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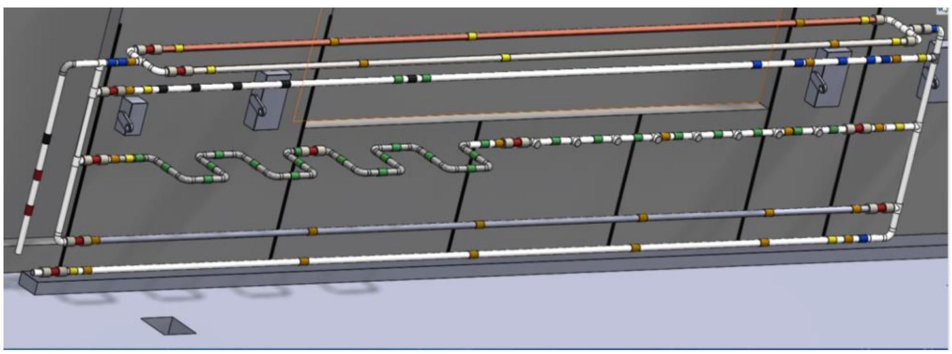
Subject: Flow Loop Fluid Mechanics Lab Design – CHE 4080: Process Design & ME 4060

Group Name: EERB Fluid Loop Design Team



Design of an Interdisciplinary Flow Loop

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EXECUTIVE SUMMARY: Ashley Skoog, Taten Knight, Adrun James

A multidisciplinary water flow loop teaching lab was designed to teach students the fundamentals of fluid mechanics in the new Engineering Education and Research Building (EERB) starting this coming spring semester. The loop will demonstrate flow across straight-run pipes and elbows, the use of various instruments, the capability of a centrifugal pump, and have capacity to add or remove modular experiments. The first section is a straight run where the major losses due to surface roughness through pipe of two different materials (Schedule 80 PVC and galvanized steel) will be characterized by pressure drops and flow development. The second section is the instrumentation and valving run where different types of flowmeters and valves will be compared. This can be done by utilizing pressure gauges, characterizing flow development, examining throttling capability, and juxtaposing measurement accuracy and precision of these devices. The third experiment is the fitting section where a comparison of 90° short radius elbows, 90° long radius elbows, and stubbed off tees will be used to demonstrate how the geometry of fittings effect the frictional losses of the system. The fourth section will be modular, meaning that operators will be capable of removing it and inserting another experimental design. One portion of the modular section will demonstrate flow through packed beds and the characteristics of water hammer. The other portion will be a packed bed section, which demonstrates the difference in packing material and packing diameter, and how these parameters can affect pressure drops across the packed bed. The water hammer section demonstrates the amount of force shock waves exerted on pipe sections when a valve is closed too quickly. The driver of the entire rig is the centrifugal pump; it demonstrates net-positive suction head, pump efficiency, brake horsepower, and the effects of cavitating a pump. This design was developed by taking into consideration the requested objectives of the Ellbogen Foundation and individual professors, while meeting Wet Lab, International Building Code, ADA requirements, OSHA, and Lock Out-Tag Out codes within the building, and considering fundamental fluid dynamics concepts that are applied in the industrial world. A budget was set in place of $50,000, and within that budget we were able to construct a multidisciplinary water loop with a current price of $23,979.34. Future work for this project includes assembling the project and completing acceptance testing to guarantee that the intended experiments can be performed.

PROJECT SCOPE: Rob Cincotta, Ashley Skoog, Max Dickerman**,** Adrun James, Taten Knight

Pre-existing pipe flow labs in the engineering department did not meet the demands of a multidisciplinary space to teach students the fundamentals of fluid mechanics. Each lab is individually lacking key instrumentation and valves students will find in an industrial setting. This use of multiple laboratory spaces is also highly inefficient for the college. Therefore, a new multidisciplinary water flow loop was designed to meet the goals established with faculty from chemical engineering, civil engineering, and mechanical engineering in a meeting on October 12th, 2018. In this meeting, primary goals were established: demonstrating major losses in straight runs of pipe, minor losses from fittings, exposing students to common valves and meters used in industry, and the characterization of pump performance. Secondary goals were set to demonstrate pipe network characteristics, show how a packed bed works, and demonstrate how cavitation and water hammer affect the system in a safe and controlled manner.

There are safety, practical, economic, water feed and drainage, electrical, and pump specification constraints for this rig. Safety constraints are found in the water hammer and centrifugal pump section of the rig. The water hammer section deals with pressure surges that can produce jumping pipes. To allow the pipe motion to occur, a specific mounting and shock mitigation system (leeway mounting near the ball valve, surge arrestor, and pressure release valve) will be put into place to protect people and other systems in the room. Another safety constraint deals with the elbow upstream of the air arrestor in the water hammer section, where the pressure surge could have enough force to torpedo the elbow off the rig. To accommodate this problem, a pressure release valve set 5 psi below maximum elbow capability will be placed in between elbow and air arrestor. Thus, diverting the water into the drain station below the modular section. Another safety constraint deals with cavitating the centrifugal pump with low NPSH (net positive suction head) for an extended period of time. This will cause noise pollution and a decreased life of the pump. We wish to show this in lab and thus short intervals of pump cavitation will be observed. This should not have a major impact on the pump, contingent on the operators restricting cavitation time. A shock absorbing rubber pad mounted underneath the pump is included to dampen the noise and vibratory response of the ground. A different safety constraint deals with electrical breaker boxes and electrocuting oneself since the breaker boxes are placed on the west wall of the lab, less than a foot away from the rig. Worst case scenario a pipe ruptures, and electrocution and black out could occur if the breakers are not GFCI protected. If GFCI breakers are not installed, our current approach is to shrink the size of the flow rig and shift the rig away from the breaker boxes.

Important practical constraints with our design are the viability of PVC valves over a 15 –20-year lifetime, how the flow rig is to filled/drained, ADA accessibility, height limitation, and achieving fully developed flow upstream/downstream of flowmeters for accurate flow measurement. Wear on the PVC valves is inevitable, so it is paramount that they can be taken out of the loop and either repaired or replaced. For this reason, we are opting for valves that are set in place with unions, or flanges, as opposed to being threaded or glued. To evacuate all the air within the flow rig we will be filling it from the bottom left corner of the rig and venting out air through a vent valve in the top right corner. A drain valve will be placed above the laboratory's grated floor drain as well. Including a vent valve will allow us to know the static pressure of the rig and ensure that the rig does not pull a vacuum while draining. ADA accessibility was brought up early in the design process, and individuals in a wheelchair should be able to operate the pump, VFD, and valves on the metered line. The clearance is very tight between the apparatuses, and it may be that some wheelchairs may not be able to fit between the loop and the HVAC rig. The loop will be designed so that it is accessible to individuals of any height; it will not exceed 6 feet high to be within reach of students. Fully developed turbulent flow is required for accurate volumetric flow measurement as a scientific/technical constraint. A common industry heuristic is ten pipe diameters upstream and five pipe diameters downstream of the flowmeter for accurate measurement.

There is an economic constraint on this rig in the form of a $50,000 budget. An overall budget spreadsheet was created to make sure expenses did not exceed the budget. To have an environmental constraint in this system, it would mean that the fluid in the system has been altered in some other way and can be harmful to drain the fluid causing problems at a wastewater treatment plant. This is not the case. The feedstock specification constraint includes the type of water (hardness, etc.) being used in the system will control the type of material being used for long term use. We are filling via the water lines built into the building, so these water specifications will be acquired via building specifications.

Introduction: Rob Cincotta, Ashley Skoog, Max Dickerman, Aline Muanza, and Shelbi Hrkach

General Information: Rob Cincotta, Ashley Skoog

The space provided for this project is shown in **Figure 1**, the rig will be place along the west wall of the Engineering Education and Research Building (EERB) inside the black frame. A pre-existing HVAC lab designed by the civil engineering department will be in place next to the flow rig with 1-2 ft of space between the apparatus for people to operate both simultaneously. Space available for the flow rig includes 42 ft in length with a width of 1 ft from the wall. Drains, air lines, and water lines are built into the lab for easy access for the flow rig.

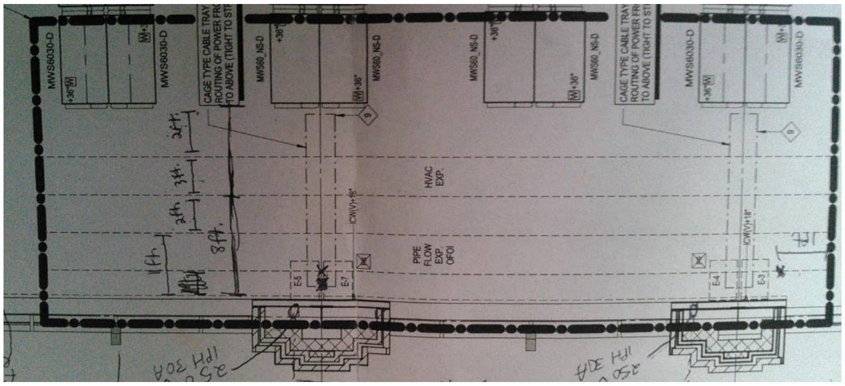


***Figure 1**: Floor plan of the EERB interdisciplinary fluids lab. The fine dotted rectangles at the top of the figure signify the water flow rig and HVAC rig.*

Appendix D.1 will show the in P&ID form. The five horizontal, parallel lines in the rig show (top to bottom): a line of straight-run pipe, a line with various measurement devices, a line with many ells in series, a line with unions for inserting specialty experiments, and a line for another straight-run pipe. These horizontal lines will be fed from and drain to common vertical lines at either end of a centrifugal pump. Any of the experiment lines can be closed by ball valves at either end and are designed to operate individually. The bulk of the rig will be made of grey schedule 80 PVC pipe with a nominal diameter of 1½ inches. The apparatus will span 25 ft and be mounted to the floor using unistrut to maximize space between the flow rig and the HVAC rig. The elbowed section will have 24 total fittings, where 8 are standard 90-degree elbows, 8 are long sweep elbows, and 8 are tees with the branches capped to demonstrate how the geometry of fittings effect the frictional losses of the system. The metered line will demonstrate five flowmeters, from operator's left to right: a magnetic meter, a turbine flow meter, a paddlewheel meter, a vortex meter, and an orifice plate. Additionally, the meter line will include various valve types to demonstrate to students. The modular section features two threaded unions on either end. Initially, the design provides a packed bed experiment and water hammer demonstration in this section. Both the packed bed and water hammer section will be using 2-inch nominal Schedule 80 PVC pipe. The packed bed and water hammer section will run parallel to each other, so that the pressure surge of the water hammer does not affect the packed bed section. Installation and removal of a module will likely require a minimum of two people. Duplicate items of each type of meter, valve, and fitting will be cut in half and mounted as display items to demonstrate the mechanisms by which these devices work.

Design Considerations: Taten Knight, Adrun James

As part of any design challenge, decisions are made concerning the design or selection of parts and assemblies. Often these decisions are made based on input from multiple constraints. Constraints often conflict when there is a tradeoff between multiple desired final outcomes. Safety, cost, weight, and ease of use are a few of the constraints considered by the design team throughout this project. The following table describes the specific constraints, which steer the selection of the final design of each project component.

Table 1. Design Considerations Overview

Item	Consideration	Other Constraints	Possible Solutions	Final Decision
Design Life	Must be usable for 15+ years	Material prices, varying use cases	Purchase low wear materials and components	PVC Piping and Valving where applicable
Visual Appeal	One of the undergraduate showpieces for the EERB Building	Material Pricing, Space constraints	Design with attention to visual detail with regards to space, placement, and overall layout	Scale Solidworks model with all major components accurately represented
Expansion of Use Cases	May utilize flow rig for a wider number of experiments than initially intended	Space, modularity, initial design scope	Include modular section	Include modular section with sufficient room to expand design
Undergraduate Class Use	Initial scope includes the use of the apparatus by undergraduates to supplement fluid dynamics courses	Non-specific experiments provided. General knowledge of fluid dynamics courses	Client input concerning use cases taken into consideration and used for final design	Final functionality (above) based on client input

General Pipe Flow Calculations: Rob Cincotta, Adrun James

Relevant parameters of the pipe flow systems generally vary with the flowrate. Of interest are flowrates where the fluid becomes turbulent. Onset of turbulence occurs at high Reynolds numbers (in excess of 4000), calculated as:

(1): $Re = \frac{4Q}{\pi d \mu} \geq 4000$

Where:

Re is the Reynolds number, dimensionless

Q is the volumetric flowrate

d is the characteristic length, hydraulic diameter for pipe flow

μ is the dynamic viscosity

To better understand how a pipe network will behave with a given pump, system parameters like head loss and pressure are often plotted against flowrate as system curves. These curves can be generated using methods discussed by Munson et al. (2013) which require dimensionless friction factors for straight pipe and loss coefficient values for fittings. Friction factors are determined using Zigrang-Sylvester equation:

(2): $\frac{1}{\sqrt{f}} = 4.0log_{10}\left(\frac{\frac{e}{d}}{3.7} - \frac{5.02}{Re}log_{10}\left(\frac{\frac{e}{d}}{3.7} + \frac{13}{Re}\right)\right)$

Where:

f is the Darcy friction factor, dimensionless

e/d is the relative roughness, dimensionless

Zigrang-Sylvester equation approximates the Darcy friction factor more accurately than the more common Haaland equation and is reliable over a larger range of Reynold's numbers (Zigrang & Sylvester, 1982). From this friction factor, head loss can be determined with the Darcy-Wiesbach equation:

(3): $h_L = \frac{2fL\bar{v}^2}{dg}$

Where

h_L is the head loss in ft

L is the length of the pipe in ft

v is mean linear velocity of the fluid in ft/s

d is inner diameter of the pipe in ft

g is the acceleration due to gravity in ft/s^2

For minor losses, another equation is used to related head to the loss coefficients:(3):

(4): $h_L = \sum(K_L)\frac{\bar{v}^2}{2g}$

Where

K_L is the loss coefficient of a pipe fitting, dimensionless

The above head losses are additive and can be used with the extended Bernoulli equation assessed from the pump discharge line to the pump suction line to calculate an overall system pressure drop:

(5): $p_{out} - p_{in} = \frac{\rho(\bar{v}_{in}^2 - \bar{v}_{out}^2)}{2g} + \gamma\Delta z + \gamma h_L$

Where

p is the pressure assessed at one end of the system

γ is the specific weight of the fluid

z is the change in height of the system

The equation can be simplified noting that mass is conserved, water is incompressible and that the pipe diameter is constant. Further, because the loop is assessed from the pump discharge to the pump inlet, the overall change in height is negligible. These considerations show that the first two terms on the right-hand side are negligible and only the head loss term is relevant.

Pump and VFD: Shelbi Hrkach

Pumps are devices which transfer power to liquids. The centrifugal pump is among the most common type of pump. These pumps transfer energy between the motion of a shaft and motion of a fluid tangent to the shaft. A centrifugal pump utilizes a shaft driven impeller and a volute casing to constrain fluid flow to the plane of the impeller (Munson et al, 2013). Centrifugal pumps can provide higher flowrates than most positive displacement pumps. They are also designed for use with fluids of low viscosity such as water or light oils (Hansen, 2018).

Modeling the behavior of an ideal centrifugal pump from first principles predicts a linear relationship between flow rate and pump head. In a real pump, however, energy lost from friction and other forces result in a more complicated relationship and are difficult to model on a completely theoretical basis. Because of this, centrifugal pumps are often characterized empirically. Pump performance curves are generated by measuring properties of the pump system at various conditions and performing relevant calculations. Pump curves are often plotted against flow rate and show pump head and brake power (Munson et al, 2013). These curves are typically published by the manufacturer and can be compared to the systems curves to predict optimal operating conditions, though for this application, mechanically suboptimal conditions may be acceptable due to the relatively short annual run time and educational benefit.

To precisely control the speed of the pump motor, a variable frequency drive (VFD) will be included in this setup. A VFD is a controller that works by manipulating the voltage and frequency of power supplied to the motor. This allows the speed of the pump to match the load requirement to maximize efficiency and will provide valuable experience with real-world controls (VFDS.org, 2018). The power source must be considered when selecting a VFD, as well as the input requirements of the pump to be controlled. The VFD should be able to supply more current than the nameplate full load amperage (FLA) of the pump.

The use of a VFD widens the options of pumps by providing more suitable power sources. For this case, the room is equipped with a power supply that is single phase. The pump to be used requires a three-phase input, which would otherwise be incompatible with the supply to the room. In general, the use of a VFD not only aids in energy savings, but also allows for more options in selecting the pump itself.

Cavitation: Ashley Skoog

Cavitation occurs when static pressure in a flow of liquid drops below the vapor pressure due to excessive velocities, creating a two-phase flow (Gulich, 2014). Vapor bubbles are then transported downstream to high pressure zones where static pressure again exceeds vapor pressure causing vapor bubbles to condense. When vapor bubbles condense, they start to implode and cause pitting. Elongation of pitting can cause cavitation erosion along the walls of pipes and/or eating away impeller material in a centrifugal pump. Therefore, this demonstration would need to be under a time constraint on how long cavitation should occur to permit a 20-year life span of the centrifugal pump.

There are four different types of cavitation: (1) traveling cavitation, (2) attached cavitation, (3) vortex cavitation, and (4) shear cavitation. Traveling cavitation includes microbubbles, called cavitation nuclei, forming along the flow field until a low-pressure zone, where macroscopic cavitation bubbles are formed before collapsing in a pressure recovery zone (Binama et al. 2016). Attached cavitation is like traveling cavitation, but it will stay in the same location attached to a wall. Attached cavitation will be located near the end of cavity where strong unsteady flow would occur (Binama et al. 2016). The size of the microscopic bubbles will range from 10^{-3}–10^{-1} mm, that being the case visual representation of cavitation would be hard to see to the naked eye (Binama et al. 2016). Vortex cavitation will be found near blade tips in secondary flow around an immersed propeller. The secondary flow is the result of pressure difference between vane pressure and suction pressure, where the vortex has lower pressure than the suction line making it vulnerable to cavitation (Binama et al. 2016). Shear cavitation is observed by using submerged bodies in high velocity jets where wakes occur (Binama et al. 2016). Vortex and shear cavitation will be hard to show in a diameter less than a nominal diameter of 2 inches. Traveling and attached cavitation will be hard to see, but other approaches could be used to show cavitation in the system.

A few approaches are discussed below to consider cavitation in the pump. The first approach includes wall geometry and variant velocities to produce pressure drops, this method can occur in fluid ducts and pump impellers where flow can be constricted (Binama et al. 2016). Second approach entails a high velocity unsteady flow causing pressure drops when flow temporally accelerates and decelerates (Binama et al. 2016). This approach is not desirable because some of the professors wanted the cavitation to be shown in the pump to demonstrate how cavitation could affect a pump. Third approach depends on the roughness of the wall boundary. Increasing surface roughness increases the probability of wakes forming attaching cavities (Binama et al. 2016). This approach is not feasible since the system will be using polyvinyl chloride (PVC) pipe material. The first approach is the preferred method.

The classifications of cavitation which occur in the pump also needs to be considered. There are two classifications: (1) discharge cavitation and (2) suction cavitation. Discharge cavitation occurs when the pump runs less than 10% of its best efficiency point (BEP) or when the pump's discharge pressure is extremely high and to the left of the pump curve (Parkhurst, 2014). The high pressure makes it difficult for the fluid to flow out of the pump, consequently the fluid recirculates in the pump. The vapor bubbles form when the fluid flows between impeller and the housing of the impeller at high speeds causing a vacuum at the housing wall (Parkhurst, 2014). This will affect the tips of impellers and pump housing once vapor bubbles start to implode causing intense shockwaves and pitting. Suction cavitation occurs when the pump is operating under low pressure, to the far right of the pump curve (Parkhurst, 2014). Adding air or running the pump too fast will starve the pump, preventing it from receiving sufficient flow. Vapor bubbles will form at the eye of the impeller and will be carried to lower-pressure zones causing the vapor bubbles to compress and implode at the face of the impeller (Parkhurst, 2014). Both classifications will cause damage to the pump over time. The damages caused by suction cavitation will cost less than the discharge cavitation, so suction cavitation is the preferable classification.

Parameters needed to determine if cavitation will occur in this system include inlet suction line velocity of the pump (v_1), pressure coefficient at minimum pressure ($C_{p,min}$), and cavitation number (σ). For the centrifugal pump in rig, a Baldor Electric Company, Model: 36WG0106 centrifugal pump, the suction diameter is 2.5 inches and the discharge diameter is 1.5 inches. The continuity equation can be used to adjust for diameter:

(6): $A_1 v_1 = A_2 v_2$

Where:

A_i= the area of a circle at i diameter

v_i= the velocity of the line at i diameter

The v_1 can be used to find the $C_{p,min}$ and σ. To calculate the pressure coefficient ($C_{p,min}$) at minimum pressure ($P_{min} = P_v$) (Binama et al. 2016):

(7): $C_{p,min} = \frac{P_{min} - P_1}{\rho v_1^2 / 2}$

Where:

P_1 = static pressure in psi

$P_{min} = P_v$ = vapor pressure at room temperature in psi

ρ = density of the fluid at room temperature in lbm/ft^3

As the cavitation number approaches to zero, cavitation becomes more probable in the system. The dimensionless cavitation number is defined as:

$$(8): \sigma = \frac{P_{1,cav} - P_v}{\rho v_1^2 / 2}$$

where:

$P_{1,cav} = P_v + 0.5\rho v_1^2\left(-C_{p,min}\right)$ = static pressure of P_1 at which cavitation will occur ($P_{min} = P_v$) in psi

Orifice plates Max Dickerman

One application of the Bernoulli's Equation is flow measurement using an orifice plate flowmeter. A common construction of an orifice plate flowmeter is a metal disk with a concentric hole bolted between two pieces of flanged pipe. In the flow rig, the orifice plate(s) will have a beveled or sharp edge. Per Bernoulli's Equation, as fluid approaches a contraction, its velocity increases while its pressure decreases. Due to its inertia, the fluid continues to contract until a uniform velocity profile forms downstream and perpendicular to the orifice hole. This point is known as the *vena contracta*. The *vena contracta* corresponds to the maximum fluid velocity and minimum static pressure within an orifice plate flowmeter. Applying the continuity equation to two points, one upstream and one downstream of the plate, allows for the upstream volumetric flowrate to be characterized by equation nine and appropriate unit conversion factors (Wilkes 2006):

$$(9): Q = C_D \times A_1 \sqrt{\frac{2 \times (p_1 - p_2)}{\rho \times \left(\frac{A_1^2}{A_O^2} - 1\right)}}$$

Where:

$C_D =$ the discharge coefficient

$A_1 =$ the cross-sectional area of the pipe above the orifice plate in ft^2

A_o= the cross-sectional area of the orifice hole in ft^2

p_1 = the pressure at point one – above the orifice plate in psi

p_2 = the pressure at point two – the *vena contracta* in psi

ρ = the fluid density in lb_m/ft^3

The discharge coefficient is found in Figure 2.10 of *Fluid Mechanics for Chemical Engineers* by Wilkes (Wilkes 2006). The change in pressure in pounds force per square inch, is found by multiplying the head loss through the orifice plate and the density of water, then dividing that product by an appropriate unit conversion. Since the flow rig will be characterized by turbulent flow, equations three and nine are used to find the head loss through an orifice plate ("Calculation of Flow Through Nozzles and Orifices" 2015):

For $Re_{pipe} > 2500$

$$(10): K = \left[2.72 + \left(D_{orifice}/D_{pipe}\right)^2 \times \left(4000/Re_{pipe}\right)\right] \times \left[1 - \left(D_{orifice}/D_{pipe}\right)^2\right] \times \left[\left(D_{pipe}/D_{orifice}\right)^4 - 1\right]$$

Where:

K = the loss coefficient through an orifice plate

D_{pipe} = the inside diameter of the pipe in ft.

$D_{orifice}$ = the inside diameter of the orifice hole in ft.

Re_{pipe} = the Reynolds number through the pipe upstream of the orifice plate

A common practice in literature is to define orifice diameter in terms of its beta ratio, that is, the orifice diameter divided by the inside pipe diameter. The pressure drop across an orifice plate is calculated for a range of flowrates, then these values are used to calculate the flowrate upstream of the orifice plate. This process is then iterated for a range of beta values to determine what orifice diameters may be rejected; orifice plates that result in either too high or too low of a pressure drop to be measured with the flow rig's instrumentation will not be considered.

Packed Bed: Aline Muanza

A packed bed is a hollow pipe filled with high surface area packing material. This packing can be in either a random or a structured arrangement. The purpose of the packed bed in chemical processes is to improve contact between two phases. It is usually used in adsorption and distillation processes. Packed beds can also be used to store heat in chemical plants. Packed beds can be filled randomly with small particles; items like Rasching rings. Packed beds can also be filled with catalysts particles and absorbent like zeolites pellets and activated carbon. The performance of a packed bed depends on the flow of material through it, which in turn is dependent on the packing and how the flow is managed (Geankoplis,2015). The purpose of the packed bed in the flow loop is to demonstrate pressure drop through different types of materials. The following equation, called the Ergun equation, is used to calculate pressure drop through a packed bed.

$$(11): \Delta P = \frac{150\mu Vs\Delta L}{Dp^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75\rho Vs^2\Delta L}{Dp}\frac{1-\varepsilon}{\varepsilon^3}$$

Where:

Vs = fluid velocity in ft/s

ΔL = length of the column in ft **L is the length of the bed, not the column**

ε = void fraction **changed to fraction instead of factor**

Dp = particle diameter in ft **equivalent spherical diameter, not just diameter**

ρ = density of the fluid in lb_m/ft^3

Water Hammer: Ashley Skoog

Water hammer is a surge of pressure developed when the fluid flow abruptly changes. Two main factors are necessary to create water hammer in a piping system: (1) initial velocity of the flowing water and (2) abrupt change to this flowing water velocity. Water hammer effect usually occurs when a valve is quickly closed or when a pump is shut off suddenly. The instant the fluid flow stops, the momentum force (kinetic energy) of the fluid will quickly transform into a pressure rise within the pipe (Sioux Chief Manufacturing Company). These surges cause pipes to move, banging noises, and cause leaks at pipe fittings or vessels (Ord, 2006). In this demonstration, fluid flow will be suddenly stopped using a valve, thereby demonstrating the dangers of a water hammer in a system and possible ways to control the phenomenon.

The water hammer section was a placed in the fourth loop of the system, with the packed bed experiment. The water hammer section was put at the end of the loop to prevent jumping pipes from damaging other lines. Measures will be taken so that the pressure surge will not damage the packed bed section. Some examples of measures include an air chamber, arrestors, surge tanks, and pressure release valves to dampen the shock wave, but still produce the hammer effect on the pipe. Historically, an air chamber was used in residential households for quick closing solenoid valves. Air chambers are long tubes full of compressed air to absorb the shock wave near the solenoid valves. Air chambers can only absorb a single shock. Once used, air chambers become part of the water hammer effect. Arrestors are like an air chamber that has a permanent compressible cushion of air or gas. Arrestors are common in the plumbing industry for residential, commercial, and industrial applications (Sioux Chief Manufacturing Company). The air is compressed until the momentum of the fluid is dissipated preventing the water hammer from propagating. Surge tanks contain water and are connected to a pipe to reduce high pressures within the pipe. The surge tank is open to the atmosphere and stores potential energy in height. As the surge displaces into the tank and is compressed using the potential energy, the momentum of the fluid dissipates. The fluid in the tower releases back into the pipe to balance out the low pressure. A pressure release valve is designed to open when a preset pressure level is reached; the valve relieves the pressure into another part of the system or to a purge system. In this loop system, a mixture of an air chamber and arrestor will be used with a water pressure release valve near the packed bed section or upstream elbow.

To calculate the pressure surge, one must have the wave speed (a) of the surge in meters per second (Twyman, 2016):

(12): $a^2 = \frac{K}{\rho(1+\frac{DK}{eE}\varphi)}$

Where:

K = volumetric compressibility modulus of the liquid in Pa

ρ = liquid density at room temperature in kg/m^3

e = pipe wall thickness in m

D = diameter of the pipe in m

E = pipe elasticity modulus in Pa

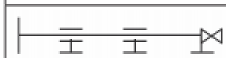
φ = factor related to the geometry of the pipe supports

Different types of material, nominal size of diameter, and mounting of the section were tested to see how it would affect the pressure surge within the pipe section. **Table** 2 shows the pipe elasticity for different materials. The smaller the elasticity the better the material returns to its original shape. Inelastic materials slow down the speed of the wave, because some of the energy is absorbed. **Table** 3 shows different mounting configuration that could affect the wave speed. In general, more mounting decreases the wave speed and mitigates movement of the pipe.

Table 2. Elasticity of different pipe material (Tayman, 2016).

Material	E, Pa
Steel	$2.077 \cdot 10^{11}$
Copper	$1.1 \cdot 10^{11}$
Bronze	$1.0 \cdot 10^{11}$
Asbestos cement	$2.3 \cdot 10^{10}$
Fiberglass reinforced	$9.0 \cdot 10^{9}$
PVC	$2.8 \cdot 10^{9}$
Polyethylene	$8.0 \cdot 10^{8}$

Table 3. Three different cases of pipe supporting of the section (Tayman, 2016).

Case	Pipe supporting condition
	Pipe anchored at the upstream end only
1	
	$\Psi = [1 / (1 + e/D)]\ [5/4 - u + 2(e/D)\ (1+u)\ (1 + e/D)]$
	Pipe anchored against any axial movement
2	
	$\Psi = [1 / (1 + e/D)]\ [1 - u^2 + 2(e/D)\ (1 + u)\ (1 + e/D)]$
	Case 2 plus longitudinal expansion joints along the pipeline
3	
	$\Psi = [1 / (1 + e/D)]\ [1 + 2(e/D)\ (1 + u)\ (1 + e/D)]$

Once the wave speed is determined for each material, nominal diameter, and support mounting of the section the pressure surge (ΔP) of each scenario is calculated (Ord, 2006):

(13): $\Delta P = -\rho a \Delta v$

Where:

$\Delta v = v_1 - v_0$ = change in velocity when initial velocity (v_0) starts at zero in ft/s

A plastic pipe system would be better suited for the water hammer section because plastic has a lower elasticity than copper or steel, so it slows the pressure wave more effectively. However, there are equal amounts of kinetic energy in both plastic and metal systems (Sioux Chief Manufacturing Company). Extra energy is absorbed into plastic pipes causing instantaneous expansion and contraction in the pipes and fittings. Water hammer itself is not the main concern, rather how the material of the fittings and pipes are able to expand and contract instantaneously. A metal system does not have the ability to expand or contract causing fittings to leak and pipes to jump. The fittings for any material will be the ones at risk from the water hammer damage. A force equation is used to see how much force would be on a 90° bend PVC pipe if there was no surge tank and pressure release valve (Engineering ToolBox, 2005).

(14): $R_x = \pi\rho\left(\frac{D}{2}\right)^2 v_1^2(1 - \cos(\beta))$

Where:

R_x = the resulting force in the x-direction in lbf

β = turning angle of a bend in degrees

(15): $R_y = \pi\rho\left(\frac{D}{2}\right)^2 v_1^2(\sin(\beta))$

Where:

R_y = the resulting force in the y-direction in lbf

(16): $R = \left(R_x^2 + R_y^2\right)^2$

Where:

R = the resulting force on the bend in lbf

Computational Fluid Dynamics (CFD) Model: Taten Knight, Adrun James

To verify the accuracy of some of the general pipe flow calculations, as well as confirm the ranges and delineations for the differential pressure meters, a SOLIDWORKS flow simulation was created based on the existing scale model. Each use case was modelled –excluding the modular section due to its dynamic complexity. The following values and specifications were used in the models:

Inlet Surface Boundary Condition: Environmental pressure of 131 PSI. Representative of differential pressure across 5HP pump at 65GPM fresh water.

Outlet Surface Boundary Condition: Outlet Volumetric Flowrate of 65 GPM

Inlet Surface Goal: Environmental pressure of 131 PSI. Goal associated with Inlet Surface Boundary Condition

Outlet Surface Goal: Maximum total pressure. Used to verify that the pump has extra power if needed.

Surface Roughness of PVC: 1.5 µm

Surface Roughness of Galvanized Steel: 150 µm

The above conditions resulted in values that were extremely close to those that were found by hand, thereby confirming these values and allowing us to move forward with the purchase of the correct metering equipment. Below is **Figure 2**, the analysis of one of the runs tested.

Figure 2. *Screenshot of SOLIDWORKS CFD analysis on ells run*

Finite Element Analysis: Taten Knight, Adrun James

The deflection of the pipes under the load will dictate the placement of the supports for the rig. In this rig we are spanning a large distance and thus the internal moment created in the pipes is large. Using traditional beam theory is a simple and easy way to accurately find the deflection of the straight pipe. The elbows section is much more difficult. The geometry alone makes beam theory difficult as it would require superimposing curved beams, or in our rig, the elbows. This is made even more difficult by the unique loading. We have reactional forces due to conservation of momentum of the water and a gravitational load from both the water and the rig's self-weight. These complications lead to the use of a finite element analysis. The program used was Abaqus. This program was used to measure the Von-Misses stress of the piping as well as the deflections. A preliminary note is that deflections drove this design. We ran into non-satisfactory deflections that would be aesthetically displeasing before the pipe strength was compromised. The deflection was held to a minimum as the flow loop must be aesthetically pleasing for its lifetime. The higher the initial stress, and therefore deflection, the more readily the material is to deflect over time.

The model was intended to find the deflections of the elbowed section and using those deflections, locate the placement of the support structure. In Abaqus standard PVC pipe material properties were used. The properties, and the model, were initially tested by comparing a straight pipe to the solution from beam theory. With satisfactory convergence of the model to the analytical solution, we moved on to the run in question. The geometry was defined as is shown in green on **Figure 3**. The Loads were added in accordance to the changes in linear momentum and the gravitational force acting on the model. Mesh Controls were an issue when defining the analysis method. A student version of Abaqus is available to students and thus a limited number of nodes were allotted. This then required that a sparse Quadratic Reduced Integration mesh be used. To check that this meshing did not corrupt the accuracy of the solution, a straight pipe was analyzed with this method. This again was satisfactory with the result of beam theory and thus the model of the elbow section was analyzed. The final results of the FE Analysis are shown color in **Figure 3** below.

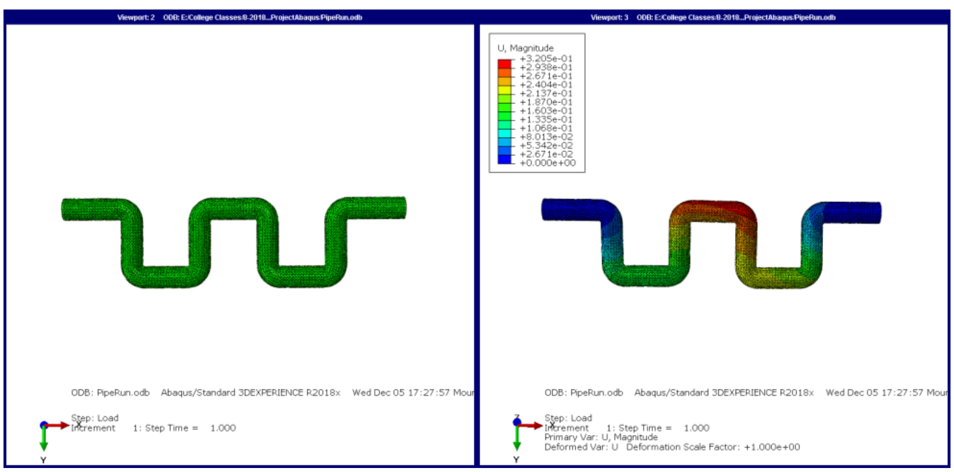


Figure 3*. Results of Finite Element Analysis*

Unistrut Support: Taten Knight, Adrun James

The piping network is designed to be supported from the ground with Unistrut. Utilizing the CFD explained earlier, the volume of water in the rig was calculated to be 0.1 cubic meters. Using this value, the load to support was determined using the specific weight of water at 62.4 pound-force per cubic foot. This load, and the deflection determined from the Abaqus and beam theory calculations, specified the number of supports needed and the distance between. Considering the load bearing capability of Unistrut posts and the deflection, it was decided that supports should be six feet apart. This also includes a support at each end for the respective manifold.

DESIGN SUMMARY AND SPECS: Rob Cincotta, Ashley Skoog**,** Aline Muanza, Max Dickerman, Shelbi Hrkach

General Information Rob Cincotta

To meet the primary teaching goals, the flow loop will have five parallel lines for experiments. From top to bottom: two lines of straight pipe in different materials, a line with various measurement devices and valves, a line with many fittings in series, and a line with unions for inserting specialty experiments. Initially, the specialty line will have packed bed experiments and a water hammer demonstration, but faculty can later design other units to be inserted in this line. **Figure 2** shows a model of this design from various perspectives.

These lines will be fed from, and drain to, common lines at either end of a centrifugal pump. Any of the experiment lines can be closed by valves at either end and are designed to operate individually. The bulk of the rig will be made of schedule 80 PVC pipe with a nominal diameter of 1 ½ inches. The vertical portion of the return line will be made of clear PVC with the same specs to observe the level of water while filling. The apparatus will span 20 ft of available wall space and be mounted against the wall to maximize space between the flow rig and the HVAC rig. The minor loss section will have 24 total fittings, 8 of which will be standard 90-degree elbows, another 8 will be long sweep elbows, and another 8 will be line flow through tees, with branches blocked after a few inches. Collectively, this is expected to demonstrate how the geometry of fittings effect the friction losses of the system. The metered line will demonstrate five flowmeters, from operator's left to right: a magnetic meter, a turbine flow meter, a paddlewheel meter, an orifice plate, and a vortex meter. The union section will feature two threaded unions a foot from either end of the run. The modules will need to have a compatible threaded piece and be 20 feet long to install into this section. Installation and removal of a module will likely require two people. Duplicate items of each type of meter, valve, and fitting will be cut in half and mounted as display items to demonstrate the mechanisms by which these devices work.

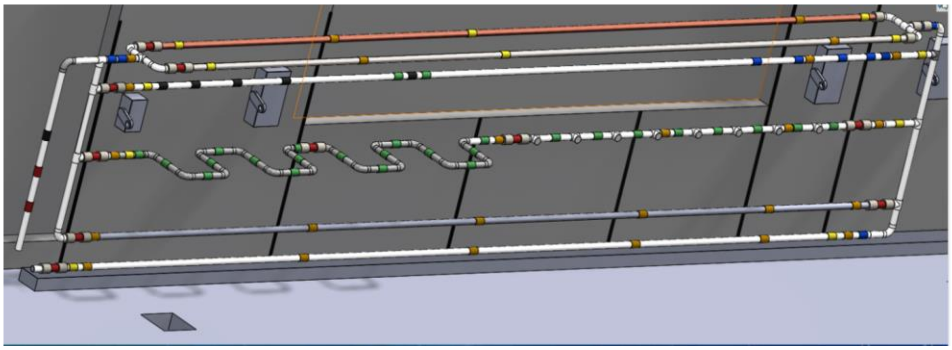


Figure 4: An isometric model made on SolidWorks to show the pipe flow rig. Inline elements are shown with colored cylinders. Red indicates throttling valves, blue is other valves, black is flow meters, yellow is analog pressure gauges, green is pressure taps, grey is unions, and orange is support mounts.

To fill and drain the apparatus, there are three taps at the bottom of the rig, one for filling the rig and two for draining the rig. There are also two additional float-operating air release valves to allow air to leave the system. The fill in section of the rig is close to the centrifugal pump on the suction line and is made to detach from the rig for service if needed. On draining, the taps at the bottom are connected to a hose and led to a drain. The valves at the top will equalize the pressure within the rig while draining. A compressed air tap is available to blow out remaining water during draining.

Pump Shelbi Hrkach

Approximate system curves of pressure drop versus flow rate for each line are plotted in **Figure 5**. The straight run system is expected to have the least resistance to flow and the lowest losses, while the elbowed run is expected to have the highest resistance and largest losses. All other lines and systems can be expected to fall somewhere between these extremes.

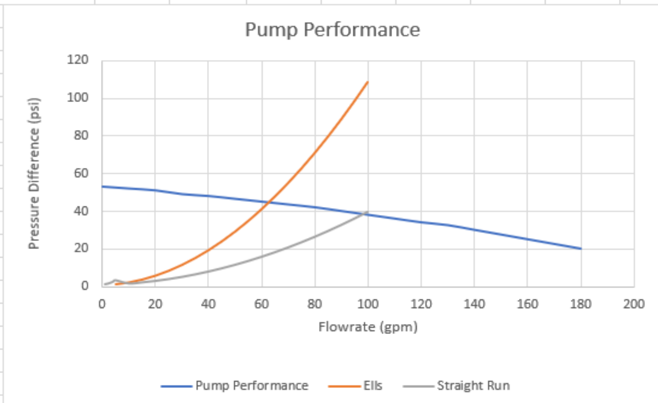


Figure 5: System curves for the flow rig operating with only the straight run open and only the ells open and operating curve for the pump. Where the pump curve intersects a system curve at the optimal operating point for that system.

The pump curve suggests that the optimal flow rate for the elbow section is about 60 gpm, and the optimal flow rate for the ells section is about 100 gpm. For this application; it is not, however, imperative that the pump operate at mechanically optimal points, so faculty are not limited to these rates in their curriculum design.

To meet the needs of this setup, a 5-horsepower pump, provided by Dr. Dellenback, will be used. The pump is manufactured by Baldor-Reliance and comes with a comprehensive list of parts and schematic. Should repair or replacement of any components be required, this information is available in the product information packet. Additionally, while this specific pump is no longer available for purchase through Baldor-Reliance, all this information is still available at www.baldor.com under the product number 36F972-106.

When either the straight or metered runs are operated individually, the pump will perform more than adequately. Even at a flowrate of 100 gallons per minute (gpm) in the straight run of PVC the total pressure drop is 39.42 psi, which is within the operating curve of this pump (Figure 5). The elbowed run will be less accommodated. With only the elbowed run open, running the pump at 100 gpm causes a pressure drop of 108.44 psi, which is above the pump's operating curve. For best performance, when the elbowed run is open, the pump should be operating below 50 gpm. It would be sensible to add this caveat to any lab instructions, perhaps including a graphical explanation.

To control the pump precisely and to reduce energy costs, a compatible VFD will also be included in this setup. The given pump requires a 3-phase input and is dual rated for 230 and 460 volts. Assuming a

10% range (a typical range for motors), this allows for 207-253 and 414-506 volts for corresponding 11.5 and 5.7 amps, respectively. Power on site is available as single phase at 30 amps and 250V. An AC Tech VFD was selected with the aid of Mr. Victor Bershinsky. It is the same brand as the VFD used by Mr. Lawrence Willey for his HVAC laboratory, and is proven to be a reliable piece of equipment. Additionally, there will be compatible power supply for Mr. Willey's VFD in the room, and therefore compatible for this VFD.

Cavitation Ashley Skoog

Suction cavitation will be used to demonstrate the cavitation within the centrifugal pump. The centrifugal pump will not need an acrylic housing, because the vapor bubbles forming in the pump will not visible to the naked eye. A valve will be added to starve the pump of fluid upstream from the suction line. As the pump runs, the valve will be closed, starving the pump of fluid. A rotameter will be placed on the discharge line of the pump, to observe the fluctuation of the flow form the pump. **Table** 4 shows the volumetric flow, velocity at a diameter 4 inches for the suction line (v_2), the velocity at diameter 2.5 inches of the suction line (v_1), pressure coefficient at minimum pressure ($C_{p,min}$), and cavitation number (σ) using Equations 5 through 8. As the cavitation number gets to zero, the closer the pressure of the fluid flow is to the vapor pressure. Using **Table** 4, volumetric flow rates of 40 to 65 gpm would be used to produce cavitation.

Table 4. Determining which volumetric flow rate would potentially produce cavitation.

Q (gpm)	V_2 (ft/s)	V_1 (ft/s)	$C_{p,min}$ (psi-ft/lbm-s^2)	$P_{1,cav}$ (psi)	σ (dimensionless)
15	0.38	0.98	-33.2	995	33.2
20	0.51	1.31	-18.6	995	18.6
25	0.64	1.63	-11.9	995	11.9
30	0.77	1.96	-8.29	995	8.29
35	0.89	2.29	-6.09	995	6.09
40	1.02	2.61	-4.66	995	4.66
45	1.15	2.94	-3.68	995	3.68
50	1.28	3.27	-2.98	995	2.98
55	1.40	3.59	-2.47	995	2.47
60	1.53	3.92	-2.07	995	2.07

Packed Bed Aline Muanza

For this project, a series of three packed column is designed to show flow through different types of packing material. The three packed bed will be aligned in series. The first packed column will be filled with marbles of 0.55 inches each. The second column will be filled with golf balls of 1.5 inches each, and the third column will be left empty to allow future modifications. The choice for packing material was made to allow comparison of flow between particles of different diameter, but same geometry. Because water is flowing through the columns, the packing material will be plastic and marble to avoid any rust that can be formed over time. The columns will be three feet long with a two inches diameter. The packed bed is made of schedule 80 clear PVC pipe. A clear pipe was chosen to be able to see packing material inside the pipe and estimate the packing length.

Table 5 shows a sample calculations for the pressure drop through the marbles and through golf balls. The flowrate ranges from 15 gallons per minutes (GPM) to 65 GPM. The flowrate range was estimated based on the pump characteristics. The pressure drop is calculated using the Ergun equation mentioned above and varies from 0.41 psi at the lowest flowrate to 1.77 psi at the highest for a laminar flow of marbles.

Table 5. Pressure drop, Velocity and Flowrate in the Packed Bed section.

Flowrate(gpm)	Superficial velocity(ft/s)	Pressure drop (Pa)	Pressure drop(psi)
15	1.53	2818.64	0.41
20	2.04	3758.19	0.55
25	2.55	4697.74	0.68
30	3.06	5637.29	0.82
35	3.57	6576.84	0.95
40	4.09	7516.38	1.09
45	4.60	8455.93	1.23
50	5.11	9395.48	1.36
55	5.62	10335.03	1.50
60	6.13	11274.58	1.64
65	6.64	12214.12	1.77

Orifice Plates Max Dickerman

A beta ratio of 0.7 was picked for the loop's orifice plate as Results of orifice plate calculations with different beta values are reported in tables 9 through 13 of appendix A.1. Orifice plates with beta values from 0.3 to 0.7 are being considered given the capability of the flow rig's differential pressure sensor (0 to 100 psid). However, it is worth noting for an orifice plate with a beta ratio of 0.3, the sensor will not be able to make telemetry readings on flowrates towards the upper bound of the rig's flow regime (via linear interpolation, 44.4 to 50 gpm.

When the Reynolds number through the orifice plate is greater than 30,000, a common heuristic is to approximate the discharge coefficient as 0.61 (Brown et al.). For future calculations, refined discharge coefficient values will be used as per ASME MFC 14M (Measurement of Fluid Flow Using Small Bore Precision Orifice Meters) standards.

Instrumentation Max Dickerman

Due to maintenance concerns, the EERB flow loop will not include the fully functioning differential pressure cell initially intended. During the 2018 fall semester, the logistics of a differential pressure manifold had not fully been thought out and if/when Node-red software needs to be updated individuals willing to maintain this differential pressure cell were not identified. In its stead, differential pressure is to be measured using either of Dwyer's Series 4000 Capsuhelic (i.e. Magnehilic) Differential Pressure Gage or Series PTGD Differential Pressure Piston-Type gage as these gages are rugged and require minimal upkeep.

The use of magnehilic differential pressure gages was first suggested by Mr. Scott Morton during the first design meeting of the 2019 spring semester while the use of "pointer follower" two needle differential pressure pistons was suggested by Prof. Willey during the last design meeting of the 2018 fall semester. In the P&ID, Appendix D.1, the differential pressure magnehilic gages are represented as PID001 thru PID003 and PID005 thru PID010. The single differential pressure piston gage included in the rig – as Dwyer's magnehilic gages are more economical – is represented as PID004 in the P&ID of the appendices. Differential pressure gages PID001 and PID010 are positioned to measure the pressure drop across the loop's orifice plate flowmeter. Magnehilic gage PID001 was sized by first deciding which orifice plate to include with the flow loop then iterating equation nine over an appreciable flow regime. The results of this iteration are depicted in **Figure 6**.

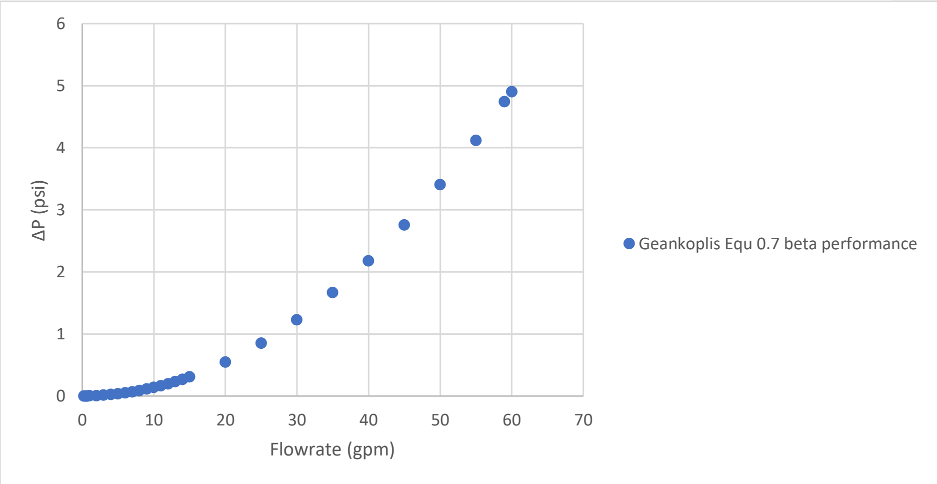


Figure 6. The pressure drop versus flow regime within the range of gauge PID001.

Differential pressure gauges PID003 thru PID005 were sized by determining the pressure drop across eight of each of the following fittings - short radius ell, long radius ell, stubbed off tee – and segments of twelve-inch length of schedule 80 pvc used to connect these fittings in series.

Water Hammer Ashley Skoog

A pneumatic ball valve using air supplied from the building to close the valve significantly fast to produce the pressure surge for the water hammer. In Appendix A.1 Table 14, the larger the nominal pipe the slower the wave speed. Overall, the wave speeds for all five material types are still high, making it hard to measure the pressure change in a split second, hence the pressure gauge picked was a pointer-test gauge to show the significant change in pressure. Figures 7 through 9 shows pressure surges of different material and mounting structures for each nominal diameter (1-, 1.5-, and 2-inches) using one designated mounting structure (Case 2). The reason why the pressure surges are negative numbers is due to having the surge go in the opposite direction of the flow. In all three figures (7-9), the wave speed is considerably higher in the metal pipes than plastic pipes. This shows how significantly different types of material could affect the results. As a safety precaution any pressure greater than 400 psi will be ruled out for safety constraints. Polyethylene has a hard time being in direct sunlight, therefore it won't be used as material in the flow system due to half of the wall is filled with windows. If we use a Schedule 40 PVC pipe, the flow rate would be constricted to 35 gpm due to maximum pressure of 170 psi for 1.5-inch nominal and 140 psi for 1-inch nominal. If we use Schedule 80, the maximum pressure would increase into the 200-psi range, this allows more of a flow rate within the section. Looking at Figures 7 through 9, one can notice that a 2-inch nominal PVC pipe will have lower pressure than other nominal PVC pipes, hence why we are using a 2-inch nominal PVC pipe. of pressure surges. Clear Schedule 80 PVC nipples will be installed to be able to see how much air is in the air arrestor (vertical section) and since it is threaded be able to replace once the pipe becomes foggy, see P&ID in Appendix D.1. The fittings that are connecting in the air arrestor will be grey Schedule 80 fittings. A pressure relief valve will be located between an elbow and the air arrestor to make sure no fittings will pop off from unexpected high pressures. In Appendix Table 14, shows the resulting force on a 90° bend elbow. In a 2-inch nominal pipe the largest resulting force is 1.518 pounds per force (lbf). Extra precautions will be made even though the force on the elbow is low, where the pipes will be threaded and not glued.

Commented [AS1]: Find out where the P&ID will go

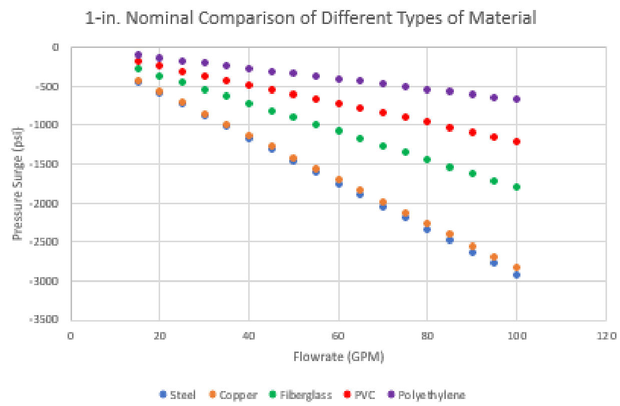


Figure 7: Comparison of different 1-inch nominal materials that produce pressure surges at different flow rates.

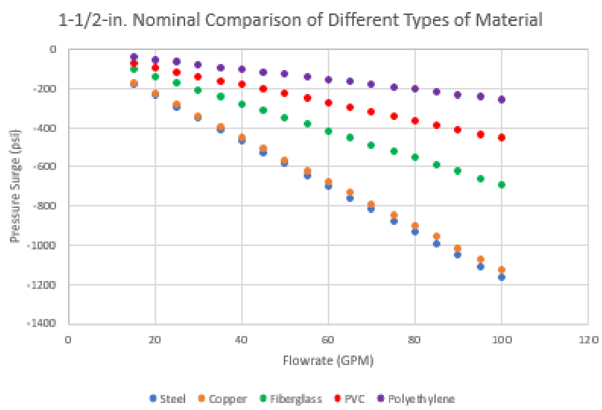


Figure 8: Comparison of different 1-1/2-inch nominal materials that produce pressure surges at different flow rates.

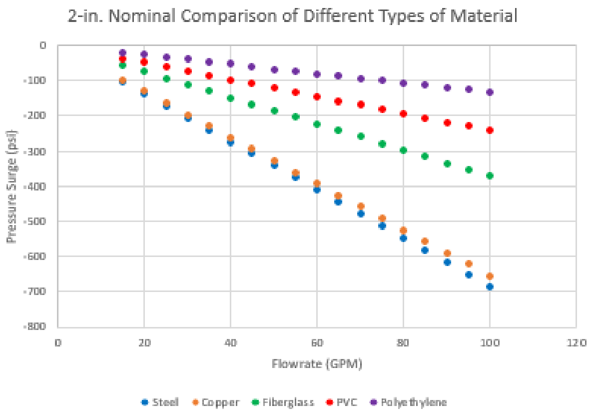


Figure 9: Comparison of different 2-inch nominal materials that produce pressure surges at different flow rates.

The professors wanted to show pipes moving and the loud banging noise in the water hammer demo. Therefore, the water hammer should include those features, but also include a conservative. The first section of the water hammer includes the pneumatic ball valve (PV001), PVC pipe, and pointer test gauges placed every 5 ft. in a 15 ft distance. The second section of the water hammer section includes a clear PVC vertical pipe designed similar to an air chamber but includes an adjustable air cushion. The conservative option includes an adjustable air cushion, where 75% of the 18-inch long vertical pipe can be used as an air cushion to absorb the kinetic energy of the shock wave by using a Schrader air valve (HV021) and a ball valve (HV020) for water drainage. Another ball valve (HV019) is positioned below the drain valve in the 18-inch long vertical pipe to allow adjustments to the air cushion when the centrifugal pump is still running. Stated above, a pressure relief valve (HV018) will be added to be conservative of the pressure surge if someone was not paying attention to the flow rate of the pump. See Appendix D.1 to further look at the water hammer section on the P&ID.

Commented [AS2]: Location of P&ID?

DESIGN ALTERNATIVES: Aline Muanza, Max Dickerman

Most packed beds have vertical orientation, but for this project, a horizontal orientation was chosen to avoid any length limitation between the second and the third run of the loop. The third packed bed is left empty to allow any design alternatives needed at the time of the experiment will be conducted. The size of the packing material is another design alternative that was considered. Calculations show that the bigger the diameter of the packing material, the lower the pressure drop can be obtained. At first, different type of rasching rings were being considered for packing material. Unfortunately, those ideas were rejected due to a lack of resources and contact from different manufacturers. Marbles and golf balls were chosen because of their easy access and their spherical shape. Using spherical particles allows a more accurate use of the Ergun equation. Another alternative design includes the water hammer demonstration. In this demonstration, multiple designs can be implemented so that the pump doesn't deadhead when the ball valve closes. The first design includes another loop (straight-run loop) running at the same time as the water hammer loop. Downfall using this design will downscale volumetric flow rates since two both runs at the same time. Other pressure release valves can be considered for more damping of the pressure surge

At the second progress report presentation, it was proposed to use handheld differential pressure gauges that students would connect to pressure taps across pipe fittings and flowmeters to determine pressure drops. This idea was scratched due to the possibility of misplacement or theft of these differential gauges. The advantage of the handheld differential pressure gauges proposed were they would force students to walk along the flow rig and manually attach the gauge across fittings, and flowmeters. The price range of the differential pressure instruments proposed at the meeting was $567 to $1245. Given the propensity of young adults to be distracted, misplace, or accidently walk away with equipment, project mentors proposed including a differential pressure manifold instead. A differential pressure manifold is both a more cost-effective means to acquire differential pressure readings and allows for automated designs to be incorporated with the flow rig. A problem to be addressed early next semester problem is how to make the differential pressure manifold more interactive for lab students (current design of the manifold in the civil engineering flow loop only allows for one operator while accompanying lab partners simply watch the differential pressure readout on a monitor). This issue will in part be address using Legris's quick connect pressure taps and adequate lengths of 0.375" inch tubing that will allow lab students not operating the differential pressure manifold the flexibility and ease to attach the lines to pressure taps at various locations on the flow rig.

INTERNATIONAL CODES AND REQUIREMENTS: Shelbi Hrkach

The International Code Council has created a set of official statements regarding the construction of new facilities and the upkeep of existing facilities. These codes provide a minimum standard that serve to protect the health, safety, and welfare of the people who use such facilities. In addition to building codes, there are codes which address plumbing, fire safety, and fuel gas. There are more codes provided by the International Code Council (ICC), but they are not all applicable to our construction. The Americans with Disabilities Act (ADA) also implements its own requirements, which are designed to ensure access to the facility for people with disabilities. The rig designed in this project is subject to both these standards. Finally, to minimize hazards and further protect the individuals using this rig, OSHA's Laboratory Safety Guidance manual is used to structure safety features for this project. Compliance with these regulations extends beyond legal requirement; to protect the safety of the students and faculty involved in this lab and to provide the most effective learning environment, adherence to these guides is key.

Wet Lab

By the definition provided by Whole Building Design Guide (WBDG), the space to be used is considered a "Wet Laboratory", so it may be necessary accommodate this in the EERB space. It may be necessary to add a protective coating to surfaces surrounding the rig, such that the immediate area is water resistant (WBDG 2019). Should there be humidity or temperature-sensitive instrumentation or devices in the room, the extra water present may cause equipment to malfunction or to become damaged. It may be necessary to adjust the heating, ventilation, and air conditioning (HVAC) supplied to the room to account for this. WBDG also mentions ADA accommodations that may be necessary to comply with government standards.

ADA Requirements

While the general ADA regulations apply to this facility and rig, there may be other accommodations to consider. The EERB will, no doubt, be built in accordance with these general rules, so there is no need to further discuss them here. According to the 2010 ADA Standards, "An alteration that decreases or has the effect of decreasing the accessibility of a building or facility below the requirements for new construction at the time of the alteration is prohibited." This project, therefore, falls under the scope of the 2010 ADA Standards, so it is necessary, for safety reasons, to consider the path of wheelchair access to and from the rig. The IBC also requires a "means of egress", which would facilitate a timely evacuation from the facility (ICC, 2017). To meet both standards, coordination with the other lab units in the room is imperative to ensure a clear, adequate path for quick access to and from the rig. Chapter 3, of the ADA Standards outlines the minimum requirements for path dimensions: "The clear floor or ground space shall be 30 inches (760 mm) minimum by 48 inches (1220 mm) minimum." (Department of Justice, 2010) Based on the dimensions we have been given, it may be necessary for the HVAC unit to be moved away from the fluids lab rig, as at present there is only a 24 inch gap allowed. The fluids lab rig is already planned to be against the rear wall, so moving that to create more space is infeasible.

The rig itself must, by law, be accessible to persons with disabilities. This may include having handles, controls of valves, and at least some instrument readouts at wheelchair-height. Due to the overall height of rig, it is not possible for all readouts and valve controls to be accessible. For this rig, the setup is defined as "unobstructed", for which there is a maximum allowable height of 48 inches (1220 mm) from the floor, and a minimum 15 inches (380 mm) from the floor for forward reach (Department of Justice, 2010). The required heights are the same for side reach. There will be at least one flow run that meets these criteria. To ensure total compliance, it is best to choose lower valves such that they meet the requirements of 309.4 of the 2010 ADA Standards: "Operable parts shall be operable with one hand and shall not require tight grasping, pinching, or twisting of the wrist. The force required to activate operable parts shall be 5 pounds (22.2 N) maximum." Valves meeting these criteria should be installed as exclusively as possible at these accessible heights. It does not seem possible to fit all runs to this standard, but because there will be available operable parts within this range, the rig should be considered ADA compliant in this regard.

International Building Code

According to the Wyoming State Fire Marshal, Wyoming has adopted the 2018 International Building Code (IBC), 2018 International Fire Code (IFC), and the 2018 International Mechanical Code (IMC). Additionally, the State Fire Marshal is listed as the building official, indicated in the 2018 International Building Code as the enforcing authority. It is possible for the building official (or an approved agency) to conduct an inspection of the facility at any time. For the sake of maintaining uninterrupted operations and the health and safety of the occupants, the codes put forth by the ICC and adopted by the state of Wyoming should therefore be carefully considered in construction. As there are no hazardous emissions expected with this rig and the only substance involved is water, it is not necessary to obtain a permit.

Most prominently, the fluids lab rig may impact means of egress, or evacuation path. Due to the water involved in this lab, it may be necessary to supply a slip-resistant surface on the exit path, in accordance with Chapter 10, 1003.4 of the IBC. This could be simply in the form of non-slip mats like those used in commercial kitchens. It is possible the passage between the HVAC lab and the fluids lab setups will need to be widened, as it is currently only at 24 inches. According to the IBC, for means of egress, this gap is not required to exceed 28 inches. For ADA purposes, however, this gap may need to greater.

OSHA

Standards set by the Occupational Safety and Health Administration (OSHA) must also be considered. The Laboratory Safety Guidance manual was used as a reference for these standards. With any laboratory environment, it is always required that appropriate personal protective equipment (PPE) be used (OSHA, 2011). There is no known chemical danger, as the only substance involved is water, but there is the possibility of flying debris should any components of the rig become compromised. Therefore, it is the recommendation of this project's members that protective eyewear (safety glasses or goggles), headwear (hard hats), and possibly ear protection (ear plugs or ear muffs) be the minimum requirement. The final determination of what is appropriate, however, is ultimately up to the administration of this department.

In accordance with OSHA's "Hierarchy of Controls", the hazards of this lab were minimized considering engineering controls, administrative controls, work practices, and PPE (OSHA, 2011). Engineering controls are defined as controls that "involve making changes to the work environment to reduce work-related hazards" (OSHA, 2011). Various safeguards are designed to be integral to the lab, such as a surge tank, a mounting system to act as a shock absorber (to be mentioned in more detail later), and a pressure relief valve. The Administrative controls are expected in the designing of lab procedures, which is beyond the scope of this project's tasks. As mentioned, the only substance to be used is water, which negates risk of chemical burns or injury during this lab, which is classified under the third measure of Work Practices. Finally, PPE is recommended based on the specific nature of the designed environment and is expected to be used in addition to whatever minimum requirement is assigned to the room. While these steps may not entirely negate the risks associated with this lab, compliance with these recommendations will minimize hazards.

Noise exposure may be a hazard associated with this lab. While it is currently unknown what level of noise is emitted by the pump, it is necessary to test this before making a final determination on what PPE is appropriate. While it is unlikely, if the pump emits noise levels greater than 85 dBA, it will be the recommendation that all those in the laboratory room be equipped with hearing protection (OSHA, 2011).

The wiring of equipment for this rig will be handled by the University of Wyoming ("qualified persons" as defined by OSHA) but is worth noting as a possible source of hazard due to the proximity of electrical equipment and water.

Lockout/Tagout

OSHA also recommends a procedure called "Lockout/Tagout", which prevents injury to those performing service or maintenance on equipment related to power supplied to such equipment. Lockout/Tagout "requires the adoption and implementation of practices and procedures to shut down equipment, isolate it from its energy source(s), and prevent the release of potentially hazardous energy while maintenance and servicing activities are being performed" (OSHA 2011). It is the duty of the administrators to finalize a lockout/tagout procedure specific to the pump, but there are steps relevant to the building of this rig. This procedure should ensure that, should power be supplied to the rig, those performing maintenance are aware (OSHA 2011). Electrical equipment should not be supplied power while construction is underway, unless a qualified person is performing maintenance and deems it unnecessary to disconnect. While students are handling the pump during construction, however, it should always be disconnected.

SAFETY AND RISK MANAGEMENT: Aline Muanza, Ashley Skoog, Taten Knight, Adrun James

Water is the main compound flowing through the rig. As a result, chemical safety was not a major concern with this design. We did use PVC cement glue and primer, where they are highly flammable when they are in liquid and vapor form. Therefore, storage of PVC primer and cement glue should be placed away from heat, sparks, open flames, and hot surfaces in a well-ventilated place. These containers need to be tightly closed so that mist or vapors are not inhaled since they are harmful to humans. Make sure to use the PVC primer and cement glue outside or in a well-ventilated area with eye protection on.

However, pump cavitation, the packed bed and the water hammer section raised a couple of safety concerns to consider. In the centrifugal pump, the main safety concern to consider is the cavitation of the pump. The section where the centrifugal pump cavitates is another safety constraint that deals with low NPSH at short intervals of running time for the pump, if not the pump will not function properly (short life) and produce high levels of noise pollution. The water hammer section deals with pressure surges that can produce jumping pipes. To allow the jumps of pipes to occur, a specific mounting system (leeway mounting near the ball valve, surge arrestor, and pressure release valve) will be installed. The water hammer section also deals with an elbow upstream of the air arrestor. A pressure relief valve will be put into place so that 5 psi below maximum pressure of the elbow will not pop off, drainage of water will go to the drains at the bottom of the rig. Utility failure could happen in the VFD, centrifugal pump, air lines, and water lines. Temperature can be a concern if low speeds and valves remain shut in the VFD causing the VFD to overheat or deadhead the pump. See HAZOP in Appendix C.1 to see further explanation on cavitation, water hammer, VFD, pump, and utilities added to the rig.

In addition to the HAZOP evaluation, a Failure Mode and Effects Analysis (FMEA) was completed. The FMEA table allows a team to identify high risk failure modes associated with individual aspects of the project. The risk value is the multiple of three risk criteria: severity, occurrence, and detection. Severity is the overall effect of the failure on the system, occurrence is the likelihood of failure, and detection is the ability to detect the issue prior to the negative effects. Each is scored from 1-10, indicating a maximum Risk Priority Number (RPN) of 1000. In **Table 6** on the following page is the FMEA table for the Flow Loop, followed by a description of the ranking system.

Table 6. FMEA Charts and Description

Failure Mode and Effect Analysis: EERB Flow Loop

Item	Item	Description	Function	Potential Failure Mode
1	PVC Pipe	PVC piping for water flow	Water path	Rupture
2	Centrifugal Pipe	Main centrifugal pipe	Pump water throughout apparatus	Motor Failure
3	Fittings	Tees, Ells, Reducer, Coupler, Union, etc.	Connects piping	Rupture
4	Pressure Gauges	Analog Pressure Gauges	Determines pressure in various runs	Null Reading
5	Demonstrative Valves	Ball, Globe, Butterfly, Gate, Diaphragm	Demonstrative valves for student exposure	Loss of Seal
6	Float Operated Air Release Valve(s)	Alert for when rig is full and pressurized	Pops open at specified pressure	Sticking
7	Check Valve	Check valve at run 2 end	Prevents back-flow into run 2	Loss of Seal
8	Unistrut Supports	Support structure for piping	Holds entire rig upright	Base fracture and exit
9	Waterhammer Section	Run for demonstration of waterhammer	Demonstration of waterhammer	Large Pressure Wave
10	Demonstrative Meters	Magnetic, Turbine, Paddlewheel, Orfice, Vortex	Demonstrative meters for student exposure	Bad readings

Failure Mode and Effect Analysis: EERB Flow Loop (2)

Item	Potential Effects of Failure	Severity (S) 1-10	Potential Causes of Failure	Occurrence Rating (O) 1-10	Current Process Controls	Detection Rating (D) 1-10	Risk Priority Number (RPN)
1	Large water loss. Exposure to electricity.	9	Over-pressurization	1	Pressure Gauges	2	18
2	Apparatus shutdown -Long Term	8	Winding wear	1	~	9	72
3	Large water loss. Exposure to electricity.	9	Over-pressurization	1	Pressure Gauges	2	18
4	Unknown pressure in single area	2	Over-pressurization, Vibration	2	Other Gauges	1	4
5	Loss of demonstration value	5	Long-term use	2	~	3	30
6	Rig is over-pressurized	4	Manufacturing tolerance	1	Pressure Gauges	1	4
7	Back-flow in run 2	1	Seal wear	1	~	1	1
8	Rig falls over	9	Vibration, Poor initial setting	1	Proper setting	8	72
9	Large water loss. Exposure to electricity.	9	Miscalculation of pressure spike	1	Inspection	4	36
10	Loss of demonstration value	5	Long-term use	2	~	3	30

	Severity Scale	Occurrence Scale	Detection Scale
10	Case 9 + Possible Injury	Failure Is Inevitable	Undetectable
9	Catastrophic Destruction (Not able to Use Again)	More than once every 3-4 days	Very Remote chance of Detection
8	Lose of Primary Functions	Once Every Week	Found with Detailed Inspection
7	Reduced Primary Function	Once Per Month	Found With Inspection
6	Lose of Secondary Fucntion	Once every three months	Found By Noise
5	Reduced Secondary Function	Once Per Year	Found By Noise and Smell
4	Minor Defect Easily Found	Once Every 1-3 Years	Found By Noise, Smell
3	Minor Defect Moderatly Found	Once Evey 3-6 Years	High Chance of Detection Without Inspection
2	Minor Defect (Scratched Part)	Once Every 6-9 Years	Very High Chance of Detection Without Inspection
1	No Effects	Once Every Freak Occurance	Everybody and their Grandma Could See that

PROJECT ECONOMICS Rob Cincotta

The Ellbogen Foundation granted this project a budget of $50,000 for parts and construction and an additional $4,000 for utilities and parts during the debugging and tuning of the final product. Price estimates for the construction of the rig assume that all parts are ordered online and shipped to the university. The rig is estimated to cost about $18,500. The largest expense for this design is measurement devices, totaling about $4,600 for flowmeters and $2,300 for pressure gauges. Valves are estimated to cost about $4,500. Fittings cost about $1,000 and pipe about $115. The costs for both modular experiments were assessed separately from the rest of the rig and found to be $1,300 and 1,900 for the water hammer and packed bed demonstrations respectively. The support structure is estimated to cost $1,500. An existing pump and some existing valves and fittings, given to the project at no cost by Dr. Dellenbach, are used in this design. If these items become unavailable, the cost could be covered in the remaining budget. A detailed, itemized budget can be found in appendix B.1.

Even with unforeseen expenses up to 50% of the total estimated cost, this project should be within the allotted budget. If the faculty is interested in other modifications or specialty experiments, these items could be covered in the excess budget, but time constraints prevent new suggestions from being implemented within the deadline. Sufficient wall space and budget remains that faculty can construct other apparatuses independent of the flow rig project if desired.

Assuming the apparatus is run for four hours per week (two hours per lab group, two lab groups a week) year-round, the pump can be expected to run at about 4200 hours over its lifetime. If running at its full capacity of 5hp, this device will require 3.728 kW to run, and will use 447.4 kWh/yr. At 12.23 cents/kWh, the rig will cost about $55 a year to run. This is a conservative estimate as electricity prices tend to be lower in the spring and summer, the rig may not be used by two lab groups a week over the summer or winter, and the pump will not be run at its full capacity for all experiments. Pumps and VFDs are reactive loads and will have a low power factor. If the university is charged for apparent power instead of real power this price may be higher; however, because the device has a short runtime, the additional cost associated with a low power factors are negligible.

For each time the apparatus is filled, about 2 cubic feet of water is needed. Assuming the apparatus is filled only once per term (4 times per year) and water costs $4.05/1000 gallons, the apparatus will cost 24.24 cents/year to fill. Assuming filling and draining each lab period, the annual cost becomes $6.30/year and the annual consumption becomes 208 cubic feet (about 1500 gallons).

Accompanying each lab group, at least one graduate assistant or faculty member is required. While an annual cost of staffing the apparatus can be approximated, it is important to note that faculty salaries and graduate stipends are usually assessed on an annual basis. Since teaching and grading are already considered among faculty and graduate assistant job duties, the apparatus would only increase the universities staffing cost if an employee regularly claims paid overtime for watching the apparatus or if a new employee is hired because of the apparatus. Neither of these cases are a foreseeable response to an additional workload of four hours a week. An opportunity cost may be associated with the time spent staffing the apparatus, but it is difficult to quantify the marginal value of this time because of the variety functions faculty perform, large and variable amount of time required to make a new publication or research proposal, and the complexity of funding systems for research and publications.

GLOBAL IMPACTS Aline Muanza, Rob Cincotta

This project is expected to improve the ability of engineering students to learn, understand, and experiment with fluid mechanics. The apparatus is expected to state-of-the-art and should be comparable to lab equipment at more expensive and prestigious institutions, like Colorado State University. In addition to use as a teaching laboratory apparatus, the flow rig may also be used as a demonstration to prospective engineering students. With above considerations, this apparatus is hoped to increase enrollment at the University of Wyoming and improve outcomes for engineering students. However, no market research or surveying has been conducted by the design team, and its global impact on the higher education and engineering professional markets is unknown.

Since the entire project budget was given to the university by a benefactor, and because less than 40% of the budget is being used, the initial capital cost of the flow rig will not have an impact on the university, state, or federal finances. Similarly, the upkeep costs are very small compared the universities total upkeep and are unlikely to increase the amount of funding the university needs from the state and federal governments each year.

Overall, this apparatus is unlikely to significantly change the university’s environmental impact because the rig’s annual utility consumption is small. All materials used in the flow rig apparatus are common in domestic plumbing, so it is expected the Laramie water treatment plant will be able to process water from the flow rig to their current standards.

CONCLUSIONS AND RECOMMENDATIONS

Cavitation Ashley Skoog

A 2-inch globe valve will be used to starve the pump of liquid at a higher volumetric flow rate. To be able to see if the pump is cavitating, a rotameter is placed at the discharge side of the pump. The rotameter will fall to a lower speed when cavitation will occur. Recommend that pressure gauges will be placed at the inlet and outlet of the centrifugal pump to see vacuum occurring in the suction line and a decrease in pressure in the discharge line for further understanding what cavitation does in a pump. Recommend using 40 to 60 gpm for a better chance of cavitating the pump.

Packed bed Aline Muanza

For the packed bed, all calculations have been finalized. A detailed calculation of both packing materials is shown in the excel sheet on the appendix section. Therefore, design alternatives such as the increase of the column diameter will be considered. Because the bed will be in a horizontal orientation, particles could move in the column. That is why wool mesh will be considered to help particles from sliding the column and possibly damage the pump.

Instrumentation Max Dickerman

Despite being decided upon late in the semester, including automated designs - such as pressure sensors - ran on affordable, open-source computer hardware will ultimately make this flow rig more intriguing for more demographics of undergraduates. Computer science and electrical engineering students with little to no interest in fluid mechanics now have a reason to care about the construction of this flow rig! Since programming can be daunting to individuals with limited exposure to it, imploring the help of both intelligent, capable teammates and staff at the Information Technology center on campus is recommended.

Water Hammer Ashley Skoog

Safety measures were the main concern for this section, therefore higher wave speeds and pressure surges were snipped from the design. Lower wave speeds and pressure surges were shown in PVC and polyethylene pipe material. Polyethylene material were snipped from the design, since polyethylene material can biodegrade from sunlight and half of our rig will get direct sunlight. A 2-inch Schedule 80 PVC pipe was determined to be the best suited nominal diameter. There are 4 different valves in this section: ball valve, pneumatic ball valve, Schrader air valve, and a pressure release valve. A clear 2-inch Schedule 80 PVC pipe will be used as an air chamber with an adjustable air cushion. The pipes and fittings need to be threaded instead of being glued for the air arrestor, so that foggy clear PVC nipples can be easily replaced. Pointer-Test gauges will be used to show pressure spikes from the passing pressure surge caused by the pneumatic ball valve. A pressure release valve will be placed in between an elbow and the air arrestor to make sure not damage will be done upstream of the section. Recommend that the volumetric flow rates do not go past 65 gpm in this section due to maximum pressure of the fittings.

Personal Protective Equipment/Safety Features Shelbi Hrkach

It is the recommendation of this group that, at minimum, protective eyewear and headwear be required for this lab. Pending testing the noise levels of the pump during operation, it is possible that ear protection be added to this list. To prevent damage to the surrounding structure, a protective water-resistant coating may be applied to the walls and floors surrounding the rig, and accessory HVAC accommodations may be necessary to control humidity. Some nonslip surface should be secured to the floor around the rig, providing safe exit from the room in case of emergency.

Schedule: Taten Knight, Adrun James

The project was scheduled to be a yearlong design project in conjunction with the class schedule of Senior Design I and Senior Design II (ME-4060/4076). The following is a list of dates and accomplishments to date. Not included are the dates when small weekly objectives were accomplished, such as "Pumping Power was Calculated." This has been addressed in the IOI's sent to Dr. Kilty. Also, not included below are the weekly Monday meetings conducted with the group.

Table 7. Schedule of tasks and events

Completed Events	
10/9/2018	Project Proposed by Dr. Dellenback
10/12/2018	Meeting with interested faculty in the College of Engineering. Discussed possible additions and functions to include in the apparatus.
10/30/2018	Toured and took major design measurements of the Laboratory space available for the rig
11/5/2018	Oral Progress Presentation I with mentors and professors
11/13/2018	Final measurements of the EERB lab taken to scale SOLIDWORKS computer drawing and flow simulation.
11/26/2018	Oral Progress Presentation II with mentors and professors
12/5/2018	Poster & PowerPoint presentation on progress of senior design project
12/10/2018	Design Summary Completed
4/29/2019	All Parts Ordered
5/7/2019	Begin Construction
Future Tasks	
Summer 2019	Complete Construction
Summer 2019	Complete Acceptance Testing
Fall 2019	Fit for student use

Task Assignment: Taten Knight, Adrun James

For the sake of project organization and accountability, a chart was created to assign tasks and sub-tasks to individuals. It contains the task, sub-task, intended date of completion, actual date of completion, and a short description of the main task. The completion date is highlighted based on its proximity to the intended completion date: tasks completed within 15 days of the intended date are green, between 15 and 30 days are yellow, and after 30 days are red.

Table 8. Work breakdown

Work Breakdown					
Tasks	**Sub-Tasks**	**People**	**Intended Completion Date**	**Completion Date**	**Description**
Initital Design	Solidworks Part Modeling	Adrun James	11/23/2018	11/28/2018	Initital design layout/ideas based on objectives.
		Taten Knight			
	Solidworks Assembly Modeling	Taten Knight	11/23/2018	11/28/2018	
	Water Hammer	Ashley Skoog	12/10/2018	11/23/2018	
	Packed Beds	Aline Mutembo	12/10/2018	11/24/2018	
Meeting Notes	Distribution	Ashley Skoog	Ongoing	Ongoing	Meeting notes and discussed tasks.
Hand Calculations	Unistrut Loading	Adrun James	12/10/2018	3/4/2019	Calculations for determining structural loads, minor and major losses, water hammer piping tolerances, and packed bed pressure losses.
	Pipe Pressure Losses	Rob Cincotta	12/10/2018	12/3/2018	
		Adrun James	1/28/2019	1/23/2019	
	Water Hammer	Ashley Skoog	12/10/2018	3/8/2019	
	Packed Beds	Aline Mutembo	12/10/2018	3/8/2019	
CFD Modeling	Orfice Plate Meter	Max Dickerman	12/10/2018	12/1/2018	Models for determing pressure drops across orfice plate and other runs.
	Pipe Runs	Taten Knight	12/10/2018	2/26/2019	
Semester 1 Report	Mechanical Engineering	Adrun James	12/10/2018	12/7/2018	1st Semester Progress Report and future plan.
		Taten Knight			
	Chemical Engineering	Aline Mutembo	12/10/2018	12/7/2018	
		Ashley Skoog			
		Rob Cincotta			
		Shelbi Hrkach			
		Max Dickerman			
Part Specification	Modular Run	Aline Mutembo	2/1/2019	4/8/2019	Determine the parts to be used for each run.
		Ashley Skoog			
	Remaining Runs	Max Dickerman	2/1/2019	4/8/2019	
	Unistrut	Taten Knight	2/1/2019	4/15/2019	
Part Ordering	~	Ashley Skoog	2/15/2019	4/29/2019	Quote and order all parts.
		Aline Mutembo			
Final Report	~	ALL	5/10/2019	5/9/2019	Final Design Report

FUTURE DEVELOPMENT: Rob Cincotta, Max Dickerman, Aline Muanza

Construction of the water flow rig is expected to begin the next three weeks. In preparation for this, quoting of supplies will be done by Friday April 5th, 2019. The SolidWorks model, flow simulations for the orifice plates to be manufactured, and a Piping and Instrumentation diagram (P&ID) are also being finalized in time for construction. Acceptance tests are being designed to verify that each section of the rig functions properly and to determine if debugging will be needed.

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Appendix A.1: Max Dickerman, Ashley Skoog

Table 9. Performance of an orifice plate with an orifice diameter to inside pipe diameter ratio (beta) of 0.3.

Flowrate (gpm)	Concentric hole ID (in.)	Beta	Reynolds thru pipe	Reynolds thru orifice	Cd	dP (psi)	Q_calc (gpm)	Q % error
15	0.483	0.3	29526	98420	0.61	11.43	14.43	3.82
20	0.483	0.3	39368	131227	0.61	20.3	19.23	3.87
25	0.483	0.3	49210	164034	0.61	31.7	24.02	3.9
30	0.483	0.3	59052	196840	0.61	45.62	28.82	3.92
35	0.483	0.3	68894	229647	0.61	62.08	33.62	3.94
40	0.483	0.3	78736	262454	0.61	81.06	38.42	3.95
45	0.483	0.3	88578	295260	0.61	102.58	43.22	3.96
50	0.483	0.3	98420	328067	0.61	126.62	48.02	3.97

Table 10 Performance of an orifice plate with an orifice diameter to inside pipe diameter ratio (beta) of 0.4.

Flowrate (gpm)	Concentric hole ID (in.)	Beta	Reynolds thru pipe	Reynolds thru orifice	Cd	dP (psi)	Q_calc (gpm)	Q % error
15	0.644	0.4	29526	73815	0.61	3.29	13.89	7.43
20	0.644	0.4	39368	98420	0.61	5.84	18.5	7.52
25	0.644	0.4	49210	123025	0.61	9.11	23.11	7.57
30	0.644	0.4	59052	147630	0.61	13.11	27.72	7.61
35	0.644	0.4	68894	172235	0.61	17.84	32.33	7.64
40	0.644	0.4	78736	196840	0.61	23.29	36.94	7.66
45	0.644	0.4	88578	221445	0.61	29.46	41.55	7.67
50	0.644	0.4	98420	246050	0.61	36.37	46.16	7.68

Table 11. Performance of an orifice plate with an orifice diameter to inside pipe diameter ratio (beta) of 0.5.

Flowrate (gpm)	Concentric hole ID (in.)	Beta	Reynolds thru pipe	Reynolds thru orifice	Cd	dP (psi)	Q_calc (gpm)	Q % error
15	0.805	0.5	29526	59052	0.61	1.16	13.15	12.33
20	0.805	0.5	39368	78736	0.61	2.06	17.51	12.47
25	0.805	0.5	49210	98420	0.61	3.22	21.86	12.55
30	0.805	0.5	59052	118104	0.61	4.62	26.22	12.6
35	0.805	0.5	68894	137788	0.61	6.29	30.58	12.64
40	0.805	0.5	78736	157472	0.61	8.21	34.93	12.67
45	0.805	0.5	88578	177156	0.61	10.38	39.29	12.69
50	0.805	0.5	98420	196840	0.61	12.81	43.64	12.71

Table 12. Performance of an orifice plate with an orifice diameter to inside pipe diameter ratio (beta) of 0.6.

Flowrate (gpm)	Concentric hole ID (in.)	Beta	Reynolds thru pipe	Reynolds thru orifice	Cd	dP (psi)	Q_calc (gpm)	Q % error
15	0.966	0.6	29526	49210	0.61	0.45	12.18	18.8
20	0.966	0.6	39368	65613	0.61	0.79	16.2	18.98
25	0.966	0.6	49210	82017	0.61	1.23	20.23	19.09
30	0.966	0.6	59052	98420	0.61	1.77	24.25	19.16
35	0.966	0.6	68894	114823	0.61	2.41	28.28	19.21
40	0.966	0.6	78736	131227	0.61	3.14	32.3	19.25
45	0.966	0.6	88578	147630	0.61	3.97	36.33	19.28
50	0.966	0.6	98420	164034	0.61	4.9	40.35	19.3

Table 13. Performance of an orifice plate with an orifice diameter to inside pipe diameter ratio (beta) of 0.7.

Flowrate (gpm)	Concentric hole ID (in.)	Beta	Reynolds thru pipe	Reynolds thru orifice	Cd	dP (psi)	Q_calc (gpm)	Q % error
15	1.127	0.7	29526	42180	0.61	0.17	10.91	27.28
20	1.127	0.7	39368	56240	0.61	0.3	14.5	27.5
25	1.127	0.7	49210	70300	0.61	0.46	18.09	27.63
30	1.127	0.7	59052	84360	0.61	0.67	21.68	27.72
35	1.127	0.7	68894	98420	0.61	0.91	25.28	27.78
40	1.127	0.7	78736	112480	0.61	1.18	28.87	27.83
45	1.127	0.7	88578	126540	0.61	1.5	32.46	27.86
50	1.127	0.7	98420	140600	0.61	1.84	36.05	27.89

Table 14. Calculation of wave speed at different pipe material, nominal diameter, and structure support.

Symbols	Steel			Copper			Fiberglass reinforced plastic			PVC			Polyethylene		
	1 in. Nominal pipe	1.5 in. Nominal pipe	2 in. Nominal pipe	1 in. Nominal pipe	1.5 in. Nominal pipe	2 in. Nominal pipe	1 in. Nominal pipe	1.5 in. Nominal pipe	2 in. Nominal pipe	1 in. Nominal pipe	1.5 in. Nominal pipe	2 in. Nominal pipe	1 in. Nominal pipe	1.5 in. Nominal pipe	2 in. Nominal pipe
e (m)	0.00400	0.00508	0.00476	0.00400	0.00508	0.00476	0.00400	0.00508	0.00476	0.00400	0.00508	0.00476	0.00400	0.00508	0.00476
D (m)	0.02540	0.03810	0.05080	0.02540	0.03810	0.05080	0.02540	0.03810	0.05080	0.02540	0.03810	0.05080	0.02540	0.03810	0.05080
u	0.3	0.3	0.3	0.36	0.36	0.36	0.22	0.22	0.22	0.45	0.45	0.45	0.46	0.46	0.46
ψ Case 1	1.23	1.18	1.11	1.20	1.15	1.07	1.27	1.23	1.17	1.15	1.09	1.00	1.14	1.09	1.00
ψ Case 2	1.20	1.15	1.08	1.18	1.13	1.05	1.21	1.16	1.10	1.15	1.09	1.00	1.14	1.08	0.99
ψ Case 3	1.27	1.23	1.16	1.29	1.25	1.17	1.25	1.21	1.14	1.32	1.27	1.19	1.32	1.27	1.19
E (Pa)	207700000000	207700000000	207700000000	110000000000	110000000000	110000000000	9000000000	9000000000	9000000000	2800000000	2800000000	2800000000	800000000	800000000	800000000
K (Pa)	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000	2150000000
ρ (kg/m^3) at 72˚F	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86	997.86
ρ (kg/m^3) at 40˚F	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
a using Case 1 (m/s)	1410	1403	1384	1368	1357	1326	856	818	735	571	543	483	324	306	270
a using Case 2 (m/s)	1412	1405	1386	1369	1358	1328	872	835	752	571	543	483	324	307	270
a using Case 3 (m/s)	1409	1401	1381	1361	1348	1315	862	824	741	538	509	448	302	284	248

Appendix B.1:

Item	Total Length	Cost/unit	Quantity (unit)	Cost
Pipe				
Nominal 1.5" PVC SCH 80@ 10 ft	178	$18.28	18	$329.04
Nominal 2" PVC SCH 80@ 10 ft	59	$25.44	6	$152.64
Nominal 1.5" Copper pipe @ 10 ft	30	$8.93	3	$26.79
Nominal 1.5" Galvanized Steel @ 10 ft	30	$58.99	3	$176.97
Tubing				$0.00
.25" nominal High-Density Polyethylene tubing (pressure rating 260 psi @ 73 degF)	100	$ 15.96	1	$15.96
Pipe and Tubing Total				$345.00
Fittings				$0.00
NDS socket x 1-1/2 in. Dia. 1-1/2 in. socket Union		$ 10.99	25	$274.75
NDS FPT x 1-1/2 in. Dia. 1-1/2 in. FPT Union		$ 10.99	23	$252.77
NDS Slip x 2 in. Dia. 2 in. Slip Union		$ 13.99	14	$195.86
NDS 2 in. FPT x 2 in. Dia. FPT Union		$ 13.99	6	$83.94
1.5" Scd. 80 FNPT coupling		$ 5.87	1	$5.87
1.5" Scd. 80 MNPT to Spigot adapter		$ 4.44	1	$4.44
2" x 2" PVC Nipple, Pipe Schedule 80, Gray		$ 5.56	14	$77.84
1-1/2" x Close Thread PVC Nipple, Pipe Schedule 80, Gray		$ 1.69	48	$81.12
Mag Meter fittings				
1" x 3" PVC Nipple, Pipe Schedule 80, Gray		$ 1.34	2	$2.68
1/2" x Close Thread PVC Nipple, Pipe Schedule 80, Gray		$ 0.72	2	$1.44
Turbine meter fittings				$0.00
1-1/4" x 8" PVC Nipple, Pipe Schedule 80, Gray		$ 3.71	3	$11.13
PVC Coupling, FNPT x FNPT, 1-1/4" Pipe Size		$ 5.98	3	$17.94
Reducing Bushing 1.5" MNPT x 1.25" FNPT		$ 6.50	2	$13.00
Reducing Bushings 0.75" spigot x 0.25" FNPT		$ 1.71	59	$100.89
Reducing Bushings 0.75" spigot x 0.5" FNPT		$ 1.71	2	$3.42
PVC Coupling, Socket x Socket, 1-1/2" Pipe Size		$ 6.71	3	$20.13
PVC Elbow, 90°, Socket x Socket, 1-1/2" Pipe Size		$ 4.45	18	$80.10
1-1/2" 90° Long Sweep Elbow, Hub x Hub Fitting Connection Type		$ 3.99	8	$31.92
PVC Elbow, 90°, Socket x Socket, 2" Pipe Size		$5.84	4	$23.36
PVC Tee, Socket x Socket x Socket, 1-1/2" Pipe Size		$ 14.64	10	$146.40
PVC Van-Stone Flange, Socket, 1-1/2" Pipe Size - Pipe Fitting (4 holes)		$9.60	2	$19.20
Flange Gasket -EPDM (158)			2	
Standard Butterfly Valve Bolt Kit				
LC Series Shut-Off MNPT Inline Coupler for LC and PLC Inserts		$26.39	20	$527.80
.75'' to .125'' reducing bushing Solvent x FNPT		$0.75	2	$1.50
PVC Reducing Tee, Socket x Socket x Socket, 1-1/2" x 1-1/2" x 1/2" Pipe Size - Pipe Fitting		$12.08	2	$24.16
Copper Male adapter		$14.04	2	$28.08
Copper reducing tees		$18.46	8	$147.68
Copper 0.5'' FNPT adapter		$2.62	8	$20.96
brass reducing bushings .5'' x .25''		$4.77	8	$38.16
Galvanized coupling		$13.02	3	$39.06
Pressure Taps				$0.00
PVC Reducer Tee, Socket x Socket x FNPT, 1-1/2" x 1-1/2" x 3/4" Pipe Size - Pipe Fitting **cut in half length wise will yield pvc saddles**		$ 9.03	52	$469.56
PVC Reducing Bushing, Spigot x FNPT, 3/4" x 1/4" Pipe Size - Pipe Fitting		$ 1.71	59	$100.89
In-Line Pipe Thread Insert .25'' MNPT w/shutoff valve		$ 29.78	58	$1,727.24
0.25'' Flare connections		$ 1.95	40	$78.00
MC Series Shut-Off MNPT Inline Coupler for MC and PMC Inserts		$ 24.96	22	$549.12
304 Stainless Steel Coupling, FNPT, 1/4" Pipe Size - Pipe Fitting		$ 3.15	20	$63.00
Brass reducing adapter .75'' x .5'' brass		$ 10.82	1	$10.82
PVC Reducing Bushing, MNPT x FNPT, 1-1/2" x 1" Pipe Size		$ 6.50	4	$26.00
PVC Reducing Bushing, MNPT x FNPT, 1" x 1/2" Pipe Size		$ 7.36	1	$7.36
PVC Reducer Tee, Socket x Socket x FNPT, 2" x 2" x 3/4" Pipe Size - Pipe Fitting **cut in half length wise will yield pvc saddles**		$ 13.74	7	$96.18
Fittings Total				$5,403.77
Valves				
1-1/2" Ball Valve		$ 16.99	11	$186.89
butterfly valve (4 bolts) - lever handle style, EPDM		$ 294.57	2	$589.14
three way ball valve		$ 213.75	2	$427.50
FNPT Gate Valve, Inlet to Outlet Length: 3-9/16", Pipe Size: 1-1/2", Max. Fluid Temp.: 140°F		$75.45	2	$150.90
1-1/2" Check Valve, Archetype: Single, Inline Silent, Slip x Slip		$16.48	1	$16.48
1-1/2" Male Adapter, Spigot x MNPT Fitting Connection Type for check valve		$1.74	2	$3.48
globe 1.5'' FNPT		$281.90	1	$281.90
globe 2'' FNPT			1	$0.00
1-1/2" PVC True Union Diaphragm Valve - Socket		$ 208.97	2	$417.94
Pressure reducing valve (10 to 25 psi range) and backflow preventor		$ 97.08	2	$194.16
Clean Water Air Release Valve, 1/2" Inlet Size, 1/2" Outlet Size		$ 136.99	3	$410.97
1/2" x Close Thread Chrome Plated Brass Pipe Nipple, Pipe Nipple		$ 8.65	2	$17.30
PVC Transition Adapter, FNPT x SPG, 1/2" Pipe Size - Pipe Fitting		$ 35.76	2	$71.52
PVC Reducing Bushing, Spigot x Socket, 1-1/2" x 1/2" Pipe Size - Pipe Fitting		$ 4.83	2	$9.66
Valves Total				$2,679.36
Gauges				$0.00
Magnehelic dP gauge 0-1 psid		$ 401.00	2	$802.00
Magnehelic dP gauge 0-4 psid		$ 401.00	4	$1,604.00
Magnehelic dP gauge 0-5 psid		$ 401.00	2	$802.00
Magnehelic dP gauge 0-0.5 w.c.		$ 401.00	1	$401.00
Differential Pressure Piston-Type Gauge (two needle design i.e. follower pointer) 0-5 psid		$ 486.00	1	$486.00
brackets for magnehelic gauges			10	$0.00
connections			20	$0.00
4" General Purpose Pressure Gauge, 0 to 200 psi		$ 69.35	6	$416.10
4" General Purpose Pressure Gauge, 0 to 200 psi		$ 71.96	4	$287.84
Max Pointer Test Gauge, 0-160 psi		$ 15.27	4	$61.08
Gauges Total				$4,860.02
Flowmeter				$0.00
Rotameter		$689.49	1	$689.49
Paddlewheel		$386.28	1	$386.28
Paddlewheel Cut away		$405.67	1	$405.67
Magnetic		$680.45	1	$680.45
Vortex Shedding meter		$927.00	2	$1,854.00
Orifice Plate Flowmeter				$0.00
Orifice Flanges		$ 271.43	2	$542.86
Van stone flanges for orifice to line connection		$ 17.14	2	$34.28
Neoprene gaskets for orifice flanges		$ 7.86	4	$31.44
Operating Cost ($/half hour) for both water jet and CNC machine		$40.00	1	$40.00
SS304 Steel ($/unit) where unit = 1 ft^2		$ 84.00	1	$84.00
Labor cost ($/hr)		$60.00	1	$60.00
Flowmeter Total		$184.00		$4,808.47
Waterhammer Demo				
2" x 12" Clear PVC Nipple, Thr, Schedule 80		$ 88.20	1	$88.20
2" x 3" Clear PVC Nipple, Thr, Schedule 80		$ 22.05	1	
PVC 2" Tee FNPT x FNPT x FNPT (grey color)		$ 16.56	1	$16.56
PVC Male Adapter, MNPT x Socket, 2" Pipe Size		$ 15.92	1	$15.92
PVC Transition Adapter, FNPT x SPG, 2" Pipe Size		$ 202.98	1	$202.98
PVC Socket/FNPT x Socket/FNPT Ball Valve, Lever, 2" Pipe Size		$ 53.91	4	$215.64
1/2” Black Uniseal® Pipe-to-Tank Seal		$ 1.45	2	$2.90
2" x 10 ft PVC Pipe, Pipe Schedule 80 gray		$ 25.44	3	$76.32
2" Spring Return Pneumatic Actuated Ball Valve, 3-Piece		$ 530.72	1	$530.72
2" x 3/4" Sch 80 PVC Reducing Tee - Soc x Fipt		$ 5.64	4	$22.56
3/4" x Close Thread PVC Nipple, Pipe Schedule 80, Gray		$ 0.73	4	$2.92
2" Mueller Ball Valve PVC		$ 19.99	4	$79.96
Brass Calibrated Adjustable Relief Valve, 3/4" MNPT Inlet Type, 1/2" FNPT Outlet Type		$ 32.24	1	$32.24
PVC Male Adapter, MNPT x Socket, 1/2" Pipe Size - Pipe Fitting		$ 2.56	1	$2.56
PVC Elbow, 90°, Socket x Socket, 1/2" Pipe Size - Pipe Fitting		$ 1.37	1	
1/2" x 10 ft PVC Pipe, Pipe Schedule 80		$ 6.59	1	$6.59
PVC Reducing Bushing, Spigot x Socket, 2" x 1-1/2" Pipe Size - Pipe Fitting		$ 6.32	2	$12.64
PVC Elbow, 90°, Socket x Socket, 1-1/2" Pipe Size - Pipe Fitting		$ 4.45	18	$80.10
Waterhammer Demo Total				$1,308.71
Packed Bed				
2" x 10 ft. PVC Pipe, Pipe Schedule 80, clear		$ 120.95	0	$0.00
2" x 10 ft PVC Pipe, Pipe Schedule 80 gray		$ 25.44	3	$76.32
PVC Thread Ball Valve, Tee, 2" Pipe Size		$ 78.85	4	$315.40
2" x 2" PVC Nipple, Pipe Schedule 80, Gray		$ 1.79	8	$14.32
Series SGZ 2.5" Industrial Pressure Gage (manehelic gauges - ?)		$ 401.00	3	$1,203.00
2" x 1/4" Schedule 80 PVC Tee Socket x Socket x Thread		$ 8.39	3	$25.17
14 mm marbles, 60 count		$ 12.61	1	$12.61
1.5" Golf ball packing		$ 8.99	1	$8.99
2” PVC Vent Screen (out diameter is to big for inner diameter of pipe)		$ 15.99	3	$47.97
Packed Bed Total				$1,655.81
Air Line Components (everything is in copper) <- everything at ace hardware				$0.00
Pressure Release valve		$14.99		$0.00
Ball Valve				$0.00
Copper Pipe				$0.00
90 degree Copper elbows				$0.00
copper tees				$0.00
Service Building Service (bringing air line to the west wall)				$0.00
Additional Modular Components Total				$0.00
Support Structure				
Post Base			7	$153.78
Vertical Supports (Slotted)	10		6	$119.98
Bracket			30	$692.70
Horizontal Supports	10		2	$59.20
Horizontal Supports	20		2	$59.20
Conduit Clamp			32	$29.17
Closure Strip	10		12	$332.44
Wedge Anchor			50	$150.00
End Caps			50	$60.49
Hillman 1/2 in. Dia. x 1-1/2 in. L Zinc Plated Steel Hex Bolt 50 pk	120 pieces	$26.99	3	$ 80.97
Hillman 1/2 Zinc-Plated Steel SAE Hex Nut 50 pk	120 pieces	$9.29	3	$ 27.87
Hillman Zinc-Plated Steel 1/2 in. USS Flat Washer 50 pk	240 pieces	$9.29	5	$ 46.45
$9.29				$1,658.47
Misc.				
Drip pan		$ 480.00	1	$480.00
VFD		$422.37	1	$422.37
Pump (centrifugal)			1	
Vibration pad		$ 7.54	8	$60.32
VFD mount				
Teflon tape (PTFE thread seal tape)		$ 1.49	2	$2.98
Mill Rose Blue Monster Clear All Weather Cement For PVC 8 oz.		$ 9.99	6	$59.94
Oatey Clear Primer and Cement For CPVC/PVC 32 oz.		$ 19.99	3	$59.97
DeWalt Impact Ready 1/4 in. Dia. x 3-13/64 in. L High Speed Steel Drill Bit 1/4 in. Quick-Change		$ 7.99	1	$7.99
Y Strainer		$ 166.16	1	$166.16
Eastman Steel Pre-Charged Expansion Water Tank		$37.99	1	$37.99
Misc. Total				$1,259.73
Rig Total w/o tax, shipping, or handling				$23,979.34

Appendix C.1**: Table 15** Ashley Skoog

Equipment reference and operating conditions	**Deviation from operating conditions**	**What event could cause this deviation?**	**Consequences of this deviation**	**Additional implications of this consequence**	**Process Indications**	**Notes and questions**
Centrifugal Pump	Flow					
	Less	Constriction on suction line	Pump cavitates	Damage to pump	Rotameter	What is the life of the pump? Consider a pump that can handle cavitation a little bit better than other centrifugal pumps.
	More	Rupture in suction line	Pump cavitates	Damage to pump	PI009 & PI010	Estimate release quantity
	Pressure					
	More	HV023 is closed suddenly	Deadhead Pump	Damage to pump	HV020 opens	When running the water hammer section, HV020 opens to a specific pressure (hydraulic relief).
		HV001 fails closed	Deadhead Pump	Damage to pump	PI001	Indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV003 fails closed	Deadhead Pump	Damage to pump	PI001	When running the straight-run line, indicate pressure for deadheading the pump.
		HV006 fails closed	Deadhead Pump	Damage to pump	PI001	When running the instrumentation line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV007 fails closed	Deadhead Pump	Damage to pump	PI001	When running the instrumentation line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
Equipment reference and	**Deviation from operating conditions**	**What event could cause this deviation?**	**Consequences of this deviation**	**Additional implications of this consequence**	**Process Indications**	**Notes and questions**

operating conditions						
		HV008 fails closed	Deadhead Pump	Damage to pump	PI001	When running the instrumentation line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV009 fails closed	Deadhead Pump	Damage to pump	PI001	When running the instrumentation line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV010 fails closed	Deadhead Pump	Damage to pump	PI001	When running the instrumentation line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV012 fails closed	Deadhead Pump	Damage to pump	PI001	When running the ell line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV013 fails closed	Deadhead Pump	Damage to pump	PI001	When running the ell line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV014 fails closed	Deadhead Pump	Damage to pump	PI001	When running the ell line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV015 fails closed	Deadhead Pump	Damage to pump	PI001	When running the ell line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV016 fails closed	Deadhead Pump	Damage to pump	PI001	When running the modular line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?

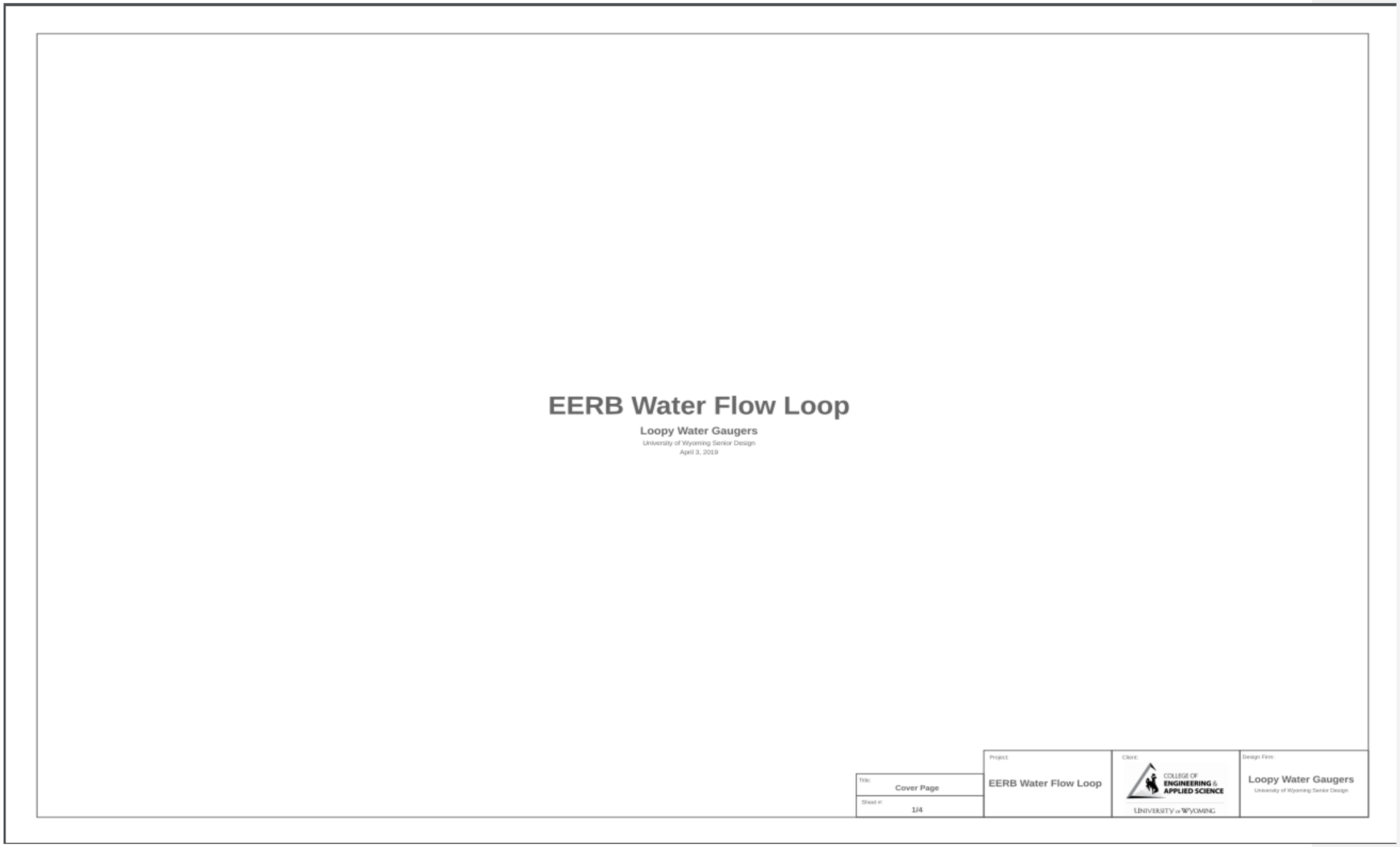
Equipment reference and operating conditions	Deviation from operating conditions	What event could cause this deviation?	Consequences of this deviation	Additional implications of this consequence	Process Indications	Notes and questions
		HV018 fails closed	Deadhead Pump	Damage to pump	PI001	When running the packed bed line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV019 fails closed	Deadhead Pump	Damage to pump	PI001	When running the packed bed line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
		HV020 fails closed	Deadhead Pump	Damage to pump	PI001	When running the packed bed line, indicate pressure for deadheading the pump. May want to include a pressure regulator before the pump?
	Less	HV004 fails closed	Pump cavitates	Damage to pump	PI010	When running the straight-run line, indicate pressure for deadheading the pump.
		HV011 fails closed	Pump cavitates	Damage to pump	PI010	When running the instrumentation line, indicate pressure for deadheading the pump.
		HV024 fails closed	Pump cavitates	Damage to pump	PI010	When running the modular line, indicate pressure for cavitating the pump.
	Utility Failure - Electrical					
	Failure	No electric power	Pump cannot operate		If lights are on and breaker closed, likely short in VFD or motor.	Have coordinator trained in servicing equipment, have extra day in semester to make up for outages.
VFD	Temperature					

Equipment reference and operating conditions	Deviation from operating conditions	What event could cause this deviation?	Consequences of this deviation	Additional implications of this consequence	Process Indications	Notes and questions
	More	Low speeds	Overheat the VFD	Bearing and insulation life will be reduced		Make sure to display the minimum speed the VFD before it shortens the life of the instrument. Have TA trained on the equipment.
	Utility Failure - Electrical					
	Failure	No electrical power	VFD cannot operate		If lights are on and breaker closed, likely short in VFD or motor.	Have clear lab instructions, have TA trained in using equipment
	Temperature					
	More	HV001 fails closed	Deadhead Pump	Damage to pump	PI001 & TI001	How much temperature is produced? Will it warp the pipes in this section?
Adding water to the Rig	Pressure					
	more	HV025 fails open	Burst of pipes	Damage the pipes	PI009, PI010, & PI012	Is there a counter measure on burst pipes? Are the electrical work on the wall FD approved?
		HV026 fails open	Burst of pipes	Damage the pipes	PI1011 & PI012	Is there a counter measure on burst pipes? Are the electrical work on the wall FD approved?
		HV027 fails open	Burst of pipes	Damage the pipes	PI011	Is there a counter measure on burst pipes? Are the electrical work on the wall FD approved?
	Utility Failure - Water					

Equipment reference and operating conditions	Deviation from operating conditions	What event could cause this deviation?	Consequences of this deviation	Additional implications of this consequence	Process Indications	Notes and questions
	Failure	Pumps are down in the building	No water added to the rig		PI011 & PI012	
	Venting					
	none	HV002 fails closed	Burst of pipes	Damage the pipes	PI's on the straight run	Is there a counter measure on burst pipes? Are the electrical work on the wall FD approved?
		HV005 fails closed	Burst of pipes	Damage the pipes	PI's on the straight run	Is there a counter measure on burst pipes? Are the electrical work on the wall FD approved?
Water Hammer Section	Draining					
	more	HV022 fails open	Drainage of Pipe	Loss of reagant	Visually see water drained in the drain	If HV022 fails, how much volume would one expect to drain out of the system when running the pump?
	none	HV022 fails closed	Water Hammer the section without any cushion for surge tank		HV020 & site glass above HV022 & PI001	Make sure the HV020 is set to ~5 psi lower than the maximum pressure of reducer fitting on the line.
	Venting					
	none	HV021 fails closed	No cushion for the surge tank		site glass above HV022	
	more	HV021 fails open	Water spewing out of vent	Shortages of Electrical power	water spewing out of the elbow	This can only occur when the pump is running and when HV022 is open (T-port, not for drainage). May want to put box, so that water does not spew on electrical boxes.

Equipment reference and operating conditions	Deviation from operating conditions	What event could cause this deviation?	Consequences of this deviation	Additional implications of this consequence	Process Indications	Notes and questions
Cavitation	Time					
	more	Pump runs too long when cavitating	Pitting starts to develop on the blades and mountings in the centrifugal pump	Overtime the pump can be rendered useless for flow rate within the rig	Rotameter	Have TA understand how long the pump can handle cavitation. Estimate the life of the pump when it is being cavitated.

Appendix D.1 : **Figure 10. Table 16.** P&ID Max Dickerman



Instrument Terminology					
	First Letter		Succeeding Leters		
	Measured or	Modifier	Readout or	Output Function	Modifier
A	Analysis		Alarm		
B	Burner		User's Choice	User's Choice	User's Choice
C	Conductivity			Control	
D	Density or Specific Gavity				Differential
E	Voltage (EMF)		Primary Element		
F	Flowrate	Ratio (Fraction)			
G	Gage (Dimensional)		Glass		
H	Hand (manually Initiated)				High
I	Current (Electrical)		Indicate		
J	Power	Scan			
K	Time or Time Schedule			Control Station	
L	Level		Light (Pilot)		Low
M	Moisture or Humidity			Control Station	
N	User's Choice		User's Choice	User's Choice	User's Choice
O	User's Choice		Orifice (Restriction)		
P	Pressure or Vacuum		Point (Test Connection)		
Q	Quantity or Event	Integrate or Totalize			
R	Radio-Activity		Record or Print		
S	Speed or Frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multi-Variable		Multi-Variable	Multi-Variable	Multi-Variable
V	Vibration			Valve, Damper, or Louver	
W	Weight or Force		Well		
X	Unclassified		Unclassified	Unclassified	Unclassified
Y	User's Choice			Relay or Compute	
Z	Position			Unclassified Final Control	

Symbol List

SC	Variable Frequency Drive		Ball Valve		Magnetic Flowmeter
FI	Flow Indicator		Butterfly Valve		Turbine Flowmeter
PI	Presure Indicator		Check Valve		Paddlewheel Flowmeter
TI	Temperature Indicator		Diaphragm Valve		Vortex Shedding Flowmeter
	Centrifugal Pump		Gate Valve		Y Strainer
	Accumulator		Globe Valve		
	Rotameter		Pressure Relief Valve		
	Orifice Plate with flanges and taps		PVC Pipe Adapter		
	Pressure Tap Saddle		Float-Operated Air Release Valve		
	PVC Union		Pressure Reducing Valve		
	Backflow Preventer		Three way ball valve		
	Pneumatic Valve		Packed Bed		
	Pressure Tap		Fuse Disconnect		
	Air compressor		Schrader Air Valve		
	0.75" Hose coupling		PVC Nipple		

Identification of Instrument Connection

	Capillary
	Electrical
	Capillary (HDPE tubing)
	.75" tubing

Instrument Control Tag Legend

PI	PI
Control Panel Mounted	Locally Mounted

Title: Legend	Project: EERB Water Flow Loop	Client: COLLEGE OF ENGINEERING & APPLIED SCIENCE, UNIVERSITY of WYOMING	Design Firm: Loopy Water Gaugers
Sheet #: 2/3			University of Wyoming Senior Design

Process Designation

Component	Description	Specifications	Component	Description	Specifications
FI001	Rotameter	Flow regime (gpm): 20 - 100 Req'd fitings: 2 - 1.5" MNPT PVC nipples	HV001	Globe Valve	Nominal Size: 1.5" Max Pressure Rating: 150 psi Connection Type: FNPT
FI002	Magnetic flowmeter	Flow regime (gpm): 0 - 110, Flow accuracy: +/- 1% between 10 & 100% of maximum flow Installation requirements: 2" upstream 1" downstream Req'd fitings: 2 - 1" MNPT PVC nipples 1.5" x 1" reducing bushings	HV002	Float-Operated Air Release Valve	Max Vent Capacity 6 scfm @ 150 psi Min Pressure: 5 psi Max Pressure: 175 psi Connection Type: 0.5"
FI003	Turbine flowmeter	Flow regime (gpm): 1 - 100, Accuracy: +/- 0.05% of reading, Installation requirements: 15" upstream and 7.5" downstream Req'd fitings: 2 - 1.5" x 1.25" reducing bushings	HV003	Ball valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
FI004	Paddlewheel	Flow regime (gpm): 10 -100 Accuracy: +/- 2.0% Installation requirements 22.5" upstream 7.5" downstream	HV004	Three way ball	Nominal Size: 1.5" Max Pressure Rating: 150 psi Port: Full L Connection Type: FNPT x FNPT x FNPT
FI005	Orifice flowmeter	Orifice Plate(s): 0.125" think 304 SS plates w/ 0.966" bore diameter Orifice Flanges: 1.5" Sch.80 PVC FLANGE, 1.5" THICK WITH 2 - 1/4" FPT SIDE TAPS, 300# DRILLING -(6.125" OD FLANGE WITH 4-.875" ø HOLES ON A 4.50" BOLT CIRCLE) Req'd fittings: 2 - 1.5" VAN STONE FLANGE WITH PVC RING PVC SCH 80 SOC, 300# DRILLING - (6.125" OD FLANGE WITH 4-.875" ø HOLES ON A 4.50" BOLT CIRCLE) 4 - 1.5"- 300# DRILLING NEOPRENE GASKET, 1/8" THICK (6.125" OD WITH 4-.875" ø HOLES ON A 4.50" BOLT CIRCLE)	HV005	Three way ball valve	Nominal Size: 1.5" Max Pressure Rating: 150 psi Port: Full L Connection Type: FNPT x FNPT x FNPT
FI006	Vortex Shedding flowmeter	Flow regime (gpm): 0 - 100, Flow accuracy: 2% FS, Installation requirements 16.1" upstream 8.05" downstream Req'd fitings: 1.5" MNPT PVC nipples	HV006	Float-Operated Air Release Valve	Max Vent Capacity 6 scfm @ 150 psi Min Pressure: 5 psi Max Pressure: 175 psi Connection Type: 0.5"
PI001	Analog Pressure	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin	HV007	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI002	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV008	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI003	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV009	Gate Valve	Nominal Size: 1.5" Max Pressure Rating: 200 psi Handle Type: Hand Wheel Connection Type: FNPT
PI004	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV010	Diaphragm Valve	Nominal Size: 1.5" Max Pressure Rating: 150 psi Connection Type: Socket
PI005	Analog Pressure	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin	HV011	Butterfly Valve	Nominal Size: 1.5" Max Pressure Rating: 150 psi Connection Type: 4 - 0.5" bolts on a 3.875" bolt circle
PI006	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV012	Check Valve	Nominal Size: 1.5" Max Pressure Rating: 150 psi Connection Type: FNPT
PI007	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV013	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI008	Analog Pressure	Scale: 0 - 160 psi, 2.5" nominal dial, Accuracy: +/- 3-2-3% (FS), Connection: Top, Connection Type: 0.75" FGHT, Model # PETM213LF	HV014	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI009	Analog Pressure	Scale: 0 - 160 psi, 2.5" nominal dial, Accuracy: +/- 3-2-3% (FS), Connection: Top, Connection Type: 0.75" FGHT, Model # PETM213LF	HV015	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI010	Analog Pressure	Scale: 0 - 160 psi, 2.5" nominal dial, Accuracy: +/- 3-2-3% (FS), Connection: Top, Connection Type: 0.75" FGHT, Model # PETM213LF	HV016	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI011	Analog Pressure	Scale: 0 - 160 psi, 2.5" nominal dial, Accuracy: +/- 3-2-3% (FS), Connection: Top, Connection Type: 0.75" FGHT, Model # PETM213LF	HV017	Ball Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI012	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV018	Pressure Relief Valve	Inlet Size: 0.75" Outlet Size: 0.5" Pressure Range 50 to 175 psi
PI013	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV019	Ball Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PI014	Analog Pressure gauge	Scale: 0 - 200 psi, 4" nominal dial, Accuracy: +/- 2-1-2% of full scale (FS), Connection: Bottom, Connection Type: 0.5" MNPT, Glycerin Filled Model # 201L-402G	HV020	Ball Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID001	Magnehelic gauge	Scale: 0 - 5 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 4% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV021	Schrader Air Valve	Connection Size: 0.25" Quick Coupler x 0.25" Tee
PID002	Magnehelic gauge	Scale: 0 - 1 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV022	Ball valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID003	Magnehelic gauge	Scale: 0 - 4 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting	HV023	Ball Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID004	Differential Pressure Piston	Scale: 0 - 5 psid, max pressure: 3000 psig for aluminum body, 4.5" nominal dial, Accuracy: +/- 2% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV024	Ball Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID005	Magnehelic gauge	Scale: 0 - 4 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV025	Ball Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID006	Magnehelic gauge	Scale: 0 - 1 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV026	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID007	Magnehelic gauge	Scale: 0 - 4 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting	HV027	Globe Valve	Nominal Size: 2" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
PID008	Magnehelic gauge	Scale: 0 - 4 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV028	Ball valve	Nominal Size: 3/4" Max Pressure Rating: 150 psi Connection Type: FNPT x FNPT
PID009	Magnehelic gauge	Scale: 0 - 1 psid, max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV029	Backflow Preventer and Pressure Reducing Valve	Nominal Size: 0.5" Factory Set Pressure: 30 psi Pressure Range: 10 to 25 psi Connection Type: 0.5" FNPT
PID010	Magnehelic gauge	Scale: 0 - 0.5 w.c., max pressure: 500 psig, 4" nominal dial, Accuracy: +/- 3% (FS), Connection Type: 4 0.25" FNPT ports (2 0.25" plugs, four flush mounting adapters, mounting screws are a standard accessories) Req'd accessories: bleed fittings and surface mounting bracket Note: Install bleed fittings on the top pair of guage pressure taps	HV030	Ball Valve	Nominal Size: 1.5" Max Pressure Rating: 225 psi Connection Type: Socket/FNPT x Socket/FNPT
SC001	Variable Frequency Drive	AC Drive, 5 hp, 208-240V, 3 Phase, NEMA 1 Indoor Only	PV001	Pneumatic Ball Valve	Nominal Size: 2" Max Pressure Rating: 250 psi Required Pressure: 80 psi Max Inlet Pressure: 120 psi Connection Type: Socket/Thread
TI001	Type T Thermocouple	425°F Rating, Ungrounded junction 304 SS Sheath, Sheath Diameter 0.125" Req'd fittings: 0.125" quick disconnect and reducing bushing	Y001	Accumulator	Nominal Connection Size: 0.5" Max Pressure Rating: 150 psi
			Y002	Y Strainer	Mesh 50, 2" FNPT connections, 150 psi max pressure rating
			Y003	Air Compressor	

Title: Spec Sheet

Sheet #: 3/4

EERB Water Flow Loop

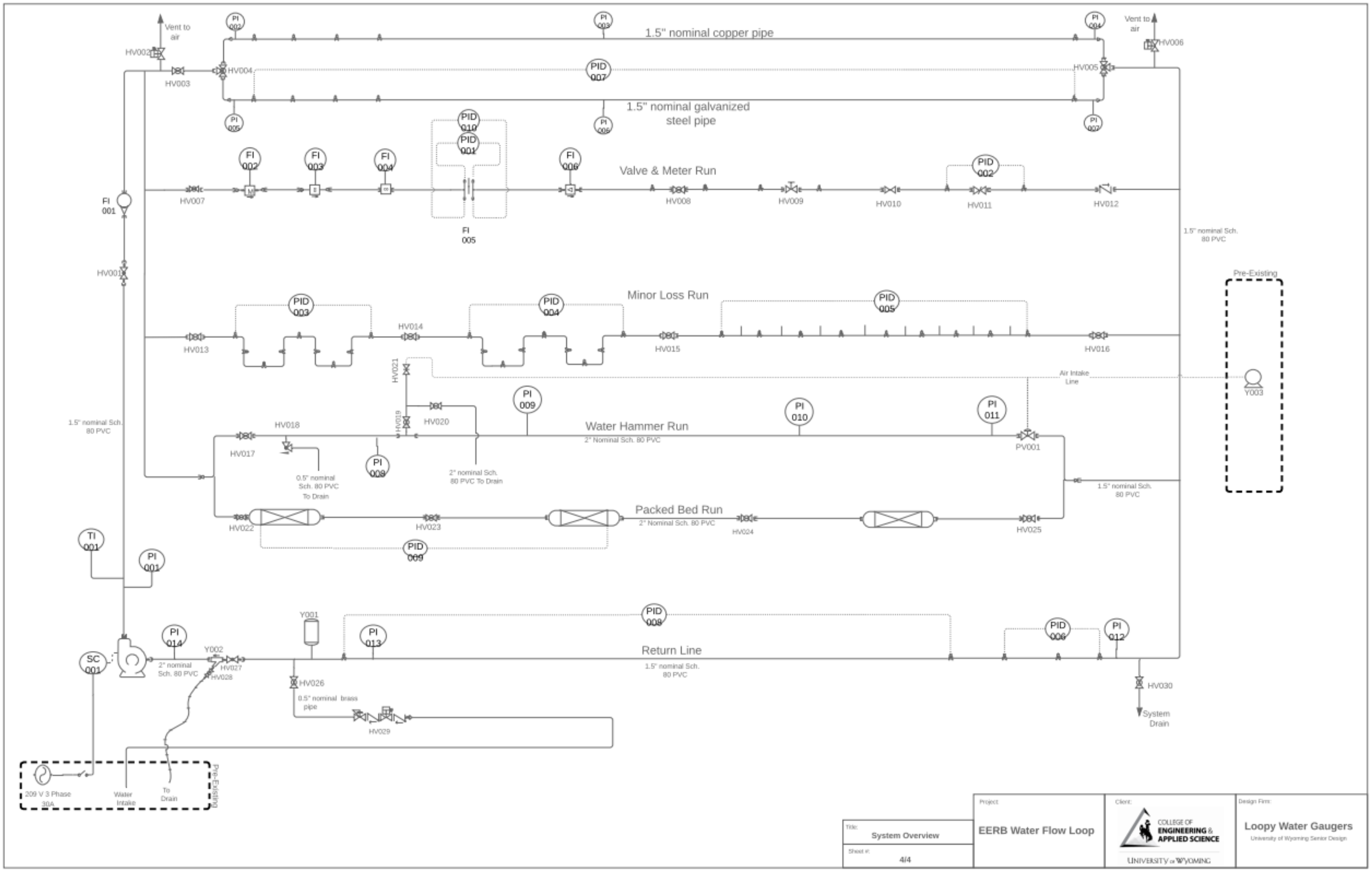
COLLEGE OF ENGINEERING & APPLIED SCIENCE

UNIVERSITY of WYOMING

Design Firm:

Loopy Water Gaugers

University of Wyoming Senior Design


1.5" nominal copper pipe
1.5" nominal galvanized steel pipe
Vent to air
Valve & Meter Run
Minor Loss Run
Water Hammer Run
2" Nominal Sch. 80 PVC
Packed Bed Run
2" Nominal Sch. 80 PVC
Return Line
1.5" nominal Sch. 80 PVC
Pre-Existing
Air Intake Line
0.5" nominal Sch. 80 PVC To Drain
2" nominal Sch. 80 PVC To Drain
2" nominal Sch. 80 PVC
0.5" nominal brass pipe
System Drain
209 V 3 Phase 30A
Water Intake
To Drain
Title:
System Overview
Sheet #:
4/4
Project:
EERB Water Flow Loop
Client:
COLLEGE OF ENGINEERING & APPLIED SCIENCE
UNIVERSITY OF WYOMING
Design Firm:
Loopy Water Gaugers
University of Wyoming Senior Design