measure how much head loss occurs at various points throughout the pipe system. The current system is inaccurate and malfunctions. The team's job is to build a new lab and have accurate sensors to give us proper data. In order to achieve the proper data, one must have sufficient sensors to read what is occurring within the system. Multiple sensors are used to show the different ways to achieve the same result. The sensors that are being applied to this system include two invasive and one non-invasive. There will also be volumetric flow meters and sensors placed at the beginning of the pipe system and throughout the system.

5.5.3.1 Sensor Selection:

5.5.3.1.1 Invasive:

Invasive sensors are applied within the system itself and they are physically interacting with the flow. One type of invasive sensor is a standard liquid manometer. This manometer measures the difference in pressure over two points. Using the volumetric flow rate that was calculated form the volumetric flow meter, one can use this and the pressures to obtain the head loss over that section of pipe. The manometer will have many taps that it can connect to in order to measure the pressure drop over the bends, joints, and diameter changes of the pipes. It is possible to instead use a multi-tubed vertical manometer system that measures all the different pressures at one time. However, the client does not want us to use such device. The manometer the team decided to use is the Dwyer 475-000-Fm 1 inch digital manometer. This manometer measures in both inches of H_2O and kPa, with an accuracy of ± 0.5% for temperatures of 15.5 to 25.5°C and ±1.5% for 25.5 to 40°C. The team will be using room temperature water, which is about 23°C. The resolution of this device is 0.001 inches of H_2O and has a range of 0 to 1 inch of H_2O. The device can also be used in metric as well as English units. A secondary invasive sensor that will be utilized is a pitot static tube.

The pitot static tube will be placed at one position within the system, most likely along a straight length of pipe. The pitot static tube measures the velocity of the fluid it is interacting with and using that velocity one can find the pressure at that point. The pitot static tube is an integral part of the system and cannot be moved around like the manometer can. However, it still uses a similar manometer to read the data that the pitot static tube is recording. This pitot static tube is compatible with the manometer that has been chosen. When comparing this device with other methods of pressure readings, the pitot static tube came out to be the best choice for this particular experiment. It also is highly requested by the client to be used.

5.5.3.1.2 Non-invasive:

The final sensor being used for this experiment is the FD-Q series ultrasonic flowmeter by KEYENCE. This particular type of sensors measure the time it takes for an ultrasonic signal to transmit from point A to point B. When the flow rate increases, the time between these two points decreases. As the time decreases the signal begins to accelerate. Using the correlation between the duration of the signal and the speed of the flow, the volumetric flow sensor can measure the instantaneous flow rate. This sensor does not need to be interacting with the flow in any physical manner and so it can be moved to any point on the system and still maintain its accuracy. Unlike the other sensors that normally reads for the pressure, this type of sensor has an output of mV. The team can make a correlation with the given pressures and voltage using both the manometer and the Volumetric flow sensor to achieve a result of head loss. The team decided this particular sensor due to its ability to be easily moved around the system with ease. Comparing other devices of similar function, this one has bases that can be easily installed and moved around. Other devices tend to be more difficult to operate as well as move around the system. The FD-Q series flow sensor is capable of measuring flows greater than what the team is using, while remaining accurate. It has an accuracy of ± 0.1%, a resolution of 0.1mV, and a range of 0 to 100 mV.

When deciding which sensors to buy for this system, the team first had to decide what Reynold's range was needed. The Reynold's number range needed to be large enough so the team can visually see a curve when all the data is plotting into a graph. Next, the team needed to decide on how strong the pump needed to be. It needed to be strong enough to achieve the flow needed to reach the Reynold's numbers but also enough so that it will not break down under the stress of utilizing a volumetric flow meter. In the past, having the volumetric flow meter present would put so much stress on the pump that it would eventually break down. After the pump has been picked out, the team needed to know how the pipe system will look like, in terms of where the joints and fittings will be and how large or small the diameter are. During the process of creating the design, the team needed to consider where the sensors were going to be placed in order to achieve accurate readings.

5.5.3.2 Results:

The two invasive and one non-invasive sensors are able to read and accurately record the pressures, velocities and voltages that are needed to obtain the head loss throughout different parts of the system. The Reynold's number can also be calculated and from those calculations the team can show the relation of the head loss to the Reynold's number to the variation in pipe setup. To pick the best sensors the team needed an adequate pump that fulfilled all the requirements, after the pump the team designed the overall layout, and with that overall layout the sensors can be placed. The overall goal of this senior design project is to rebuild and improve a currently out of use lab experiment. The experiment shows the how head loss and pressures and other pieces of data can be obtained using multiple different sensors. However, the main goal of this lab is to show how the correlation between the change in head loss and Reynold's number.

5.5.4 Pump Section - Michael Garelick

The current pipe flow experiment does not have a sufficient Reynolds number range for measuring a tangible flow and the head of the current pump is too small to measure a difference. The main ways to improve the pipe flow system are by improving the pump, the pipe flow system, the transducers, and the overall materials of the pipes. In this report, the analysis regarding the decision of the pump and flow control will be explained. The pump selection is one of the first important decisions for the experiment redesign because it defines the total available head of the system and the maximum flow rate that can be achieved through the pipes.

5.5.4.1 Assumptions:

In order to better understand the pump situation better and accurately simplify the calculations, some assumptions will be made initially. The following assumptions have been made for the pump analysis:

1. The flow provided by the pump and through the pipes will always be turbulent.
2. The fluid used inside the pump will be pure water at 25 °C with a kinematic viscosity, ν, of 8.96*10^-7 m^2/s [5].
3. The head loss due to the change in height of piping to and from the pump is negligible.
4. The pump will match all respective specifications that the manufacturer lists exactly.
5. The flow will be incompressible and have steady flow through the pump and pipe system.
6. The flow will have uniform properties at all locations in the pipe system.

These assumptions will allow the simplified Reynolds number and flow rate equations to be accurately applied to the pipe system. The assumptions will be utilized along with the constraints to analyze pump possibilities.

5.5.4.2 Variables:

To start the selection of the pump for the pipe experiment redesign, the variable inputs/constraints for the pump need to be established. The following inputs/constraints will be applied for the project:

1. The maximum current from the wall outlet source to the pump will be 20 amps. This constraint is applied due to the fact that the outlet closest to the future location of the experiment has a maximum current of 20 amps able to be drawn from it/
2. The maximum voltage able to be safely used for a pump will be 120 VAC. This maximum is due to the same constraint listed in the previous input.
3. The desired Reynolds number range requested by the client is 10^4 to 10^6.
4. The cost of the pump will not be a considered constraint due to the fact that the client's unspecified cost constraints for the pump specifically.
5. The inside diameter of the pipe system will be set to a minimum of 0.5 inches.

These variables were defined from meetings with the client and examination of the old pipe flow experiment.

5.5.4.3 Analysis:

To start the analysis, the desired output needs to be defined; the output variable for the pump analysis is the required flow rate driven by the pump to meet the Reynolds number range constraint. The equations that will be used for the Reynolds number range constraints will be the definition of the Reynolds number in Eq. (5) and the flow rate equation based on flow that is steady state, incompressible, and has uniform properties in Eq. (6).

$$R_e = \frac{VD}{\nu} \tag{5}$$

$$Q = VA \tag{6}$$

By combining Eq. (5) and Eq. (6), the formula to find the flow rate based on variable inputs has been derived and shown in Eq. (7).

$$Q = 0.25\pi R_e \nu D \tag{7}$$

Given the provided inputs and Eq. (7), the desired flow rate for a Reynolds number of 10^6 through a 0.5 inch pipe with pure water at 25 °C would be about 141.658 gpm. From this calculated flow rate, the closest pump that follows that maximum flow rate along with the previously indicated constraints will be utilized in the pipe flow experiment redesign.

The pumps considered for the redesign were from the Grainger Choice catalog which listed several pumps from different manufacturers [24]. Several pump designs were considered and the ones closest to matching the constraints and maximum required flow rate have been compared in a Spec Table. The Spec Table for the top 4 pump possibilities are shown in Table 1.

Table 4 - Spec Table for pipe experiment redesign pumps

Pump Item Number	Maximum Flow Rate (GPM) at Head (ft)	Voltage (VAC)	Current (Amps)
1N506	84 at 40	120/240	20/11-10
1N516	84 at 40	120/240	17.4/9.0-8.7
2ZXP7	99 at 30	115/208-230	16.6/9.4-8.3
4JMX6	130 at 5	115/230	18.0/9.0

Based on the compiled information in the Spec Table, the best pump selection would either be Item Number 2ZXP7 or Item Number 4JMX6. Both follow the voltage and current constraints applied but do not meet the required maximum flow rate to reach a Reynolds number of 10^6. Even though the 4JMX6 pump has the highest achievable flow rate, the pump head at that value is low and may not be enough to measure through the experiment pipe system. The 2ZXP7 pump has a lower maximum flow rate, however the head value for that maximum has a higher head to measure. Based on these results, the pump that must be chosen will be the Item Number 4JMX6: Dayton Chemical Resistant Pump.

Finally, for the simplicity of using the pump, the students performing the experiment with the pipe system will flip on a switch connected to the pump to turn it on just like the previous experimental setup. This aspect will be kept because it is safe and there are no added constraints to require a change in that method of actuation. The flow rate of the flow out of the pump will also be kept similar by having the students actuate a valve. This similarity is due to a client request for an analog method of controlling the flow rather than a variable pump or a closed system controller. The location of the valve will change to be closer to the pump so that the flow rate can be closer watched and changed more accurately than the previous design.

5.5.4.4 Results:

The optimal chosen pump is the Item Number 4JMX6: Dayton Chemical Resistant Pump. This pump will not be able to reach the highest Reynolds number of 10^6, however, it will ideally reach a Reynolds number of 9.177*10^5 which may be good regarding the fact that all other constraints were met. The pump will be utilized in a similar system to the old experiment setup except the controlling valve will be next to the pump outlet rather than on the experimental table. This pump has a low maximum head compared to the pump indicated before the pump analysis.

6 PROPOSED DESIGN – First Semester

The plan for implementation of the design is simple, the team will be building the design to competition. Unlike other designs that require access to resources that are not available for university students, or have construction costs in the tens of thousands of dollars; the select can be constructed with the majority of the components supplied from a local hardware store. The only parts that being sourced from specialty suppliers are the pump, sensors, and reservoir, with the current design using an out sourced table but that can be replaced with a table fabricated by the students using the universities facilities. As such, the construction of the most complicated parts within the project are out sourced, and instead, the team only has to assemble all of the purchased parts into the final design. To provide insight into the construction process and increase the chances of a successful build, the team will be following the prototyping strategy as detailed in 5.3 Prototyping. Even with the benefit of having the previous design, special care and planning is needed to ensure a successful build, the process of which is detailed below.

6.1 Bill of Materials

As with any design, a detailed bill of materials in crucial for the construction of the design as often the designers are not directly purchasing the materials and parts for the design. Additionally, the designers must be able to defend any part or material choices and a detailed and itemized bill of materials will assist with cost analysis and comparison to different designs.

The entire bill of materials is located in 8.4 ~~8.3~~ Appendix D: Miscellaneous, Table D - 2 - Bill of Materials~~Table C - 2 - Bill of Materials~~ and Table D - 3 Bill Of Materials Web Sites~~Table C - 3 Bill Of Materials Web Sites~~, which shows an itemized list of all the items that will be needed to construct the design. One thing that needs to be noted is that for the KEYENCE flow sensor is designed to work different types of clamps which are needed to be purchased separately. When purchasing the system itself, it comes with clamps of your desired size, so only additional clamp sizes need be purchased separately. There will be one system that requires multiple clamps in order to move the system to other sections of the design system. The total in the above portion of the BOM shows the cost that is covered by the Capstone budget. The lower total only includes the sensors. The client requested that the sensors be separate from the rest of the bill of materials due to their high cost. The only part that is missing from the BOM are the miscellaneous screws, bolts, nuts, and anything else that is needed when actually building the device. It is not needed in the BOM because it is currently unknown as to how many of each of these items that are needed. Fortunately, the design is well within the budget target $2500, as such the need for miscellaneous items are predicted to not exceed the budget cap.

6.2 CAD

Based on the chosen materials and design, a SolidWorks CAD model has been created of the final Experimental Pipe System. Figures showing the details of the final design are shown in Appendix C. By creating a simulated model of the design, the team was able to better understand the spatial relationships of the components. For example, the return tube length relied on the positions of the reservoir and the end of the pipe flow system. The return tube ideally would be a quarter-circle to minimize the flow losses due to the bend. The SolidWorks CAD model will be a guide for the construction of the prototype.

6.3 Construction Plan

For the second semester of the project, the team will be focusing on the actual construction and implementation of the ideas generated in the first semester. The full year Gantt chart is shown in Appendix D Figure 1. In order to construct the pipe flow experiment, the team will have begun prototyping the design on the old experiment table with the new pump. The process of attaching the pump to the old table will be carried out by Dr. Ciocanel and his team of classroom aids that will be present over the summer term. This will give a good picture of how the system works as well as proving the validity of the computer program used to predict experimental results. This process allows to iterate the design over the summer in order to have a good near finalized design that the team, along with the client, are happy with at the start of the next semester. The team can also use the old experiment table and piping components to experiment with mounting and manufacturing techniques. A majority of manufacturing and assembling will be done in the machine shop on south campus, as long as minor off-site construction being done at a team members homes. The construction process will begin with getting the final dimensions and building the table itself to accommodate all of the components so that there is adequate room and mounting for the pump and reservoir. From here, the team can have the piping ordered and all of the sensors that are needed to run the experiment. The pipes will need to be tapped at specific locations so that the team are able to attach the pressure valves. A mechanized drill will be used to place the holes along the pipe. The pipes will be press fit together and sealed with soldering to create a strong and reliable connection. The pipes will be mounted to the table with supports affirming the stability at key points of the system. The construction will surely create the need for modification as certain aspects of the design may not be as compatible as the team expected in the design process. These will be documented and hopefully kept to a minimum so that the team is able to efficiently complete the fabrication of the design and have a functioning experiment before the end of October. Testing would begin shortly after this to attempt to have acceptable results, and if not, then improvements made to iterate the design to attain the desired results of the experiment. A lab manual will then be written up to provide to the students, TA’s, and course instructors with a step by step plan to perform the experiment as well as an analysis section to emphasize the goals of the experiment and that should be learned after performing.

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8 APPENDICES

8.1 Appendix A: Designs Considered and Selected

Table A - 1 - Pugh Chart

Pugh Chart					
Customer Requirements	Datum (Ohio Northern University Experiment)	Concept #1	Concept #2	Concept #3	Concept #4
Durability of Physical System		0	-	0	0
Three forms of flow rate measurement		+	-	+	-
1/2" min diameter		+	0	+	+
One Elbow Joint		+	+	+	+
One Tee-Joint		+	+	+	+
One Contraction Joint		+	-	+	+
One Expansion Joint		+	-	+	+
Ease of use		0	0	0	+
Ease of Assembly		-	-	-	0
Variable flow Rate		0	+	+	0
Total		5	-2	6	5

Table A - 2 - Material Decision Matrix

Decision Matrix								
Materials	Cost	Corrosion Resistance	Roughness	Strength	Sizes available	Ease of Fitting	Life Span	Weighted Total
Weights	3	5	5	4	5	4	3	
Aluminum	4	3	1	3	4	3	4	88
Concrete	3	4	3	2	1	2	5	80
Copper	2	4	1	4	4	4	4	95
Clay	1	5	5	1	1	2	4	82
Glass	2	5	1	2	3	1	5	78
Plastic	5	4	1	2	4	5	3	97
Steel	3	1	3	5	3	3	4	88

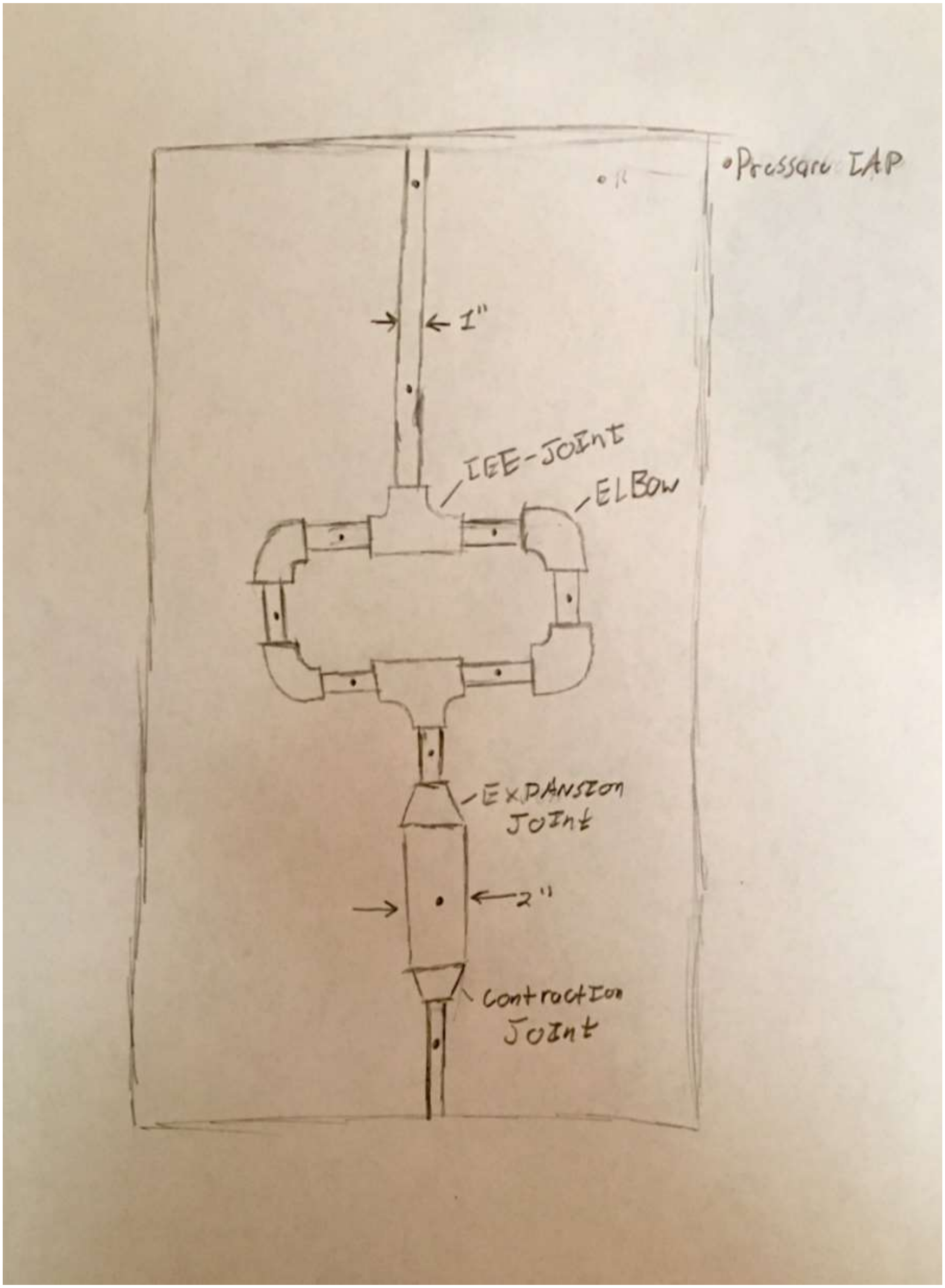


Figure A - 1 - Concept 1

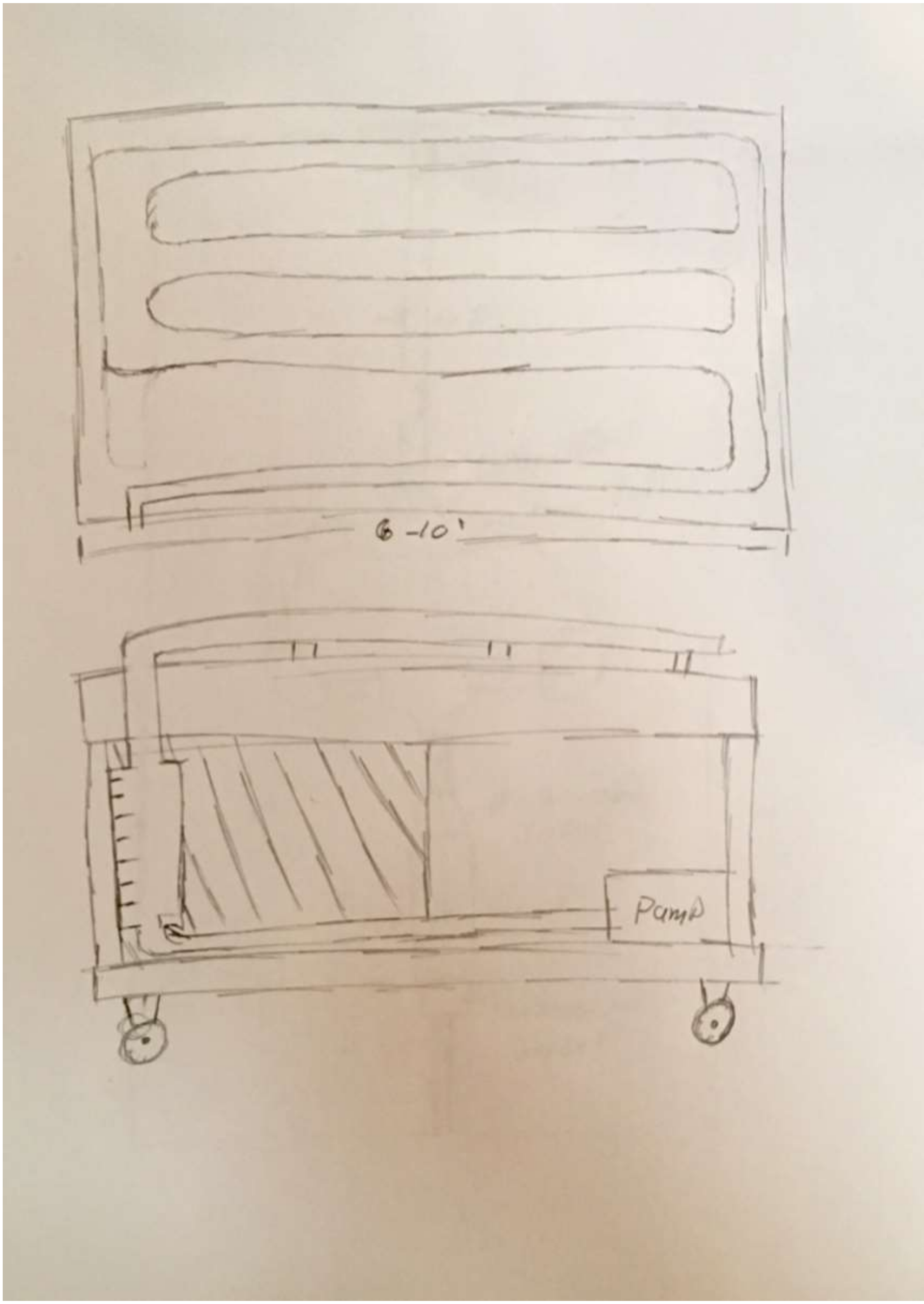


Figure A - 2 - Concept 2

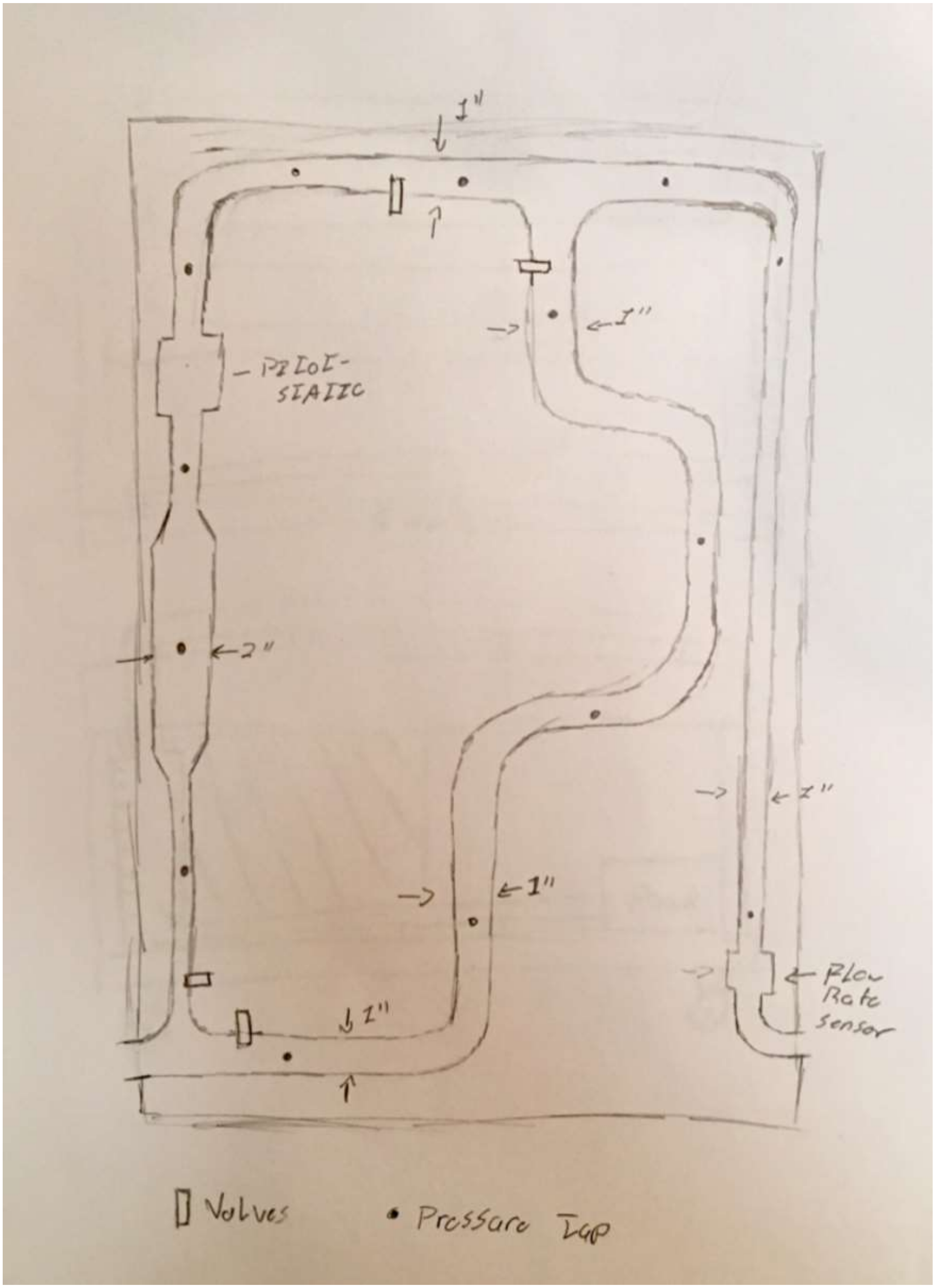


Figure A - 3 - Concept 3

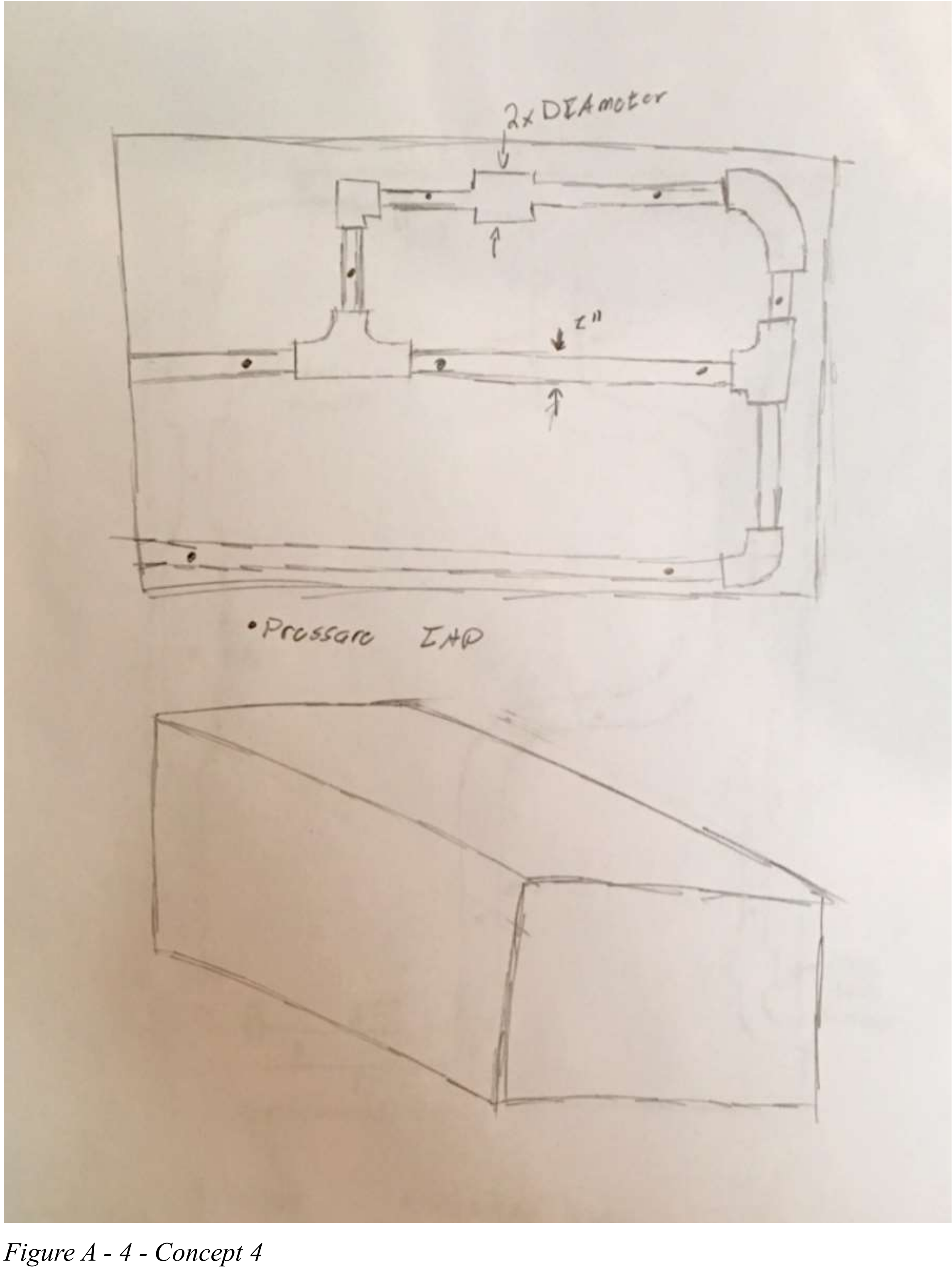


Figure A - 4 - Concept 4

8.2 Appendix B: Analytical Reports

8.2.1 Simulation and Energy Analysis

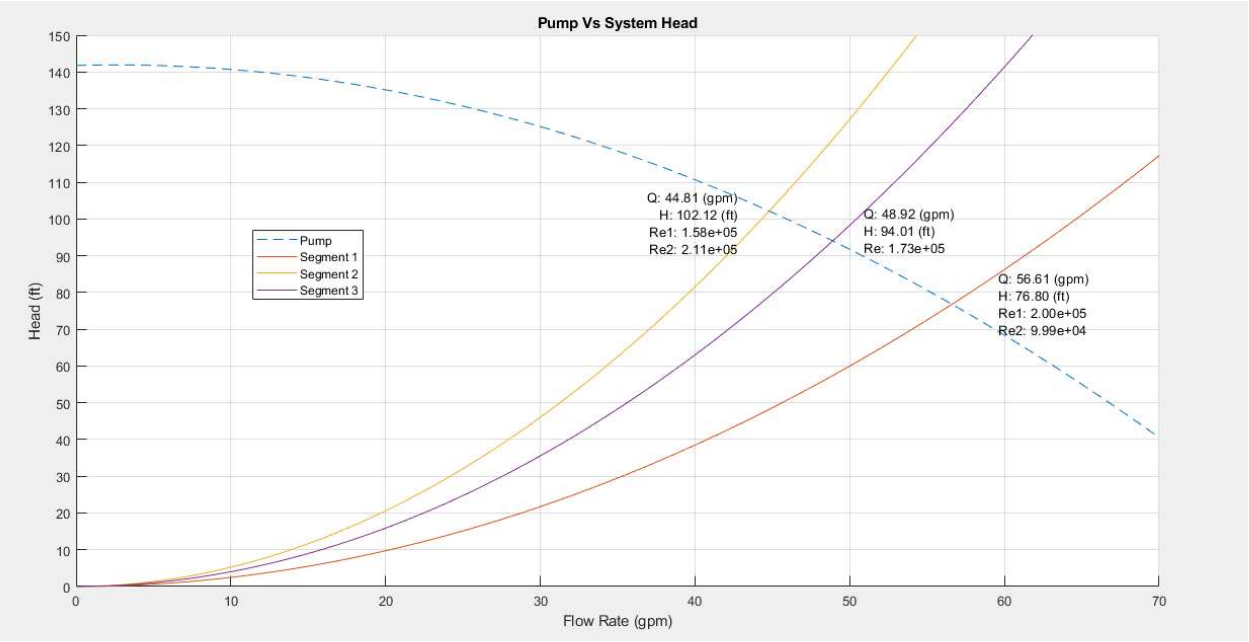


Figure B - 1 Design Simulation Results and Operation Point

8.2.1.1 Simulation Code

8.2.1.1.1 Main Script

```
% Final Design Simulation

clc; close all; clear;

% Dimensions
D0 = 0.03175; D1 = 0.0254; D2 = 0.0508; D3 = D1 - (D1*0.25); % meters
N = 3/40; % meters / length unit
e = 0.15 / 10^3;  % meters

L0 = 13*N; L3 = 30*N; L4 = 5*N; L5 = 3*N; L6 = 3*N; L7 = 5*N; L8 = 18*N; % meters
L9 = 5*N; L10 = 18*N; L11 = 10*N; L12 = 4*N; L13 = 9*N; L14 = 4*N; % meters
L15 = 3*N; L16 = N; L17 = 17*N; L18 = 3*N; L20 = 5*N; L19 = 5*N; % meters

% Pump Specs
Q = linspace(0, 100, 100); %gpm
pHead = 0; % ft
Q = 0.0000631 .* Q; % meters ^ 3/ s
pHead = 0.3048 * pHead; % meters

% Fluid Properties T = 25 C
P0 = 0; % P atm and gage
Density = 997; % kilogram / meters ^ 3
kinViscosity = 8.96E-7; % meters ^ 2 / seconds

% Additional constants
Gravity = 9.81; % meters / seconds ^ 2

% Head loss Coefficients
K90 = 0.3; Ktee = 1; Kex = 0.6; Kcon = 0.4; Kfm = 7; Kval = 0.5; Kre = 0.5;
```

```
KteeS = 0.3; Kpitot = 7;

% Initialize storage vars
Pressures = zeros(3, 32);
hLoss = zeros(3, 14);
Re = zeros(1, 3);
f = zeros(1, 3);
totalHead = zeros(3, length(Q));

for n = 1:1:length(Q)
    % Determine pressure across system
    Re0 = 4 * Q(n) / (pi * D0 * kinViscosity);
    f0 = 0.25*(log10(e/(D0*3.7)+(5.74/(Re0^0.9))))^(-2);
    Re(1) = 4 * Q(n) / (pi * D1 * kinViscosity);
    f(1) = 0.25*(log10(e/(D1*3.7)+(5.74/(Re(1)^0.9))))^(-2);

    HM = (8*(Q(n)^2)/(Gravity*pi^2))*((f0*L0/D0));
    Hm = (8*(Q(n)^2)/(Gravity*pi^2))*((1/D0^4)*(Kre)+(1/D1^4)*(K90 + Kfm));
    deltaZ = 9*N;

    % Segment 1 Simulation
    % Pump Segment
    Pressures(1, 1) = P0 + Density*Gravity*(pHead - (HM + Hm) - deltaZ -
(8*Q(n)^2)/((pi^2)*Gravity*(D1^4)));
    Pressures(1, 2) = Pressures(1, 1) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L3)/(D1)));
    hLoss(1,1) = Pressures(1, 1) - Pressures(1, 2);
    Pressures(1, 3) = Pressures(1, 2) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(1,2) = Pressures(1, 2) - Pressures(1, 3);
    Pressures(1, 4) = Pressures(1, 3) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L4)/D1);
    hLoss(1,3) = Pressures(1, 3) - Pressures(1, 4);
    % Segment 1
    Pressures(1, 5) = Pressures(1, 4) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(1,4) = Pressures(1, 4) - Pressures(1, 5);
    Pressures(1, 6) = Pressures(1, 5) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L7)/D1);
    hLoss(1,5) = Pressures(1, 5) - Pressures(1, 6);
    Pressures(1, 7) = Pressures(1, 6) + ((8*(Q(n)^2)*Density)/(pi^2))*((D1^4-D2^4)) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Kex)) ;
    hLoss(1,6) = Pressures(1, 6) - Pressures(1, 7);
    Re(2) = 4 * Q(n) / (pi * D2 * kinViscosity);
    f(2) = 0.25*(log10(e/(D2*3.7)+(5.74/(Re(2)^0.9))))^(-2);
    Pressures(1, 8) = Pressures(1, 7) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D2^4)))*(f(2)*L8)/D2);
    hLoss(1,7) = Pressures(1, 7) - Pressures(1, 8);
    Pressures(1, 30) = Pressures(1, 8) + ((8*(Q(n)^2)*Density)/(pi^2))*((D2^4-D1^4)) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Kcon)) ;
    hLoss(1,8) = Pressures(1, 8) - Pressures(1, 30);
    Pressures(1, 9) = Pressures(1, 30) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L19)/D1);
    hLoss(1,9) = Pressures(1, 30) - Pressures(1, 9);
    Pressures(1, 29) = Pressures(1, 9) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(1,10) = Pressures(1, 9) - Pressures(1, 29);
    Pressures(1, 27) = Pressures(1, 29) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L14)/D1);
    hLoss(1,11) = Pressures(1, 29) - Pressures(1, 27);
    Pressures(1, 28) = Pressures(1, 27) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(1,12) = Pressures(1, 27) - Pressures(1, 28);
```

```
    Pressures(1, 25) = Pressures(1, 28) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L15)/D1));
    hLoss(1,13) = Pressures(1, 27) - Pressures(1, 25);
    Pressures(1, 26) = Pressures(1, 25) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(1,14) = Pressures(1, 25) - Pressures(1, 26);
    % Return Segment
    Pressures(1, 32) = Pressures(1, 26) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L17/D1) + 3*K90) -
deltaZ);

    % Segment 2 Simulation
    % Pump Segment
    Pressures(2, 1) = P0 + Density*Gravity*(pHead - (HM + Hm) - deltaZ -
(8*Q(n)^2)/((pi^2)*Gravity*(D1^4)));
    Pressures(2, 2) = Pressures(2, 1) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L3)/(D1)));
    hLoss(2,1) = Pressures(2, 1) - Pressures(2, 2);
    Pressures(2, 3) = Pressures(2, 2) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(2,2) = Pressures(2, 2) - Pressures(2, 3);
    Pressures(2, 4) = Pressures(2, 3) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L4)/D1);
    hLoss(2,3) = Pressures(2, 3) - Pressures(2, 4);
    % Segment 2
    Pressures(2, 10) = Pressures(2, 4) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(2,4) = Pressures(2, 4) - Pressures(2, 10);
    Pressures(2, 11) = Pressures(2, 10) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L5)/D1);
    hLoss(2,5) = Pressures(2, 10) - Pressures(2, 11);
    Pressures(2, 12) = Pressures(2, 11) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(2,6) = Pressures(2, 11) - Pressures(2, 12);
    Pressures(2, 13) = Pressures(2, 12) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L9)/D1);
    hLoss(2,7) = Pressures(2, 12) - Pressures(2, 13);
    Pressures(2, 14) = Pressures(2, 13) + ((8*(Q(n)^2)*Density)/(pi^2))*(((1/(D1^4))-
(1/(D3^4)))) - Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D3^4)))*(Kcon)) ;
    hLoss(2,8) = Pressures(2, 13) - Pressures(2, 14);
    Re(3) = 4 * Q(n) / (pi * D3 * kinViscosity);
    f(3) = 0.25*(log10(e/(D3*3.7)+(5.74/(Re(3)^0.9))))^(-2);
    Pressures(2, 15) = Pressures(2, 14) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D3^4)))*(f(3)*L10)/D3);
    hLoss(2,9) = Pressures(2, 14) - Pressures(2, 15);
    Pressures(2, 31) = Pressures(2, 15) + ((8*(Q(n)^2)*Density)/(pi^2))*(((1/(D3^4))-
(1/(D1^4)))) - Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D3^4)))*(Kex)) ;
    hLoss(2,10) = Pressures(2, 15) - Pressures(2, 31);
    Pressures(2, 16) = Pressures(2, 31) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L20)/D1);
    hLoss(2,11) = Pressures(2, 31) - Pressures(2, 16);
    Pressures(2, 28) = Pressures(2, 16) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(2,12) = Pressures(2, 16) - Pressures(2, 28);
    Pressures(2, 25) = Pressures(2, 28) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L15)/D1));
    hLoss(2,13) = Pressures(2, 28) - Pressures(2, 25);
    Pressures(2, 26) = Pressures(2, 25) -
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(2,14) = Pressures(2, 25) - Pressures(2, 26);
    % Return Segment
```

```
    Pressures(2, 32) = Pressures(2, 26) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L17/D1) + 3*K90) - 
deltaZ);

    % Segment 3 Simulation
    % Pump Segment
    Pressures(3, 1) = P0 + Density*Gravity*(pHead - (HM + Hm) - deltaZ - 
(8*Q(n)^2)/((pi^2)*Gravity*(D1^4)));
    Pressures(3, 2) = Pressures(3, 1) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L3)/(D1)));
    hLoss(3,1) = Pressures(3, 1) - Pressures(3, 2);
    Pressures(3, 3) = Pressures(3, 2) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(3,2) = Pressures(3, 2) - Pressures(3, 3);
    Pressures(3, 4) = Pressures(3, 3) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L4)/D1);
    hLoss(3,3) = Pressures(3, 3) - Pressures(3, 4);
    % Segment 2
    Pressures(3, 10) = Pressures(3, 4) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(3,4) = Pressures(3, 4) - Pressures(3, 10);
    Pressures(3, 11) = Pressures(3, 10) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L5)/D1);
    hLoss(3,5) = Pressures(3, 10) - Pressures(3, 11);
    Pressures(3, 17) = Pressures(3, 11) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(3,6) = Pressures(3, 11) - Pressures(3, 17);
    Pressures(3, 18) = Pressures(3, 17) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L6)/D1);
    hLoss(3,7) = Pressures(3, 17) - Pressures(3, 18);
    Pressures(3, 19) = Pressures(3, 18) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(K90)) ;
    hLoss(3,8) = Pressures(3, 18) - Pressures(3, 19);
    Pressures(3, 20) = Pressures(3, 19) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L11)/D1);
    hLoss(3,9) = Pressures(3, 19) - Pressures(3, 20);
    Pressures(3, 21) = Pressures(3, 20) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Kpitot));
    hLoss(3,10) = Pressures(3, 20) - Pressures(3, 21);
    Pressures(3, 22) = Pressures(3, 21) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L12)/D1);
    hLoss(3,11) = Pressures(3, 21) - Pressures(3, 22);
    Pressures(3, 23) = Pressures(3, 22) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(Kval));
    hLoss(3,12) = Pressures(3, 22) - Pressures(3, 23);
    Pressures(3, 24) = Pressures(3, 23) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L13)/D1);
    hLoss(3,13) = Pressures(3, 23) - Pressures(3, 24);
    Pressures(3, 26) = Pressures(3, 24) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(3,14) = Pressures(3, 24) - Pressures(3, 26);
    % Return Segment
    Pressures(3, 32) = Pressures(3, 26) - 
Density*Gravity*(((8*Q(n)^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L17/D1) + 3*K90) - 
deltaZ);

    totalHead(1, n) = sum(hLoss(1, :)) * 3.28 / (Density * Gravity);
    totalHead(2, n) = sum(hLoss(2, :)) * 3.28 / (Density * Gravity);
    totalHead(3, n) = sum(hLoss(3, :)) * 3.28 / (Density * Gravity);

end

hold on
```

```
Q = Q ./ (0.0000631);
pumpCurve = -0.0223.*Q.^2 + 0.1147.*Q + 141.77;
pumpCurve(pumpCurve<0) = nan;
plot(Q, pumpCurve, '--')
plot((Q ), totalHead)
title('Pump Vs System Head')
xlabel('Flow Rate (gpm)')
ylabel('Head (ft)')
legend('Pump', 'Segment 1', 'Segment 2', 'Segment 3', 'Location','best')
grid on
ylim([0 150])
xlim([0 70])
yticks(0:10:150)

Pump_Vs_System;
text(Qs(1,1) + 3, HLossesEqual(1,1), sprintf('Q: %0.2f (gpm)\nH: %0.2f (ft)\nRe1:
%0.2d\nRe2: %0.2d', Qs(1,1), HLossesEqual(1,1), Qs(1,1)* 4 * 0.0000631 /
(kinViscosity*pi*D1), Qs(1,1)* 4 * 0.0000631 / (kinViscosity*pi*D2)));
text(Qs(2,1) - 2, HLossesEqual(2,1) - 3, sprintf('Q: %0.2f (gpm)\nH: %0.2f (ft)\nRe1:
%0.2d\nRe2: %0.2d', Qs(2,1), HLossesEqual(2,1), Qs(2,1)* 4 * 0.0000631 /
(kinViscosity*pi*D1), Qs(2,1)* 4 * 0.0000631 / (kinViscosity*pi*D3)),
'HorizontalAlignment','right');
text(Qs(3,1) + 2, HLossesEqual(3,1) + 3, sprintf('Q: %0.2f (gpm)\nH: %0.2f (ft)\nRe:
%0.2d', Qs(3,1), HLossesEqual(3,1), Qs(3,1)* 4 * 0.0000631 / (kinViscosity*pi*D1)));
```

8.2.1.1.2 Secondary Script

```
% Dimensions
D0 = 0.03175; D1 = 0.0254; D2 = 0.0508; D3 = D1 - (D1*0.25); % meters
N = 3/40; % meters / length unit
e = 0.15 / 10^3;  % meters

L0 = 13*N; L3 = 30*N; L4 = 5*N; L5 = 3*N; L6 = 3*N; L7 = 5*N; L8 = 18*N; % meters
L9 = 5*N; L10 = 18*N; L11 = 10*N; L12 = 4*N; L13 = 9*N; L14 = 4*N; % meters
L15 = 3*N; L16 = N; L17 = 17*N; L18 = 3*N; L20 = 5*N; L19 = 5*N; % meters

% Pump Specs
Q = 10; %gpm
pHead = 0; % ft
Q = 0.0000631 * Q; % meters ^ 3/ s
pHead = 0.3048 * pHead; % meters

% Fluid Properties T = 25 C
P0 = 0; % P atm and gage
Density = 997; % kilogram / meters ^ 3
kinViscosity = 8.96E-7; % meters ^ 2 / seconds

% Additional constants
Gravity = 9.81; % meters / seconds ^ 2

% Head loss Coefficients
K90 = 0.3; Ktee = 1; Kex = 0.6; Kcon = 0.4; Kfm = 7; Kval = 0.5; Kre = 0.5;
KteeS = 0.3; Kpitot = 7;

% Initialize storage vars
Pressures = zeros(3, 32);
hLoss = zeros(3, 14);
Re = zeros(1, 3);
f = zeros(1, 3);
totalHead = zeros(3, length(Q));
running = 1;
```

```
error = 10^(-3);
Qs = zeros(3, 1);
HLossesEqual = zeros(3, 1);


while running == 1
    % Determine pressure across system
    Re0 = 4 * Q / (pi * D0 * kinViscosity);
    f0 = 0.25*(log10(e/(D0*3.7)+(5.74/(Re0^0.9))))^(-2);
    Re(1) = 4 * Q / (pi * D1 * kinViscosity);
    f(1) = 0.25*(log10(e/(D1*3.7)+(5.74/(Re(1)^0.9))))^(-2);

    HM = (8*(Q^2)/(Gravity*pi^2))*((f0*L0/D0));
    Hm = (8*(Q^2)/(Gravity*pi^2))*((1/D0^4)*(Kre)+(1/D1^4)*(K90 + Kfm));
    deltaZ = 9*N;

    % Segment 1 Simulation
    % Pump Segment
    Pressures(1, 1) = P0 + Density*Gravity*(pHead - (HM + Hm) - deltaZ -
(8*Q^2)/((pi^2)*Gravity*(D1^4)));
    Pressures(1, 2) = Pressures(1, 1) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L3)/(D1)));
    hLoss(1,1) = Pressures(1, 1) - Pressures(1, 2);
    Pressures(1, 3) = Pressures(1, 2) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(1,2) = Pressures(1, 2) - Pressures(1, 3);
    Pressures(1, 4) = Pressures(1, 3) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L4)/D1);
    hLoss(1,3) = Pressures(1, 3) - Pressures(1, 4);
    % Segment 1
    Pressures(1, 5) = Pressures(1, 4) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(1,4) = Pressures(1, 4) - Pressures(1, 5);
    Pressures(1, 6) = Pressures(1, 5) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L7)/D1);
    hLoss(1,5) = Pressures(1, 5) - Pressures(1, 6);
    Pressures(1, 7) = Pressures(1, 6) + ((8*(Q^2)*Density)/(pi^2))*((D1^4-D2^4)) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Kex)) ;
    hLoss(1,6) = Pressures(1, 6) - Pressures(1, 7);
    Re(2) = 4 * Q / (pi * D2 * kinViscosity);
    f(2) = 0.25*(log10(e/(D2*3.7)+(5.74/(Re(2)^0.9))))^(-2);
    Pressures(1, 8) = Pressures(1, 7) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D2^4)))*(f(2)*L8)/D2);
    hLoss(1,7) = Pressures(1, 7) - Pressures(1, 8);
    Pressures(1, 30) = Pressures(1, 8) + ((8*(Q^2)*Density)/(pi^2))*((D2^4-D1^4)) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Kcon)) ;
    hLoss(1,8) = Pressures(1, 8) - Pressures(1, 30);
    Pressures(1, 9) = Pressures(1, 30) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L19)/D1);
    hLoss(1,9) = Pressures(1, 30) - Pressures(1, 9);
    Pressures(1, 29) = Pressures(1, 9) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(1,10) = Pressures(1, 9) - Pressures(1, 29);
    Pressures(1, 27) = Pressures(1, 29) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L14)/D1);
    hLoss(1,11) = Pressures(1, 29) - Pressures(1, 27);
    Pressures(1, 28) = Pressures(1, 27) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(1,12) = Pressures(1, 27) - Pressures(1, 28);
    Pressures(1, 25) = Pressures(1, 28) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L15)/D1));
    hLoss(1,13) = Pressures(1, 27) - Pressures(1, 25);
```

```
    Pressures(1, 26) = Pressures(1, 25) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(1,14) = Pressures(1, 25) - Pressures(1, 26);
    % Return Segment
    Pressures(1, 32) = Pressures(1, 26) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L17/D1) + 3*K90) - deltaZ);

    % fprintf('Q: %0.2f\tH system: %0.2f\tH pump: %0.2f\n',  Q/0.0000631,
(sum(hLoss(1, :)) * 3.28 / (Density * Gravity)), (-0.0223*(Q / 0.0000631)^2 +
0.1147*(Q / 0.0000631) + 141.77))

    if abs((sum(hLoss(1, :)) * 3.28 / (Density * Gravity)) - (-0.0223*(Q /
0.0000631)^2 + 0.1147*(Q / 0.0000631) + 141.77)) <= error
        running = 0;
        Qs(1,1) = Q;
        HLossesEqual(1,1) = (sum(hLoss(1, :)) * 3.28 / (Density * Gravity));
    else
        Q = Q + (0.0000631*error*(-(sum(hLoss(1, :)) * 3.28 / (Density * Gravity)) +
(-0.0223*(Q / 0.0000631)^2 + 0.1147*(Q / 0.0000631) + 141.77)));
    end
    % pause(0.1)
end

% Pump Specs
Q = 10; %gpm
pHead = 0; % ft
Q = 0.0000631 * Q; % meters ^ 3/ s
pHead = 0.3048 * pHead; % meters

running = 1;
while running == 1

    % Segment 2 Simulation
    % Pump Segment
    Pressures(2, 1) = P0 + Density*Gravity*(pHead - (HM + Hm) - deltaZ -
(8*Q^2)/((pi^2)*Gravity*(D1^4)));
    Pressures(2, 2) = Pressures(2, 1) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L3)/(D1)));
    hLoss(2,1) = Pressures(2, 1) - Pressures(2, 2);
    Pressures(2, 3) = Pressures(2, 2) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(2,2) = Pressures(2, 2) - Pressures(2, 3);
    Pressures(2, 4) = Pressures(2, 3) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L4)/D1);
    hLoss(2,3) = Pressures(2, 3) - Pressures(2, 4);
    % Segment 2
    Pressures(2, 10) = Pressures(2, 4) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(2,4) = Pressures(2, 4) - Pressures(2, 10);
    Pressures(2, 11) = Pressures(2, 10) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L5)/D1);
    hLoss(2,5) = Pressures(2, 10) - Pressures(2, 11);
    Pressures(2, 12) = Pressures(2, 11) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(2,6) = Pressures(2, 11) - Pressures(2, 12);
    Pressures(2, 13) = Pressures(2, 12) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L9)/D1);
    hLoss(2,7) = Pressures(2, 12) - Pressures(2, 13);
    Pressures(2, 14) = Pressures(2, 13) + ((8*(Q^2)*Density)/(pi^2))*(((1/(D1^4))-
(1/(D3^4)))) - Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D3^4)))*(Kcon)) ;
    hLoss(2,8) = Pressures(2, 13) - Pressures(2, 14);
    Re(3) = 4 * Q / (pi * D3 * kinViscosity);
    f(3) = 0.25*(log10(e/(D3*3.7)+(5.74/(Re(3)^0.9))))^(-2);
```

```
    Pressures(2, 15) = Pressures(2, 14) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D3^4)))*(f(3)*L10)/D3);
    hLoss(2,9) = Pressures(2, 14) - Pressures(2, 15);
    Pressures(2, 31) = Pressures(2, 15) + ((8*(Q^2)*Density)/(pi^2))*(((1/(D3^4))-
(1/(D1^4)))) - Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D3^4)))*(Kex)) ;
    hLoss(2,10) = Pressures(2, 15) - Pressures(2, 31);
    Pressures(2, 16) = Pressures(2, 31) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L20)/D1);
    hLoss(2,11) = Pressures(2, 31) - Pressures(2, 16);
    Pressures(2, 28) = Pressures(2, 16) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(2,12) = Pressures(2, 16) - Pressures(2, 28);
    Pressures(2, 25) = Pressures(2, 28) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L15)/D1));
    hLoss(2,13) = Pressures(2, 28) - Pressures(2, 25);
    Pressures(2, 26) = Pressures(2, 25) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Ktee));
    hLoss(2,14) = Pressures(2, 25) - Pressures(2, 26);
    % Return Segment
    Pressures(2, 32) = Pressures(2, 26) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L17/D1) + 3*K90) - deltaZ);

    % fprintf('Q: %0.2f\tH system: %0.2f\tH pump: %0.2f\n', Q/0.0000631, (sum(hLoss(2,
:)) * 3.28 / (Density * Gravity)), (-0.0223*(Q / 0.0000631)^2 + 0.1147*(Q / 0.0000631)
+ 141.77))

    if abs((sum(hLoss(2, :)) * 3.28 / (Density * Gravity)) - (-0.0223*(Q /
0.0000631)^2 + 0.1147*(Q / 0.0000631) + 141.77)) <= error
        running = 0;
        Qs(2,1) = Q;
        HLossesEqual(2,1) = (sum(hLoss(2, :)) * 3.28 / (Density * Gravity));
    else
        Q = Q + (0.0000631*error*(-(sum(hLoss(2, :)) * 3.28 / (Density * Gravity)) +
(-0.0223*(Q / 0.0000631)^2 + 0.1147*(Q / 0.0000631) + 141.77)));
    end
end

% Pump Specs
Q = 10; %gpm
pHead = 0; % ft
Q = 0.0000631 * Q; % meters ^ 3/ s
pHead = 0.3048 * pHead; % meters

running = 1;
while running == 1

    % Segment 3 Simulation
    % Pump Segment
    Pressures(3, 1) = P0 + Density*Gravity*(pHead - (HM + Hm) - deltaZ -
(8*Q^2)/((pi^2)*Gravity*(D1^4)));
    Pressures(3, 2) = Pressures(3, 1) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L3)/(D1)));
    hLoss(3,1) = Pressures(3, 1) - Pressures(3, 2);
    Pressures(3, 3) = Pressures(3, 2) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(K90));
    hLoss(3,2) = Pressures(3, 2) - Pressures(3, 3);
    Pressures(3, 4) = Pressures(3, 3) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L4)/D1);
    hLoss(3,3) = Pressures(3, 3) - Pressures(3, 4);
    % Segment 2
    Pressures(3, 10) = Pressures(3, 4) -
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(3,4) = Pressures(3, 4) - Pressures(3, 10);
```

```
    Pressures(3, 11) = Pressures(3, 10) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L5)/D1);
    hLoss(3,5) = Pressures(3, 10) - Pressures(3, 11);
    Pressures(3, 17) = Pressures(3, 11) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(3,6) = Pressures(3, 11) - Pressures(3, 17);
    Pressures(3, 18) = Pressures(3, 17) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L6)/D1);
    hLoss(3,7) = Pressures(3, 17) - Pressures(3, 18);
    Pressures(3, 19) = Pressures(3, 18) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(K90)) ;
    hLoss(3,8) = Pressures(3, 18) - Pressures(3, 19);
    Pressures(3, 20) = Pressures(3, 19) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L11)/D1);
    hLoss(3,9) = Pressures(3, 19) - Pressures(3, 20);
    Pressures(3, 21) = Pressures(3, 20) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Kpitot));
    hLoss(3,10) = Pressures(3, 20) - Pressures(3, 21);
    Pressures(3, 22) = Pressures(3, 21) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L12)/D1);
    hLoss(3,11) = Pressures(3, 21) - Pressures(3, 22);
    Pressures(3, 23) = Pressures(3, 22) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(Kval));
    hLoss(3,12) = Pressures(3, 22) - Pressures(3, 23);
    Pressures(3, 24) = Pressures(3, 23) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(f(1)*L13)/D1);
    hLoss(3,13) = Pressures(3, 23) - Pressures(3, 24);
    Pressures(3, 26) = Pressures(3, 24) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*(KteeS));
    hLoss(3,14) = Pressures(3, 24) - Pressures(3, 26);
    % Return Segment
    Pressures(3, 32) = Pressures(3, 26) - 
Density*Gravity*(((8*Q^2)/((pi^2)*Gravity*(D1^4)))*((f(1)*L17/D1) + 3*K90) - deltaZ);


    % fprintf('Q: %0.2f\tH system: %0.2f\tH pump: %0.2f\n', Q/0.0000631, (sum(hLoss(3, 
:)) * 3.28 / (Density * Gravity)), (-0.0223*(Q / 0.0000631)^2 + 0.1147*(Q / 0.0000631) 
+ 141.77))

    if abs((sum(hLoss(3, :)) * 3.28 / (Density * Gravity)) - (-0.0223*(Q / 
0.0000631)^2 + 0.1147*(Q / 0.0000631) + 141.77)) <= error
        running = 0;
        Qs(3,1) = Q;
        HLossesEqual(3,1) = (sum(hLoss(3, :)) * 3.28 / (Density * Gravity));
    else
        Q = Q + (0.0000631*error*(-(sum(hLoss(3, :)) * 3.28 / (Density * Gravity)) + 
(-0.0223*(Q / 0.0000631)^2 + 0.1147*(Q / 0.0000631) + 141.77)));
    end
end

Qs = Qs / 0.0000631;

fprintf('Operating Flow Rates:\n\tSegment 1: %0.2f (gpm)\n\tSegment 2: %0.2f 
(gpm)\n\tSegment 3: %0.2f (gpm)\n', Qs(1,1), Qs(2,1), Qs(3,1))
```

8.3 Appendix C – CAD Model

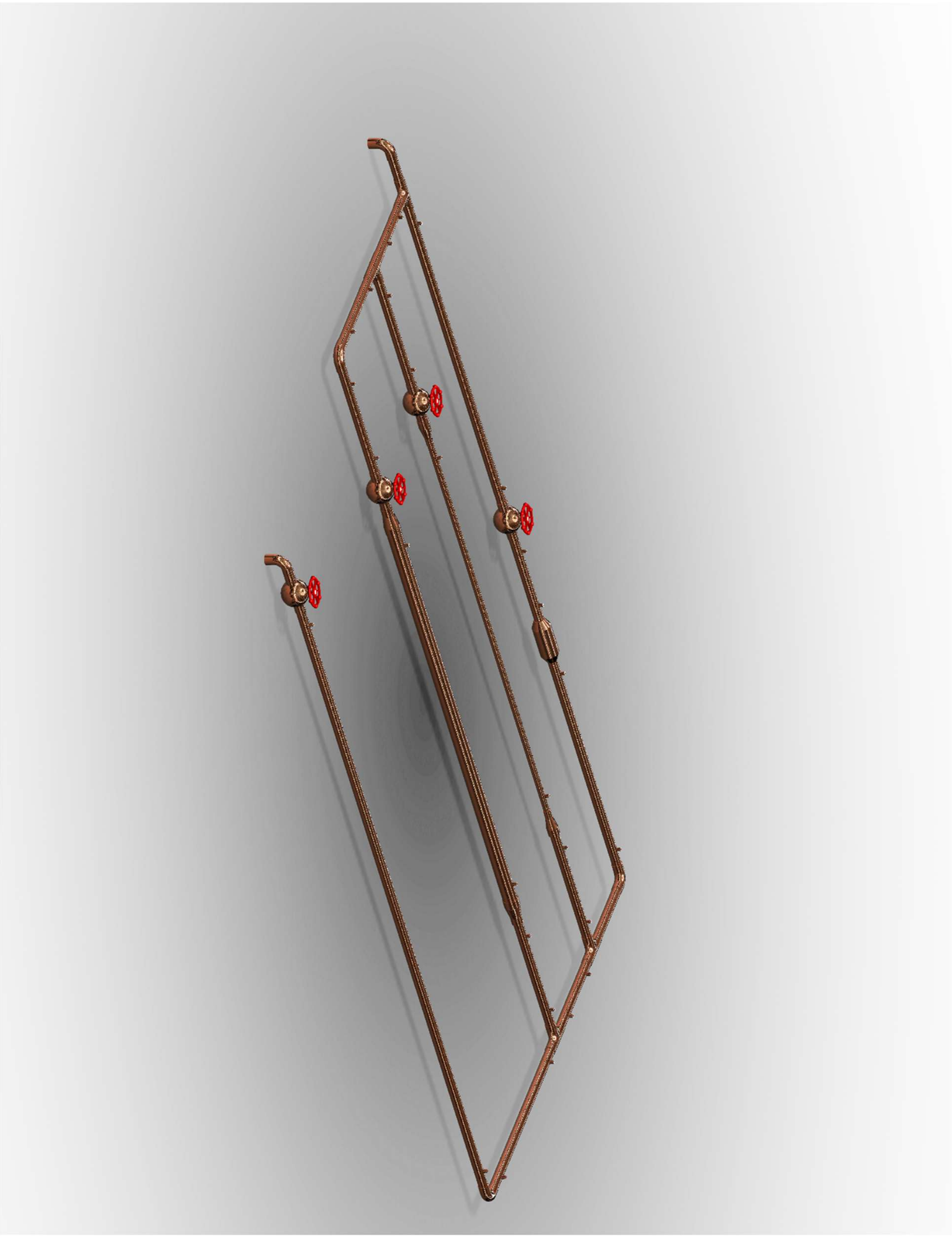


Figure C - 1 Upper Section Assembly

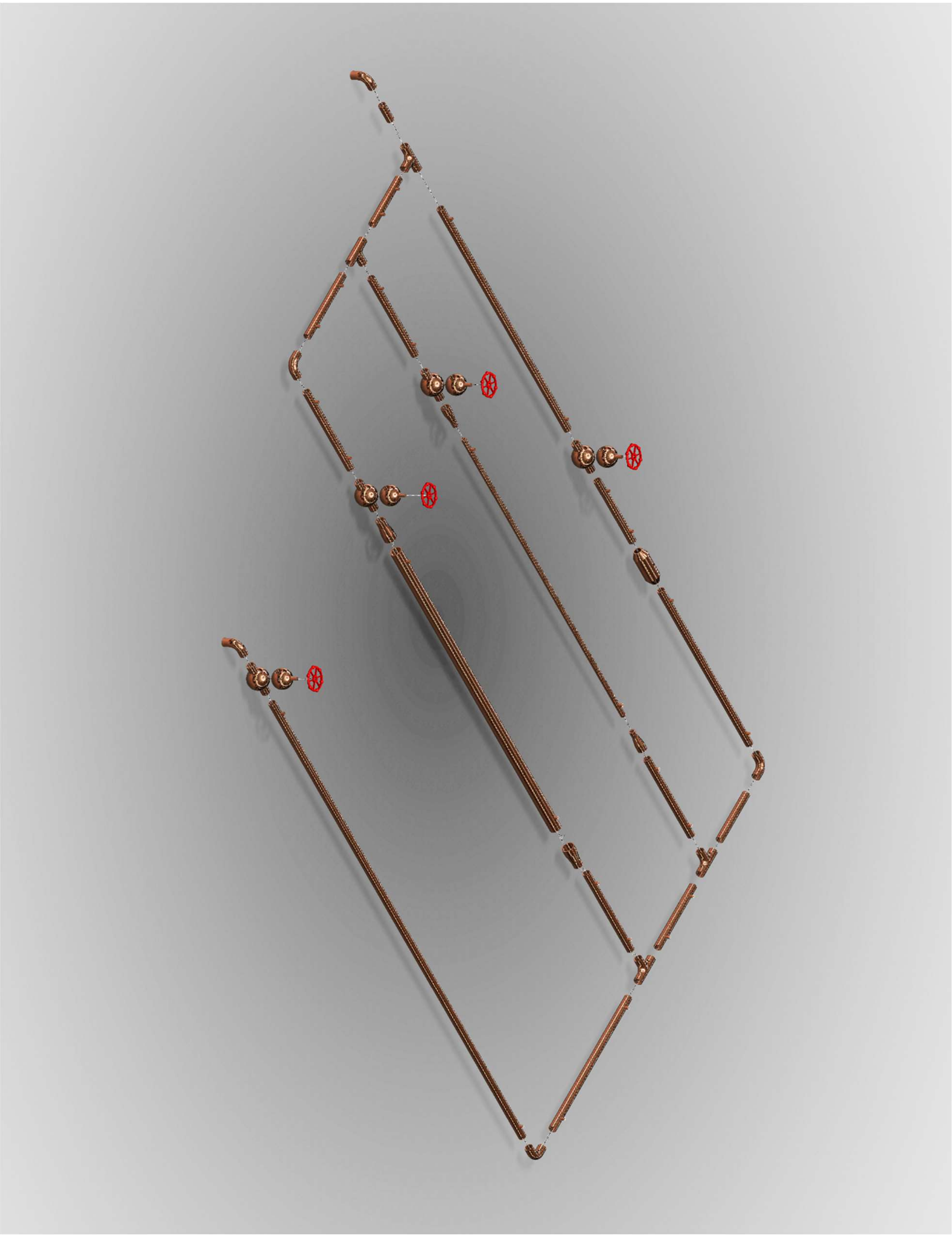


Figure C - 2 - Upper Exploded View

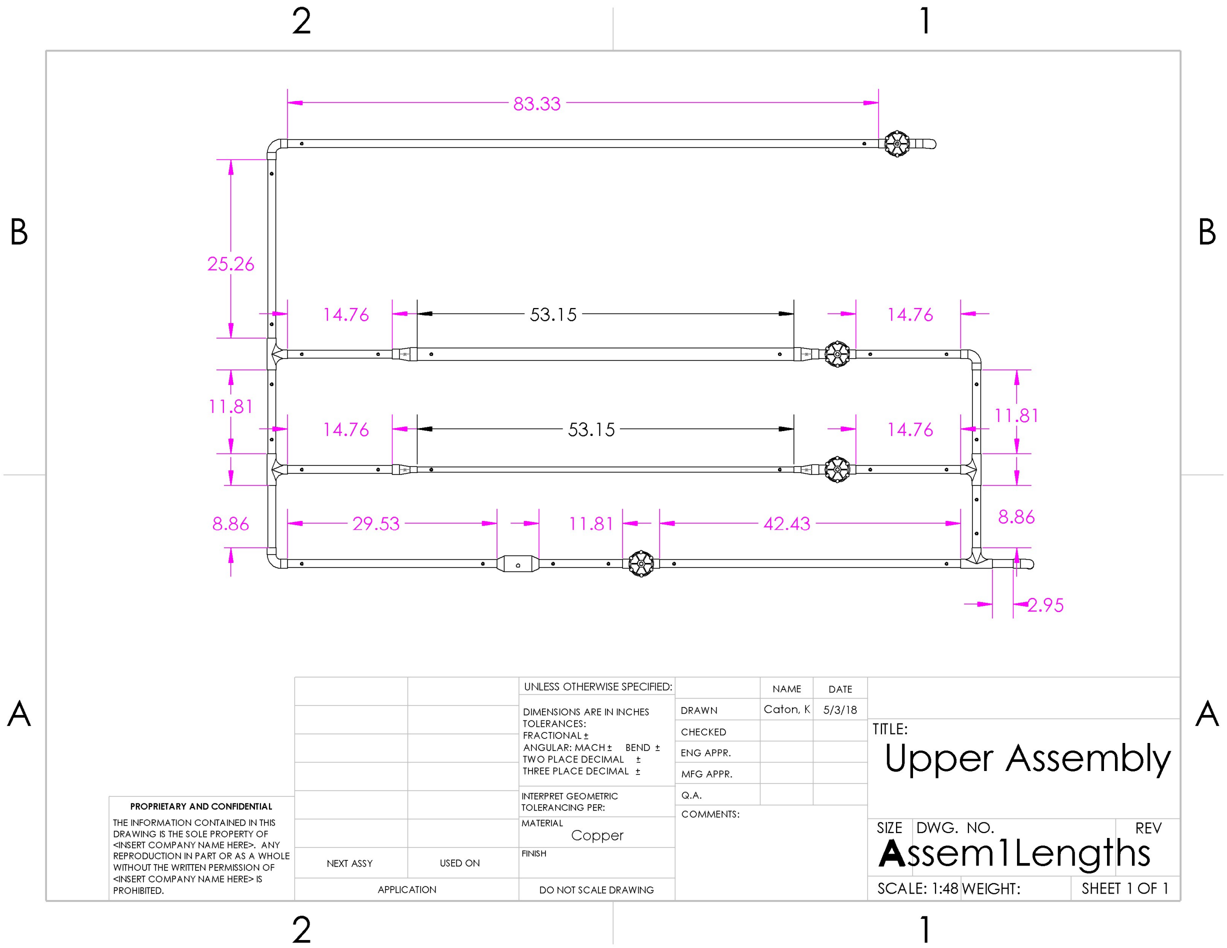


Figure C - 3 - Upper Segment Pipe Lengths

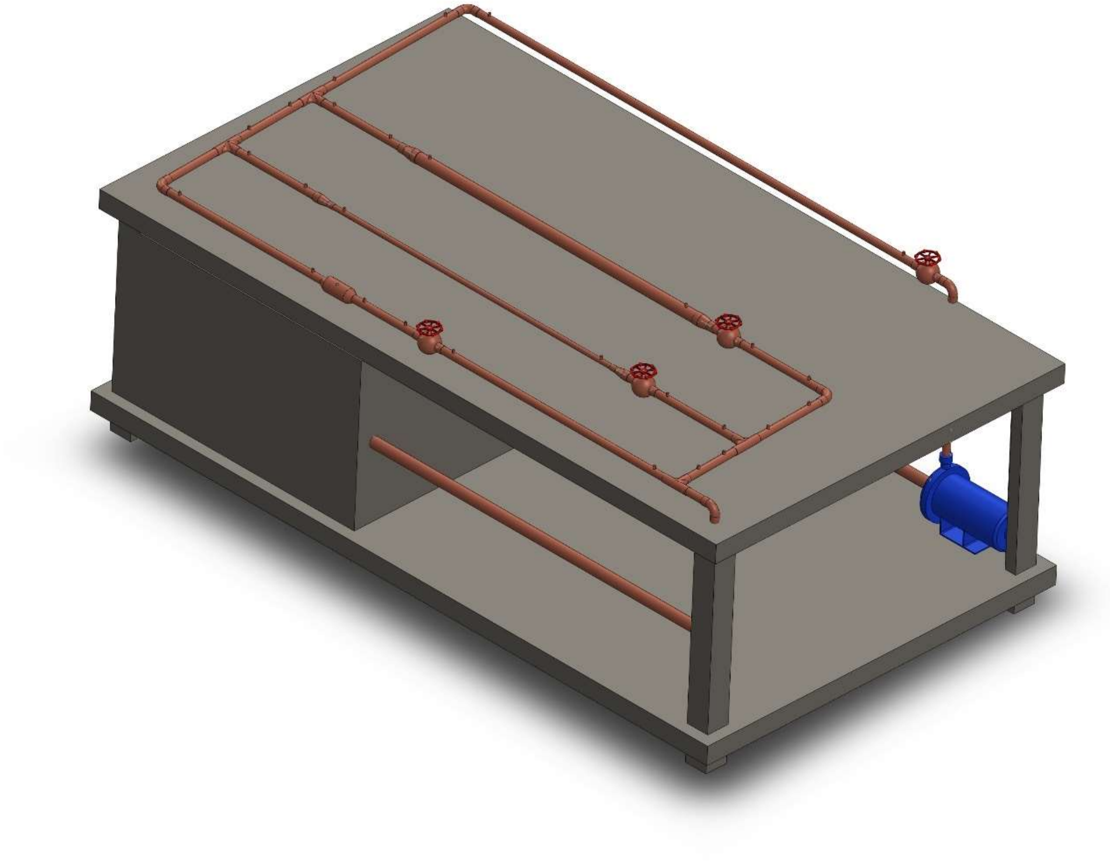
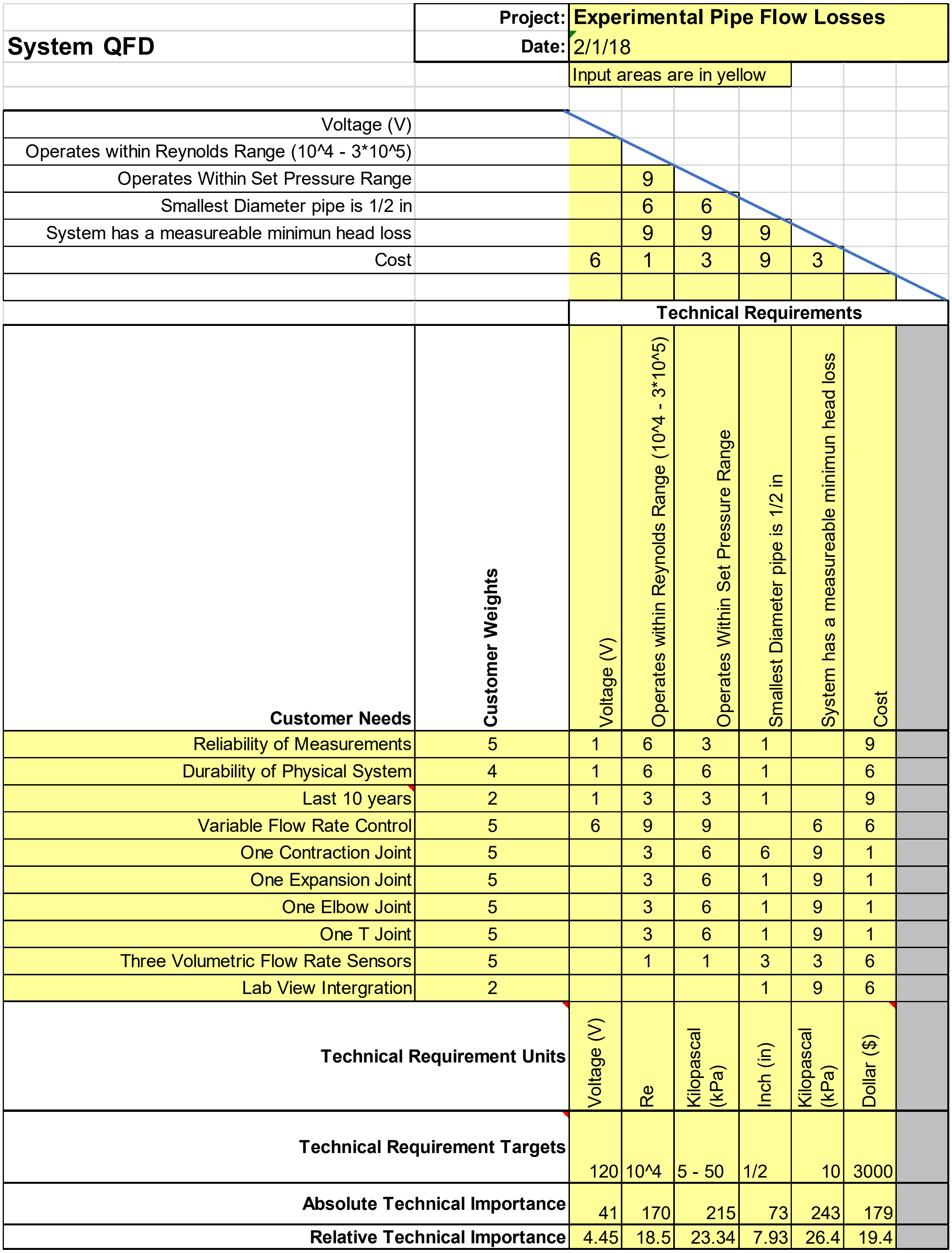


Figure C - 4 Complete Assembly

8.4 Appendix D: Miscellaneous

Table D - 1 - House of Quality



System QFD

Project: **Experimental Pipe Flow Losses**

Date: 2/1/18

Input areas are in yellow

Voltage (V)						
Operates within Reynolds Range (10^4 - 3*10^5)						
Operates Within Set Pressure Range		9				
Smallest Diameter pipe is 1/2 in		6	6			
System has a measureable minimun head loss		9	9	9		
Cost	6	1	3	9	3	

Technical Requirements

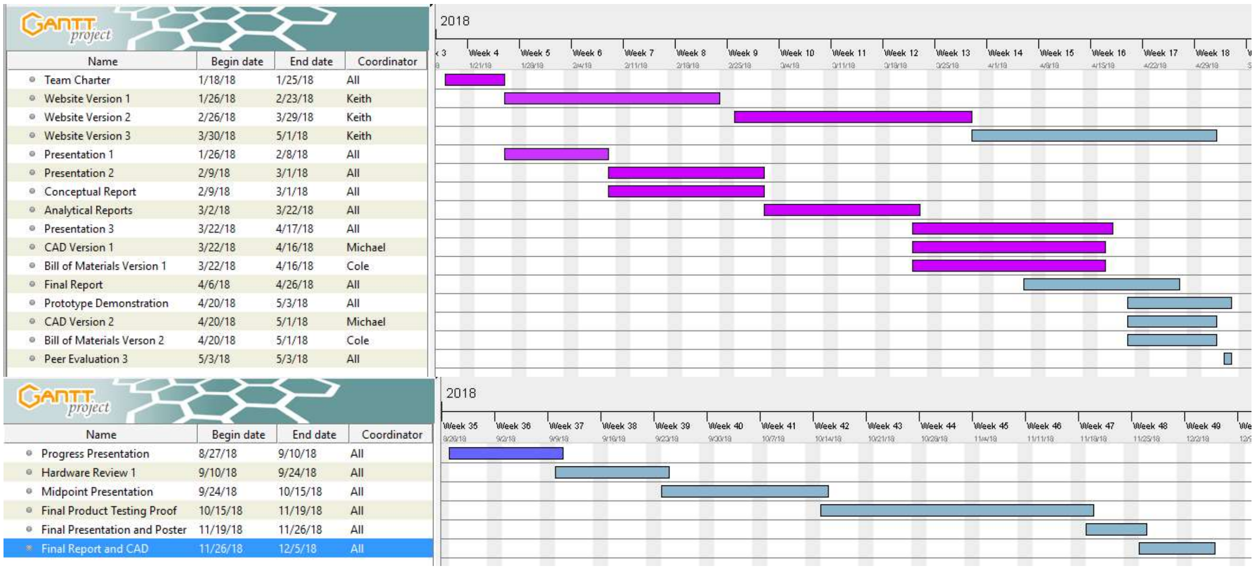
Customer Needs	**Customer Weights**	Voltage (V)	Operates within Reynolds Range (10^4 - 3*10^5)	Operates Within Set Pressure Range	Smallest Diameter pipe is 1/2 in	System has a measureable minimun head loss	Cost
Reliability of Measurements	5	1	6	3	1		9
Durability of Physical System	4	1	6	6	1		6
Last 10 years	2	1	3	3	1		9
Variable Flow Rate Control	5	6	9	9		6	6
One Contraction Joint	5		3	6	6	9	1
One Expansion Joint	5		3	6	1	9	1
One Elbow Joint	5		3	6	1	9	1
One T Joint	5		3	6	1	9	1
Three Volumetric Flow Rate Sensors	5		1	1	3	3	6
Lab View Intergration	2				1	9	6
Technical Requirement Units		Voltage (V)	Re	Kilopascal (kPa)	Inch (in)	Kilopascal (kPa)	Dollar ($)
Technical Requirement Targets		120	10^4	5 - 50	1/2	10	3000
Absolute Technical Importance		41	170	215	73	243	179
Relative Technical Importance		4.45	18.5	23.34	7.93	26.4	19.4

Table D - 2 - Bill of Materials

Capstone Bill Of Materials						
Item	Quantity	Price per unit ($)	Price ($)	Item #	Manufactu	Source
1 in x 10 ft Copper Pipe	4	35.93	143.72	100354226	Cerro	Homedepot
1/2 in x 10 ft Copper Pipe	1	9.76	9.76	100354198	Cerro	Homedepot
1 in Copper Elbow Joint 90 deg	6	4.98	29.88	100346976	Unknown	Homedepot
1 x 1/2 in Copper Reducer	2	4.51	9.02	100348139	Unknown	Homedepot
1 in Copper Tee Joint	4	11.58	46.32	100343973	Unknown	Homedepot
Centrifugal Pump	1	775	775	4XY85	Goulds W	Grainger
Regency 30 in x 72 in work table	1	155.99	155.99	600T3072G	Regency	Webstauran
NIBCO Ball Valve 1 in copper	4	14.49	57.96	S-FP-600A	NIBCO	Supply.com
10 Gal Hydraulic Reservoir	1	370.50	370.50	24W703	Grainger	Grainger
Total			1598.15			
Dr. Ciocanel's Budget						
Item	Quantity	Price per unit ($)	Price ($)	Item #	Manufactu	Source
Keyence Flow Sensor System	1	790	790	FD-Q series	Keyence	Keyence
Keyence Flow Sensor clamps	3	60	180	FD-Q20C (1/2 in	Keyence	Keyence
				FD-Q50C (1 1/2-2 in)		
Dwyer Digital Manometer	1	217.08	217.08	YX-68062-66	Dwyer	Davis Instru
Portable static pressure tip	1	12.79	12.79	G2603474	Dwyer	Zoro
Total			1199.87			

Table D - 3 Bill Of Materials Web Sites

Item	Website
1 in x 10 ft Copper Pipe	https://www.homedepot.com/p/Cerro-1-in-x-10-ft-Copper-Type-L-Hard-Temper-Straight-Pipe-1-L-10/100354226
1/2 in x 10 ft Copper Pipe	https://www.homedepot.com/p/Cerro-1-2-in-x-10-ft-Copper-Type-M-Hard-Temper-Straight-Pipe-1-2-M-10/100354198?MERCH=REC-_-SearchPLPHorizontal1_rr-_-NA-_-100354198-_-N
1 in Copper Elbow Joint 90 deg	https://www.homedepot.com/p/1-in-Copper-Pressure-90-Degree-Cup-x-Cup-Elbow-C607HD1/100346976
1 x 1/2 in Copper Reducer	https://www.homedepot.com/p/1-in-x-1-2-in-Copper-Pressure-FTG-x-C-Fitting-Reducer-C6002HD112/100348139
1 in Copper Tee Joint	https://www.homedepot.com/p/1-in-Copper-Pressure-Tee-C611/100343973
Centrifugal Pump	https://www.grainger.com/product/GOULDS-WATER-TECHNOLOGY-120-240VAC-Open-Dripproof-4XW85
Regency 30 in x 72 in work table	https://www.webstaurantstore.com/regency-30-x-72-18-gauge-304-stainless-steel-commercial-work-table-with-galvanized-legs-and-undershelf/600T3072G.html
NIBCO Ball Valve 1 in copper	https://www.supply.com/shop?nid=489177&d=13116-13060&wmh_cid=242274502&wmh_aid=15352618702&wmh_kid=117838584982&gclid=EAIaIQobChMItcbCpZXo2gIVDNRkCh0K9gS-EAQYAiABEgLj7fD_BwE
10 Gal Hydraulic Reservoir	https://www.grainger.com/product/GRAINGER-APPROVED-10-Gal-22-1-4-x-14-x-12-1-24W703
Total	
Dr. Ciocanel's Budget	
Item	Website
Keyence Flow Sensor System	Call: 1-888-KEYENCE
Keyence Flow Sensor clamps	Call: 1-888-KEYENCE
Dwyer Digital Manometer	http://www.davis.com/Product/Dwyer_475_000_FM_Digital_Manometer_1_WC/YX-68062-66?referred_id=3388&gclid=EAIaIQobChMIgoGNo5ew2gIVD3R-Ch0_1QxYEAkYByABEgI7YvD_BwE
Portable static pressure tip	https://www.zoro.com/dwyer-instruments-static-pressure-tip-a-303/i/G2603474/feature-product?gclid=EAIaIQobChMI8IH1iqDm2gIVl_hkCh0IpwLOEAkYCyABEgIVVvD_BwE



Name	Begin date	End date	Coordinator
Team Charter	1/18/18	1/25/18	All
Website Version 1	1/26/18	2/23/18	Keith
Website Version 2	2/26/18	3/29/18	Keith
Website Version 3	3/30/18	5/1/18	Keith
Presentation 1	1/26/18	2/8/18	All
Presentation 2	2/9/18	3/1/18	All
Conceptual Report	2/9/18	3/1/18	All
Analytical Reports	3/2/18	3/22/18	All
Presentation 3	3/22/18	4/17/18	All
CAD Version 1	3/22/18	4/16/18	Michael
Bill of Materials Version 1	3/22/18	4/16/18	Cole
Final Report	4/6/18	4/26/18	All
Prototype Demonstration	4/20/18	5/3/18	All
CAD Version 2	4/20/18	5/1/18	Michael
Bill of Materials Verson 2	4/20/18	5/1/18	Cole
Peer Evaluation 3	5/3/18	5/3/18	All

Name	Begin date	End date	Coordinator
Progress Presentation	8/27/18	9/10/18	All
Hardware Review 1	9/10/18	9/24/18	All
Midpoint Presentation	9/24/18	10/15/18	All
Final Product Testing Proof	10/15/18	11/19/18	All
Final Presentation and Poster	11/19/18	11/26/18	All
Final Report and CAD	11/26/18	12/5/18	All

Figure D - 1 – Full Year Gantt Chart