DEPARTMENT OF MECHANICAL ENGINEERING & MECHANICS

ME 212 Engineering Capstone

Westlake Pipe & Fittings

Engineering Capstone Final Report

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Introduction

The Westlake Pipe & Fittings capstone project was initiated to develop and refine a specialized testing apparatus capable of performing high-cycle fatigue testing on restrained joint integral bell (RJIB) pipe systems. Such pipes are widely used in critical water infrastructure projects, making their reliability paramount. The primary goal was to construct a testing apparatus to get the pipe to meet stringent industry standards, including compliance with ASTM F1674 and Underwriters Laboratories (UL) requirements.

In addition to constructing the testing system, the project team was tasked with providing design recommendations aimed at improving RJIB pipe performance based on observed failure modes. Throughout the research process, the team engaged with stakeholders like employees of Westlake, ASTM, UL, Municipal water authorities, relevant professors, Lehigh Alumni, and more, to ensure the apparatus would have a durable design and would contribute to improving municipal piping systems. By integrating automated control systems, extensive data logging capabilities, and rigorous analytical techniques such as Failure Modes and Effects Analysis (FMEA), the team produced a robust foundation for ongoing improvements in fatigue testing and pipe joint design.

From conceptualization and initial prototyping to final recommendations, this project represents a comprehensive approach to advancing industry best practices. The apparatus not only adheres to strict standards but also provides insights into future enhancements. While the final prototype demonstrated significant improvements over earlier designs, the lessons learned and the roadmap provided will help future teams refine the apparatus, mitigate remaining issues such as leakage and electronic noise, and ultimately contribute to safer and more reliable water distribution infrastructure.

<u>Problem Statement</u>

The testing apparatus designed must meet the following criteria to successfully test pipes for the required UL standard

- The apparatus can withstand greater than the 1 million cycles required for testing without repair or calibration.
- One pressure cycle consists of starting at less than a base pressure and climbing to greater than the peak pressure and finally lowering back down below base pressure
- Pressure maxima and minima are no more than 5% outside of the values above.
- The apparatus logs pressure at least 10 times/ cycle, but preferably logs more often.
- Test will end automatically in the case of a failure.

Preliminary Research

Stakeholder Feedback

Understanding the needs and perspectives of stakeholders was a critical aspect of the project. The team conducted extensive interviews and consultations with a diverse group, including manufacturers, service technicians, researchers, and municipal water authorities. This research provided valuable insights into the challenges faced in the design, installation, and maintenance of RJIB pipe systems, ensuring that the final testing apparatus addressed real-world requirements effectively. Stakeholder feedback also guided prioritization of features, such as ease of use, durability, and safety measures, shaping the project's objectives and design criteria.

Makers: With Westlake's vertical integration, it is important when designing a new testing apparatus to keep in mind any changes that may cause issues anywhere in the manufacturing process from PVC to the pipes being installed. With this in mind we ensured that your needs for this project are well understood and continuously updated.

Service: One of PVC piping's main features is its longevity, so thinking ahead to the future operators and technicians charged with maintenance and operation of municipal water systems. For this population we intend on investigating which groups and individuals we can contact through our contact with the Department of Water & Sewer Resources in our local city of Bethlehem.

Users: As residents of Bethlehem, we are and know many others who are invested in the safety, quality and reliability of their house's water. We also plan on reaching out to regulators within Bethlehem's Water Authority such as Edward J. Boscola, P.E. (Director of the Department of Water & Sewer Resources). His department is in charge of over 500 miles of water main and is responsible for on average 15 million gallons of water per day.

Anonymous Stakeholder Interview Results (Table 1)

Description of Individual Interviewed	Relevance Category	Relevant Information
General Contractor	Servicing	Heavy pipes and external joints make slow work. Safety over speed. Following conventions stops mistakes.
Nuclear Maintenance Engineer	Servicing	Nobody wants to service a pipe; they tend to be out of reach and under constant use. Hoop stress is where your pipe will burst, so get hoop stress under control. It is difficult to see something malfunctioning in a pipe, so monitor many sensors.
Machine Shop Staff	Manufacturing	Threads, variations in O.D. and non axial holes in extruded pipes are difficult to manufacture. When under high pressure, joint tolerances are everything. Teflon tape seems good but tends to backfire.
Robotics Advisor	Researcher	Building a microcontroller is a lot of work given the simplicity of the DDAQ and control req'd, so just buy one. Data isn't complicated to process, so sample rate can be high with no drawbacks beside storage space.
Unsteady Flow Interactions Lab	Faculty	Turning a compressor off and on wastes energy and can lead to failure, instead they recommend a high pressure tank with a regulator for an air over water design. Safety issues at high pressure, recommend safety training. Watch out for fatigue in testing equipment, likely to fail if cheap.
Lehigh Alumnus working with carbon fiber coating		Knowledge in ASTM burst testing for steel pipes, their company uses a form of air over water to reach ~1,000 psi

Description of Individual Interviewed	**Relevance Category**	**Relevant Information**
steel pipe	Manufacturing	sustained. Recommends prototyping and a proof of concept.
Civil Engineer	Servicing	Installation and servicing of pipes is the biggest concern, modern PVC pipes will generally have a long lifespan with few issues. Temperature and ground movement are definitely factors to look out for.
Strength of Materials Professor	Faculty	Do as many hand calculations as possible to determine maximum hoop and axial stresses before using a program like Ansys to determine the most likely points of failure. Start with a simple 2D model of the pipe and get more complex.
Lehigh Design Labs Supervisor	Manufacturing	Recommends using a linear actuator or hydraulic piston in conjunction with a water piston to dive the cyclical pressurization of the sample.
Fluid Mechanics Professor	Faculty	It might be useful to use pi groups in order to scale up small scale calculations and or prof of concepts. You should include variables related to the material properties and loading conditions. One thing we can do is after setting up our system, we can create a simulation for a few test cases and see if the results obtained from the simulation matches the results obtained from our scaled down system.
Mechanical Engineering Project Manager	Manufacturing	Recommends a different design for the Certa-Lok in the case of fatigue failure. Could be improved by a U-shaped design for symmetry.
Fluid Mechanics Professor	Faculty	Through experiment or analysis, it may be possible to calculate a fatigue rate which could be used to estimate product lifespan or time-to-failure, this could provide an

Description of Individual Interviewed	Relevance Category	Relevant Information
		efficient manner to compare theoretical, and actual behavior of the test specimen.

Patents & Scientific Principles

Our team has compiled a varied base of research regarding the municipal water industry, Westlake manufacturing and design processes, as well as research into testing design, failure analysis, fatigue, and the chemistry of PVC.

Types of Pipe Fittings: Throughout our research we dove deep into the various ways PVC pipes are connected together for use in municipalities. We found that there are two primary varieties of pipe fittings, internally restrained and externally restrained. Internally restrained pipes have the restraint mechanism in the connection between the bell and the spigot or the plain end of the pipe. Externally restrained pipes have a few different forms but the most common one uses two large brackets that go on either side of the joint and utilizes tie rods that connect the brackets holding the joint together. These are particularly more bulky and require much more time to assemble than an internally restrained joint. We understand that Westlake mainly uses internally restrained pipes and that is what they are looking for in terms of a possible redesign so we tried to hoane our focus towards that while researching. What I came across in my findings were various patents from Westlake as well as some other companies that describe systems much like the Certa-Lok design with some sort of seal as well as a key or a spline that locks the bell to the spigot of the next pipe. There are also couplings that use the same principle to lock two plain ends together as seen in Figure 1.

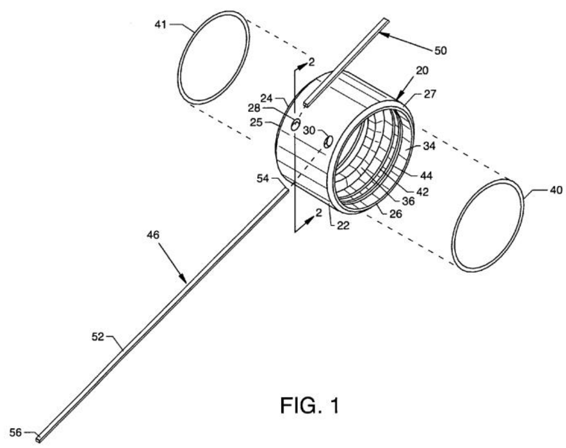

FIG. 1

There was one patent in particular that used this technique with a filament wound coupling which improved the structural properties of the connection. We also came across a design that has similar qualities but utilizes two gaskets and a built in port for a pressure transducer. This design is slightly different with much less of a bell and spigot type connection. Through this research we gained a good understanding of the Certa-Lok connection and have a somewhat vast range of other designs to gain inspiration from.

Industry Information: In order to better understand the issue of certifying these pipes, its magnitude, and possible solutions, we looked into what Westlake and other companies are manufacturing, and how they are responding to changes in the industry. As a baseline, we researched the municipal water supply market and the most recent manufacturer, installer, and user data compiled by the AWWA in order to familiarize ourselves with the industry. From the State of the Water Industry(SOTWI) report, we discovered that aging infrastructure has been the premier issue in the municipal water service industry for decades, with long term supply and capital improvements next in line(AWWA, 2023). This puts a PVC pipe manufacturer in high demand, as PVC pipes are cheaper, lighter, and can last 100 years in the ground(Westlake Pipe & Fittings, 2023). The fact that a large portion of utilities plan on lead service line replacements in 2024 and beyond increases the need for cheap and long lasting pipes(AWWA, 2023).

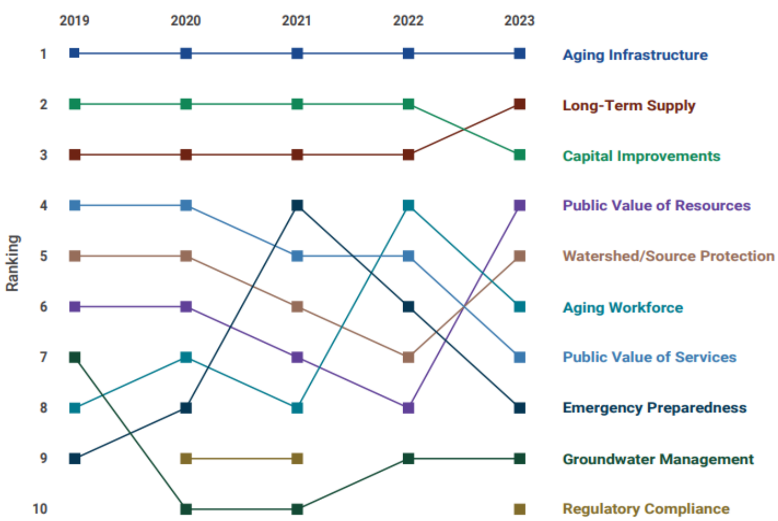

Figure 2

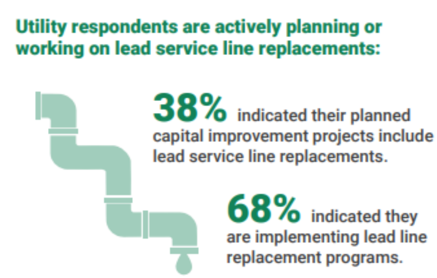

Figure 3

Digging into Westlake's products and manufacturing processes, we found many distinguishing characteristics of their pipe designs compared to other manufacturers. Westlake's novel change to existing pipe design is their Certa-Lok technology(Clapper, 2010). Certa-Lok is a method for securing pipe segments in the longitudinal direction quickly and permanently. Non-Certa-Lok pipes(figure 4 joint IB) use friction between a bell and spigot to hold pipes together, needing external support such as thrust blocks or clamps to keep thrust forces from unbalanced water momentum(Clapper, 2010). To solve this issue, Westlake's Certa-Lok line of pipes include an extra groove where the gaskets sit that provide a keyhole for a spline to hold both sections of pipe together as seen in figure 4 as the joint RJIB. This pipe design is the focus of the testing apparatus that's building was tasked to us, so special interest was placed in understanding the mechanical properties of this connection and the internal stresses around this added spline groove.

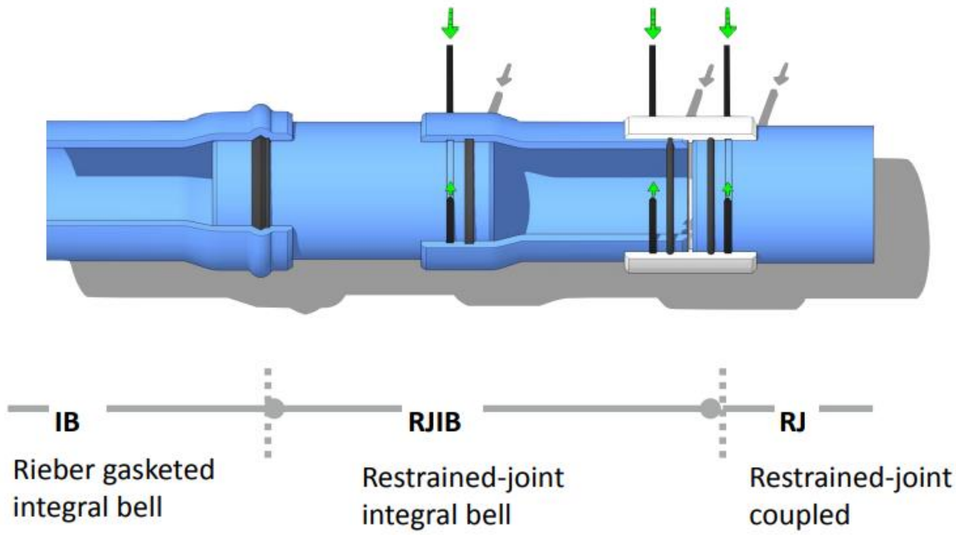

Figure 4

Westlake is also the manufacturer of the PVC used in their pipes, down to the raw resources, natural gas and salt, that form the plastic. In order to understand PVC as more than just an acronym, we familiarized ourselves with the production of PVC. PVC is manufactured from refined petroleum products and salt. Petroleum is refined into ethylene and the chlorine is separated from the salt through electrolysis. The ethylene and chlorine are then combined to create vinyl chloride monomers. These molecules then undergo polymerization to finally create polyvinyl chloride. PVC in its base state is a comparatively low cost and quality plastic, with chemical properties that make it unsuitable for most everyday applications. PVC's low cost and protection against biodegradation make it a clear choice for water piping. One of PVC's weaknesses, its ultraviolet light sensitivity, is irrelevant underground making it even more suited to this use case.

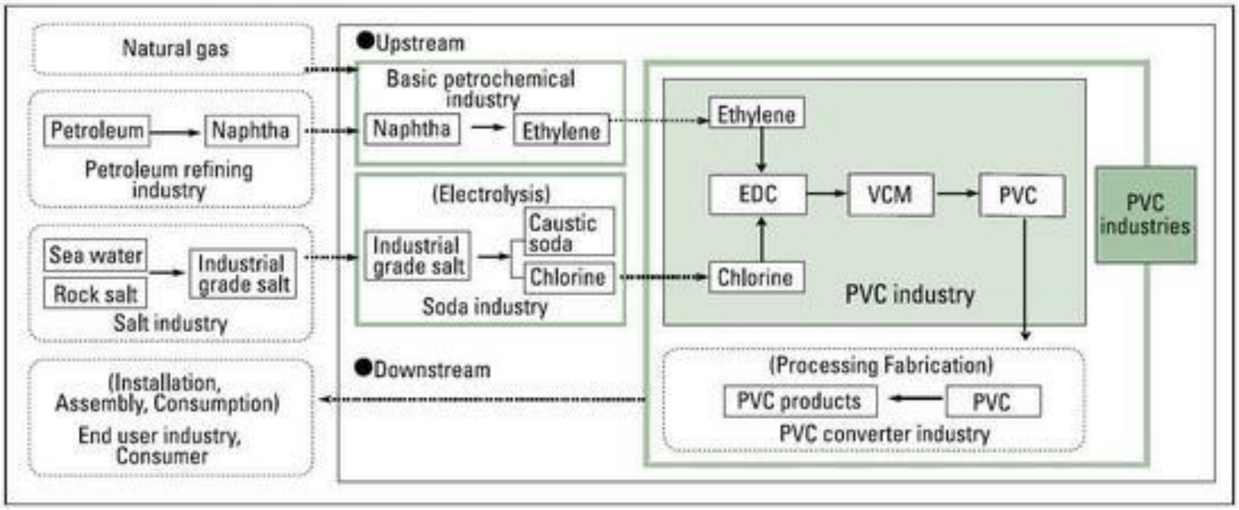

Figure 5

Pipe Failure Modes: Failure modes observed in the pipe were accelerated creep deformation and Stress Cracking Growth (SCG). These failures were attributed to the absorption of plasticizing chemicals from the soil, which led to plasticization or softening of the PVC material. This resulted in decreased mechanical strength, increased creep deformation under internal fluid pressure, and swelling and cracking due to nucleation and propagation of crazes. Both failure modes, accelerated creep deformation and SCG, were found to operate simultaneously due to the plasticization process undergone by the material in the failure zone. The chemical composition of the plasticizing substance found in the PVC pipe was identified through FTIR spectra analysis as a mixture of alcohols, aromatic compounds, and isocyanates, likely corresponding to a blend of paint thinner and polyurethane paint. It suggests that during the construction phase of a building where the pipe was installed, these substances might have been inadvertently spilled into the soil near the pipe during covering and compaction. This spill could have been accidental or due to improper disposal. The impact of this substance extended beyond the immediate failure zone, reaching distant areas, as indicated by FTIR analysis.

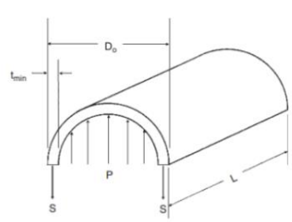

Fig. 5.2 Hoop stress due to internal pressure.

Equation 5.1

$$S = \frac{P(D_o - t_{min})}{2t_{min}}$$

where:

S = hoop stress, psi
t_{min} = minimum wall thickness, in.
P = internal pressure, psi
D_o = pipe outside diameter, in.

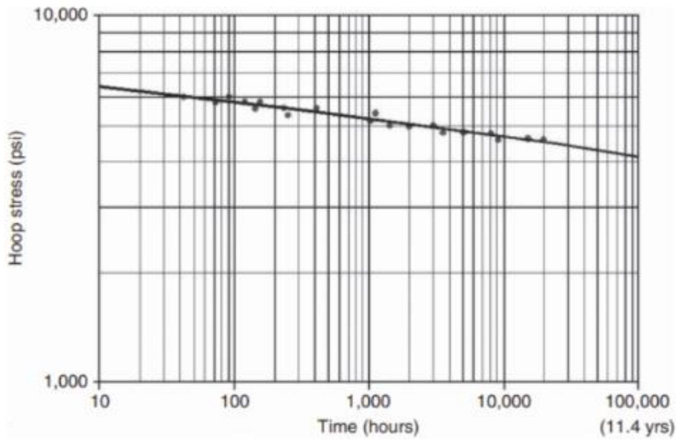

Figure 6 and 7

PVC Material Properties Over Time: Through our research, we also found several studies and sources that describe the changing material properties of PVC over time. One particular study, conducted by the Imperial College of Science and Technology in London (Williams), detailed characteristics of PVC piping material as a general function of time. This study was primarily concerned with the mechanical properties of the pipe section under a static load as they changed over time. It was found that even without cyclic pressure cycling, and thus cyclic stresses, properties such as yield strength, fracture toughness, and elastic modulus. Most polymers, including PVC are viscoelastic, meaning that they exhibit both viscous and elastic material properties. This adds some interesting characteristics to the material, most significantly, time-dependent strain. In the case of a creep test, strain and time exhibit a power law relationship, see Figure 8 below for a general outline.

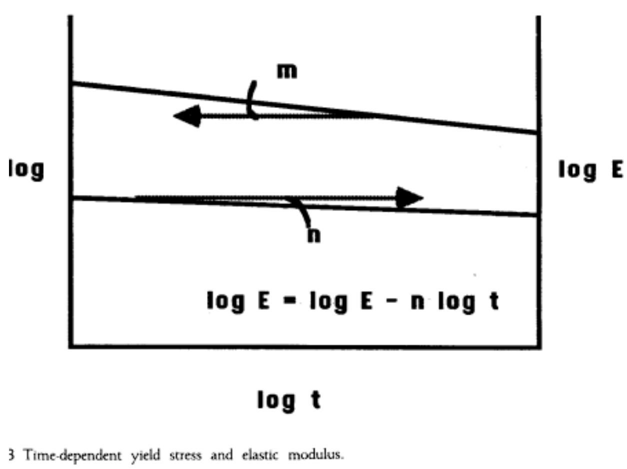

Figure 8

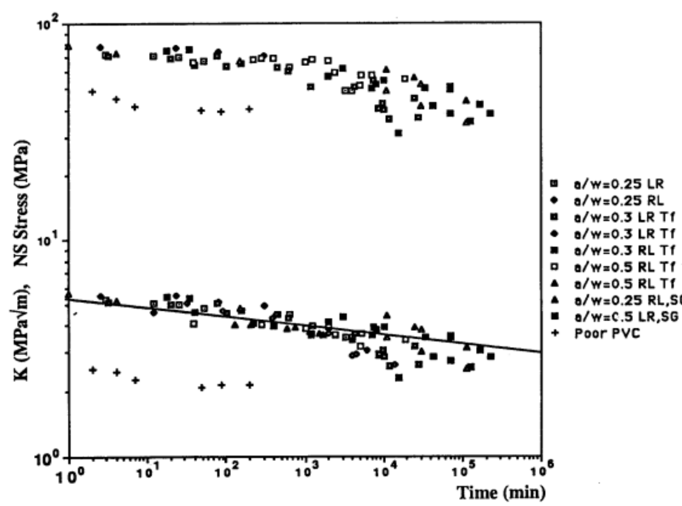

Figure 9

Figure 9 above shows the relation of time-dependent fracture in uPVC, here the relation between time and the strength of the material can be observed through the collection of data points as observed in the study. Overall, this study concludes that the fracture toughness of uPVC pipe is not a fixed or unique value, but rather varies depending on the degree of fusion of the PVC grains as well as with a power function of time. While this article primarily concerns pipes under static loads rather than cyclic stresses, these pipes must also endure static loading, thus it is important to consider in conjunction with cyclic stresses.

Test Apparatus Research: The team conducted research on various testing apparatuses to understand existing approaches for creating cyclic pressure testing devices. A meeting with Roy Dean of Westlake provided significant insights into the operation of such systems. It was determined that there are two primary types of pressure drive mechanisms used in these systems. The first involves an air-over-water system utilizing two interconnected pistons, where compressed air pressurizes water in one piston, which in turn forces water into the pipe being tested. Additionally, a detailed description of a cyclical testing setup was found in a publication by the Utah Water Research Laboratory.

The cyclic pressure from the test equipment was achieved by driving a piston within a brass cylinder back and forth a complete stroke for each pressure cycle. The driver consists of an air cylinder equipped with a piston and solenoid valves whose opening and closing are electronically controlled to achieve the desired driving speed. As the water piston is driving to one side the pipes connected to that end of the cylinder are pressurized to their highest pressure, while those pipes connected to the other side of the cylinder are at the low portion of the pressure cycle. Using a system like this would be very plausible if we could get or construct a reliable air over water piston set up. A system like this would also mostly likely require a small accumulator to account for small inconsistencies in pressure. Some downfalls of this type of system are that they tend to be slow and difficult to control the driving pressure of the air cylinder. Other possibilities using an air over water piston like this could utilize a different driving force such as mechanical linkage or a hydraulic system. The other main diver for a testing apparatus would be a high pressure water pump along with solenoids to release and regulate the pressure. This approach would require more infrastructure on the technical side to control the pump and solenoids but would most likely result in a system that is more easily adjustable. There are pumps on the market that are designed for this exact application in mind with on board pressure transducers and regulators. Designing an apparatus that incorporates one of these pumps could potentially simplify the entire system and make it more efficient and easy to use.

Further research was conducted in the long-term reliability of certain components within testing apparatus. According to findings from the University of Utah, in their testing “1.5 million cycles of pressure from 100 to 200 psi is a severe test of the pipe's durability, but also a severe test of the equipment.” (Jeppson, 9) The National Bureau of Standards conducted research into the long term durability and deterioration of transducer performance. This is of particular concern if accurate data acquisition and logging is to be maintained for certification and/or research purposes.

This study found that sensitivity and zero output changed markedly over the first 100,000 cycles, and more gradually thereafter. (Lederer, 9) After one million pressure cycles, it was observed that the transducer zero-output was ~1% off its original value full-scale, while sensitivity changed by 0.5%. While this research is not recent, the principles of a pressure transducer have not changed significantly. Based upon this data, it is important to select pressure transducers with an appropriate full span where a 1% error would still result in usable and relevant data.

Water Hammer: Water hammer is a hydrodynamic phenomenon that can deal great damage to piping systems. It is a type of hydraulic transience caused by water's incompressibility and momentum. Quickly changing the flow of a fluid, such as closing a valve quickly, creates a pressure wave that travels through the fluid and can burst pipes(Crowley, 2016). Avoiding this phenomenon requires gradual closing of all valves in a pipe network, larger pipe diameter, or adding a surge device. Surge devices include air bladders, spring loaded valves, or free surfaces that can change level. This phenomenon is relevant to the problem statement as water hammer can be responsible for surge and burst pressures that test the limits of a pipe's strength.

Airlock: Airlock is another hydrodynamic phenomenon that can create issues for piping systems. Airlock reduces the flow in a pipe by replacing some of the pipe's cross-section with gases, usually air. Gasses can enter pipes through being dissolved in the fluid contained in the pipe, entering through leaks with negative pressure gradient, or from installation(Crowley, 2016). Gases' low densities make high points in the pipes very susceptible to airlock. This reduction in cross-sectional area causes head loss.

<u>Needs & Metrics</u>

NEEDS \ METRICS	Cycles til failure for apparatus	Emergency shutdown pressure cutoff(psi)	Total Apparatus Weight(kg)	# of pressure probes	Unversal fitting system for the water(Y/N)	# of temperature probes	Avg # of clicks to access feature	DAQ Frequency(Hz)	Size of data stored(s)	Required safety zone (m^2)	Microcontroller Type(Brand)	Connection to internet(Y/N)	CSA lost to airlock(m^2)	Leakage flowrate	Creep rate of piston/bladder material(%/s)	Waterproof Rating of connections(IPX-#)	Yield Stress of Connecting Materials(Pa)	Cylindricity(+/-m)	Retooling cost($)	Apparatus Cost($)	Test Cost
Durable	X														X		X				
Measure pressure vs time				X				X	X												
Measure temperature						X		X	X												
Must keep testing environment safe during failure		X								X							X				
Able to work with multiple pipe sizes					X																
Easy to use/interactive UI							X		X												
Uses off the shelf microcontroller											X										
Remotely alerts operators of apparatus status									X			X									
Does not airlock													X								
Does not leak													X	X	X	X					
Has few joints																X					
Follows Pipe & Plumbing Conventions					X									X							
Doesn't use nylon tape or threadlock														X		X					
Cross sectional area remains the same																		X			
Handles full working pressure with factor of safety														X			X				
Requires no manufacturing retoolings																			X		
Stays Internally Restrained																		X			
Lightweight			X																		
Mobile and easily transported			X																		
Water from failure stays contained										X				X							
Less expensive than out of house options																				X	X

Figure 10

A quantitative hierarchical needs and metrics matrix is vital in our project as it guides design decisions based on objective data. By assigning quantitative metrics with bounds and ideal values to our stakeholder needs, it enables us to prioritize design efforts effectively. Continuous monitoring of performance metrics informs iterative design improvements, helps in identifying and mitigating risks early, and ensures that design decisions are data-driven and aligned with project goals. As we continue with the project, we will fill in the few blank spaces left in our matrix.

Priority	Need	Spec	Metric	Unit	Ideal Value	Min Value	Max Value
1	Creates Req'd P-t Curve	Hits target pressures	Max cycle pressure	psia	200	200	205
1			Min cycle pressure	psia	100	95	100
1		Fall within cycle time	Period	sec	6	6	10
1		Completes req'd cycles	Number of Valid Cycles per Test	#	1,000,000	1,000,000	N/A
2	Safety	Keeps Area Clean in Failure	Floor Area Affected By Failure(Wetted)	sf	?	?	?
2			Floor Area Affected By Failure(Debris)	sf	?	?	?
2		Stops Test in Failure	"Reaction Time" Between failure and stop	# of Cycles	>1	N/A	1
2		Does Not Explode	Max Pressure Before Relief Valve(Storage)	psia	Defined By Storage Vessel Rating		
2			Max Pressure Before Relief Valve(Pipe)	pisa	205	205	?
2	Long Lifetime	Rebuilds are Infrequent	Number of Cycles between repairs	#	>2,000,000	1,000,000	N/A
2		No Midtest Calibration	Calibration Drift after Full Test	psia	0	N/A	5
3	Ease of Use	Wireless Connection	(0-2)Physical,Ethernet,Wireless	#	2	0	2
3		Real Time Data	Time between updates	varies	1 hour	1 sec	1 Day
3		Simple	Clicks reqd per test	#	1	1	?
3	Cost(Time is Money!)	Out of House Costs	Cost of material	$	?	?	408000
3			Cost of servicing / replacing	$/test	?	?	17000
3		Internal Costs	Supervision Time	Person-Hours/test	0	0	60
3			Test Changeout Time	Person-Hours/test	?	?	2

Figure 11

From this matrix we created a risk assumption plot (fig. 12). A risk assumption plot aids in selecting which subsystems of our solution to prototype by systematically evaluating and prioritizing the risks associated with different needs of the design. The matrix categorizes risks based on their likelihood and impact, allowing us to focus on high-risk areas that could significantly impact the project's success if not addressed early on shown in the upper right corner. By identifying and prototyping these high-risk elements first, we can gather valuable data and insights to validate assumptions, test feasibility, and iterate on designs before committing to final design specifications. The data here is approximate and meant only to organize ideas and aid in prototyping decision making.

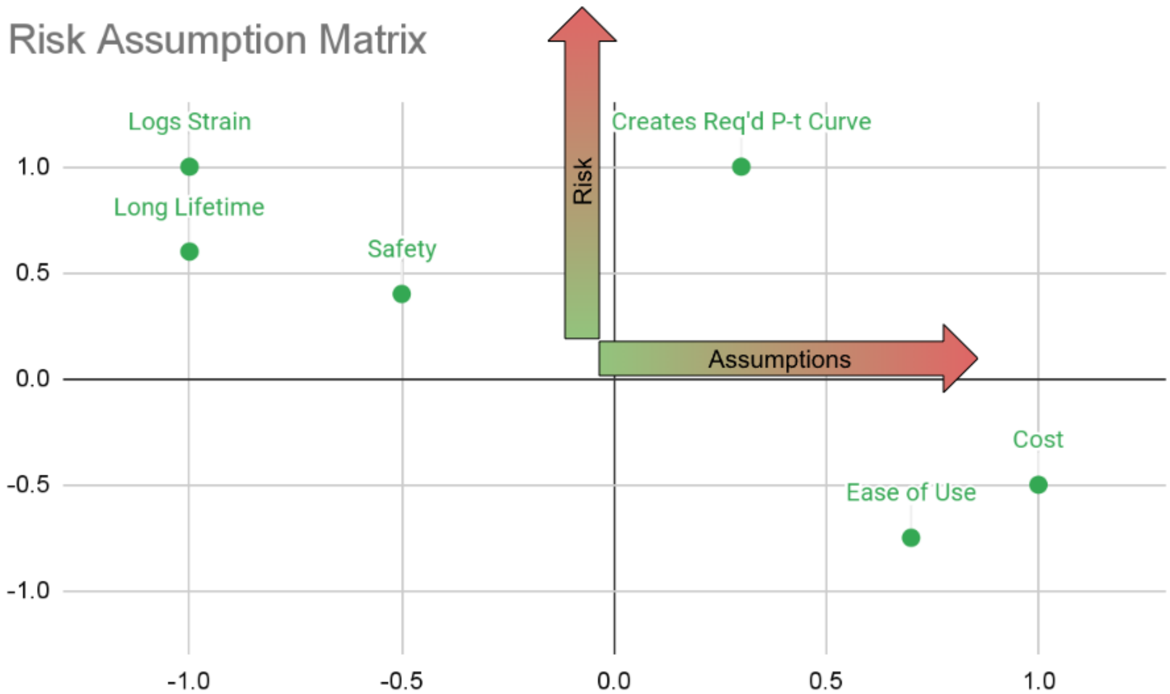
Risk Assumption Matrix
Logs Strain
Creates Req'd P-t Curve
Long Lifetime
Safety
Risk
Assumptions
Cost
Ease of Use
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0

Figure 12

Exploration

Function Diagram

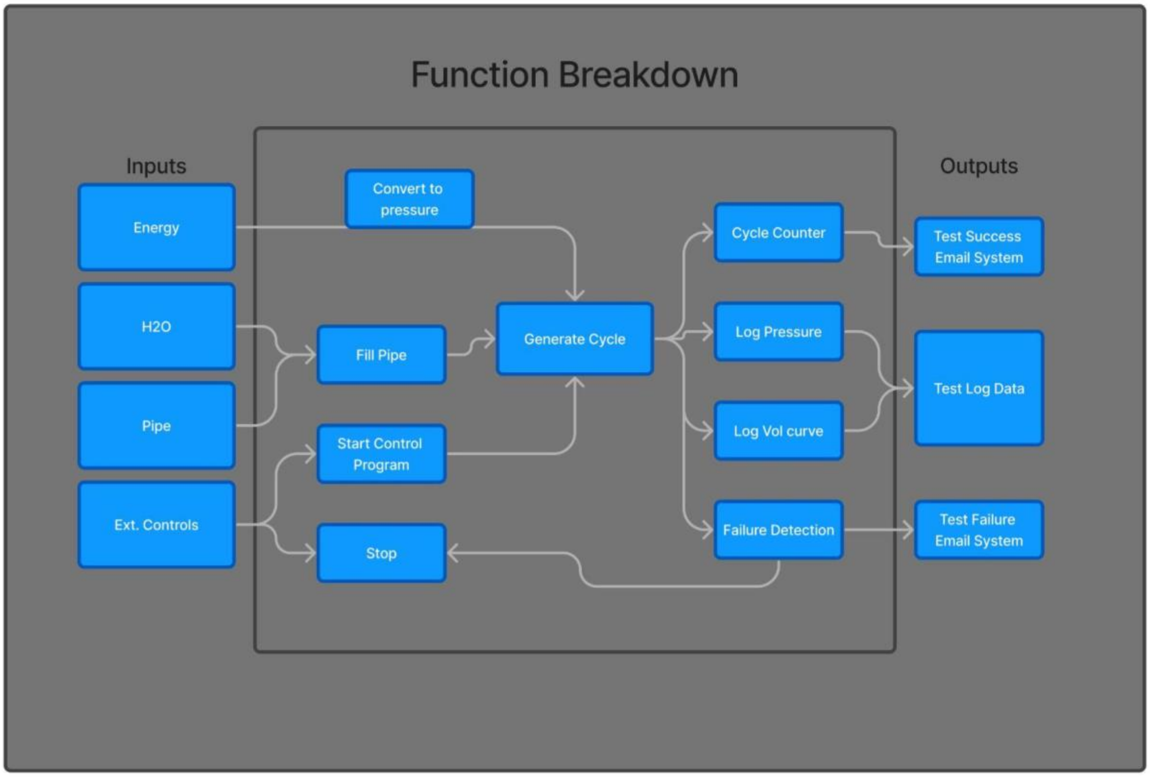

Figure 13

A black box input-output function diagram is a conceptual representation used to illustrate the relationship between inputs and outputs without revealing the internal workings of a system. The inputs to the black box are shown as arrows pointing towards the box, representing the materials and information that are fed into the system. On the other side, the outputs are represented by arrows pointing outwards from the box, indicating the results produced by the system in response to the inputs. The internal workings of the black box are deliberately abstracted or hidden, but as we continue in the ideation process, we will continue decomposing each system into smaller subsystems. Fig. 13 and tables 2.1 through 2.3 shown below represent our current level of deconstruction.

Table 2.1

Inputs	
Class	**Implementation**
Energy Our solution will require an energy source to perform work on the pressurized water within the test pipe. We have ideated multiple possible sources for this energy which we will prototype and evaluate for reliability, safety, and cost.	**Pneumatic** Compressed gasses offer a method of directly controlling pressure through valves. This energy source is nearly as readily available as electricity and offers many methods for pressure increase. **Electrical** Some electrical energy will be necessary to supply any electronic controls and components. Electric motors could also be used for actuation of the pressure control. One concern in electrically actuated pressure control is the large, repeated forces that would be sustained by any electric motors. **Gravitational** We considered gravitational potential as a possibility for part of a pressure generation system. This energy would need to be used in conjunction with others in order to have a sustainable and cycle pressure curve.
Water Water is the required working fluid for testing within the pipe section. Due to the long test duration, the possibility for leaks without failure, and the axial strain in the PVC, some water storage and distribution will be required.	**Fully Contained in Pipe** A benefit of not keeping water for other purposes is the simplification of safety and spill protection equipment. Reducing the number of fluid containing systems improves our ability to ensure a reliable testing apparatus.

Auxiliary Water usage

Auxiliary water usage could reduce the number of designed or purchased moving parts of our test apparatus. If designed using the proper equipment, a hydraulic system could prove more reliable.

Additives Cleaning

Due to the long testing times with stagnant water, we have decided it may be prudent to consider what additives we can add to the testing water to keep detritus from accumulating without chemically damaging the interior of the PVC.

Pipe

In order to conduct testing, our apparatus must be able to accept a wide range of diameters of testing pipe sections. These pipes must be fitted in a controlled environment and attached to the test apparatus. One foreseeable design constraint is designing pressure generation and control systems that can account for the differences in diameter and, most importantly, differences in displaced volume from pipe strains when cycling pressure.

Exterior Controls

Careful thought must be put into the human interaction with the built apparatus. The pipe changing and filling will likely be manual, the apparatus will need information on the pipe's dimensions, and some human safety measures should be included in the case of an unforeseen system failure.

On button

The starting process for a test.

Pipe dimension information input

Some pipe information may be required to most effectively actuate the system between different pressures.

Stop Button Press

In the event of system failure, a stop button would be used to terminate the actions of the apparatus, but the exact behavior and reliability of this failsafe changes based on implementation. The possibilities for this system are not exclusive, and implementing multiple or all solutions may provide extra reliability in failure to a known condition.

	Energy Disconnect - A manual energy disconnect ensures that all functionality of the system ceases. However this has the potential to create a sudden dispersion of energy if not done safely as in the apparatus' normal operation. *Controlled Energy Release* - A stopping signal could be used to alert the system to depressurize the testing pipe and return the apparatus to its normal standby operation, however this signal could be ineffective in the case of a control system failure.

Table 2.2

Outputs
Test End Notification Implementing a notification system to alert users of testing apparatus success or failure is critical for real-time monitoring and swift intervention, ensuring operational efficiency and minimizing downtime in the case of unexpected failure.
Intermittent Updates on status Receiving intermittent updates is crucial for detecting trends in data throughout the testing process. These updates offer real-time insights into when a pipe may burst, so more effective design changes could be implemented to increase the fatigue resistance of the joints.
Pressure-Time and Volume-Time Logs This data is the primary output of the testing apparatus and the data that will certify a pipe in the event of a successful test.

Table 2.3

System Breakdown	
Class	**Implementation**
Pipe Filling System In order to pressurize the pipes we need to fill the pipes with water. For the larger size pipes this volume of water is not negligible.	**Manual** Having the pipes manually filled at the start of a test greatly simplifies the testing apparatus' design, however it does not account for any mid test water losses. **Automatic** A small automatic refilling system would be used for small volume differences due to cyclic strains in the test pipe and other losses over time.
Control System The control system will be the most complex custom component of our solution, as it will control the rest of the system. This complexity can be seen in the high connectivity on the function diagram(fig. []). An implementation of the control system must handle pressure control, logging, and safety.	**Electronic** An integrated Raspberry Pi running a Python script would likely be the foundation of an electronic control system implementation. **Electric** An analog electrical system would use voltage generation from pressure transducers as signals along with oscillating circuitry and amplifiers to adjust the pressure generation system. **Mechanical** Volumetric sensing using a float and lever system or direct pressure sensing using hydraulics could be used to design a fully mechanical control system.

Pressure Generation System The pressure generation system must supply pressure to the water in the test pipe in accordance with the control system. The pressure generated should be responsive, consistent, and the system should be durable and hold calibration.	**Gravitational** A gravitational system would consist of pressure being generated due to a static column of fluid. Due to material and size constraints, hydraulics would need to be used in order to keep the required column height reasonable. **Hydraulic** Hydraulics operate on the concept of pressure magnification through mechanical advantage, making them a natural choice for this project. However, pressure magnification requires external generation from another source and therefore hydraulics may be part of a pressure generation system, but not the system itself. **Linear Actuator** This implementation consists of an electric motor and worm gear or rack and pinion. This actuator would then be connected to a piston where force could be applied to the working fluid of the system. **Pump** A direct pumping system would use a no-flow or low-flow two way pumping system with varying RPM to control pressure along with slight volumetric changes. **Pneumatic** A pneumatic system would consist of a gas-over-water or piston head design with a gas pressure storage vessel and valve system. **Heat water** Liquid water itself shows very low temperature dependence in volume and would

	likely not allow for the pressure control required. **Heat gas** Heating a gas would create a much more noticeable pressure increase, functioning similarly to a combustion engine. **Cool Water** Using the unique freezing volume increase property of water, pressure can be controlled by removing and adding heat to the system at water's freezing point to create a controlled freezing pipe burst effect.
Safety System Pressure vessel explosions are undesirable in a testing setup due to the potential risks of personnel injury, equipment damage, and environmental hazards resulting from the sudden release of high-pressure contents.	**Relief Valve** The simplest method of pressure regulation is the use of relief valves. Multiple relief valves should be used in each section of the test apparatus such that no section can be isolated from all relief valves. **Volume measurement by control** Sharp drops in pressure and volume could be used to measure the presence of a leak due to the loss of seal. **Leak sensors** Small electrical components that can read the moisture level at a location could be placed around the exterior of the pipe to detect the presence of water outside the control volume.

Prototyping

Design Ideation

Design A: This apparatus design is connected to the facility compressed air with a pressure magnifier to bring a storage tank to a stored pressure on the order of 1000 psi. This is then dispensed through a 200 psi regulated line to a tank with an air-water free surface to apply that pressure to the water in the pipe. The pressure is then lowered using a valve to a 100 psi regulated line. The opening and closing of the high and low pressure lines will be controlled by a microcomputer that reads the pressure in the air-water tank, which waits until switching thresholds are met. Due to the pressurized free surface, we expect to lose some volume of water through aeration which will be reintroduced through a pressurized water storage tank connected to the same microcomputer.

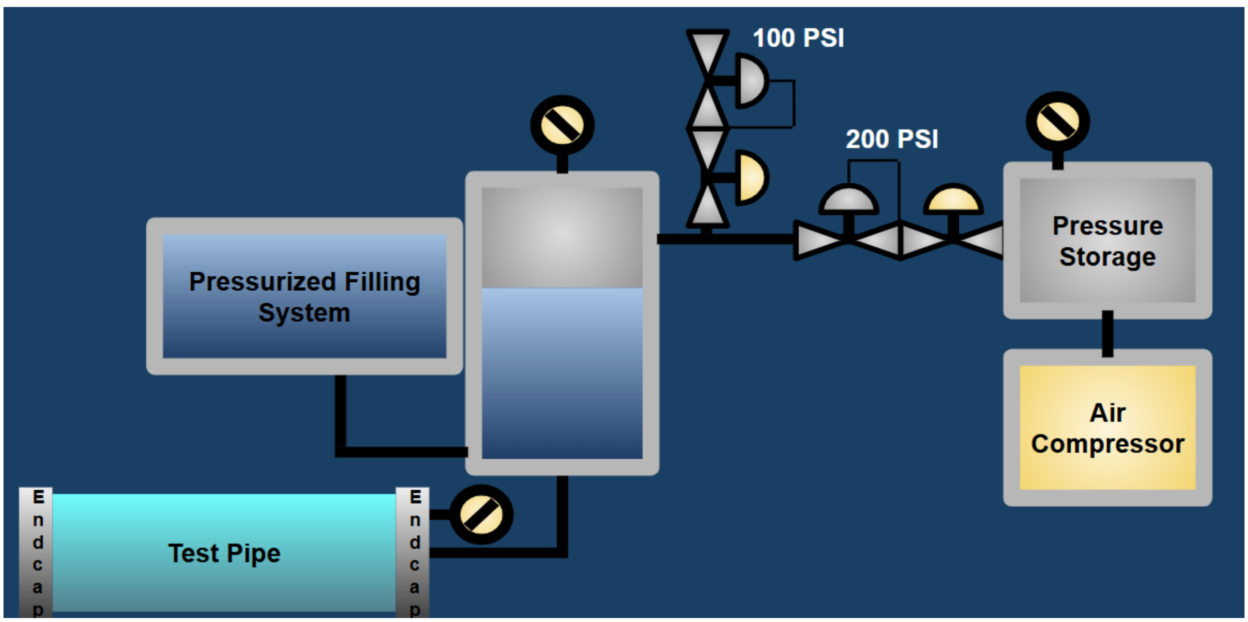

Figure 14

Design B: This design uses the same pneumatic supply and storage system, but replaces the free surface pressure application with a flexible membrane. This membrane ensures no aeration occurs, leading to a pre-test manual water filling system being sufficient. A PLC incorporates similar functionality to a microcomputer, but sacrifices customization for reliability. This design uses fully mechanical safety measures in the form of redundant pressure regulators in the high pressure lines of the system.

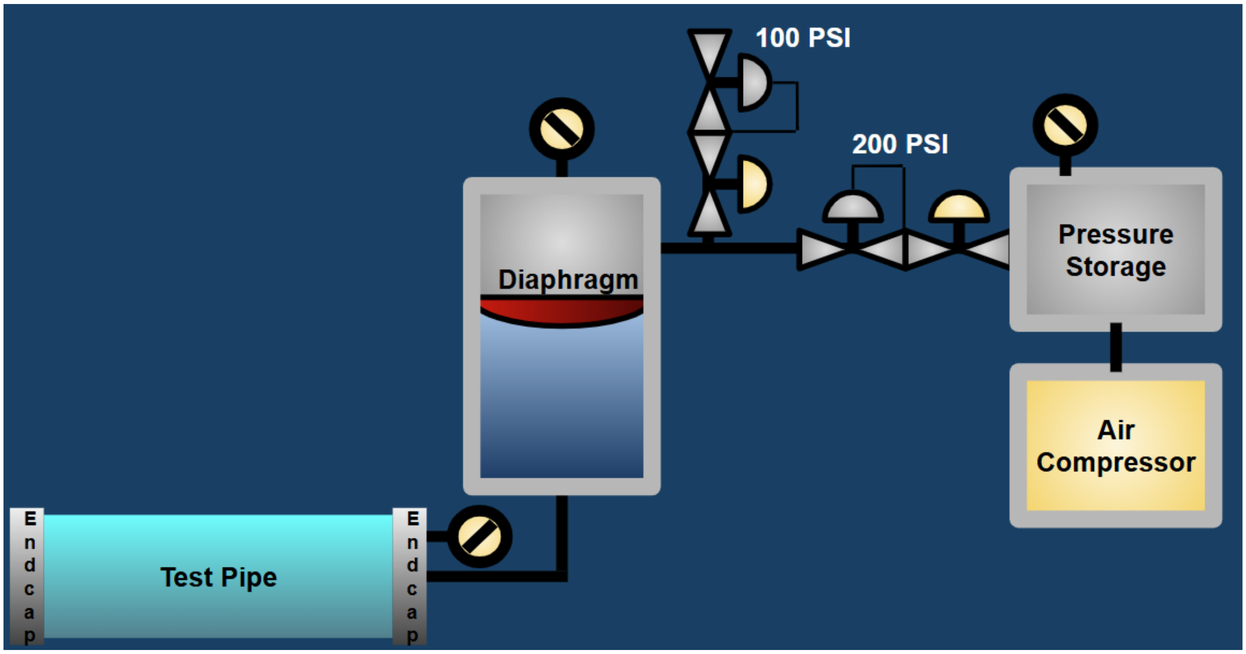

Figure 15

Design C: This design incorporates no compressed air, instead using a linear actuator and hydraulics to apply a force to a piston in contact with the water in the test pipe. This design uses mechanical feedback for a control system to change the force applied through the hydraulic system. This design is a controlled volume of water and therefore a pre-test filling system will be sufficient.

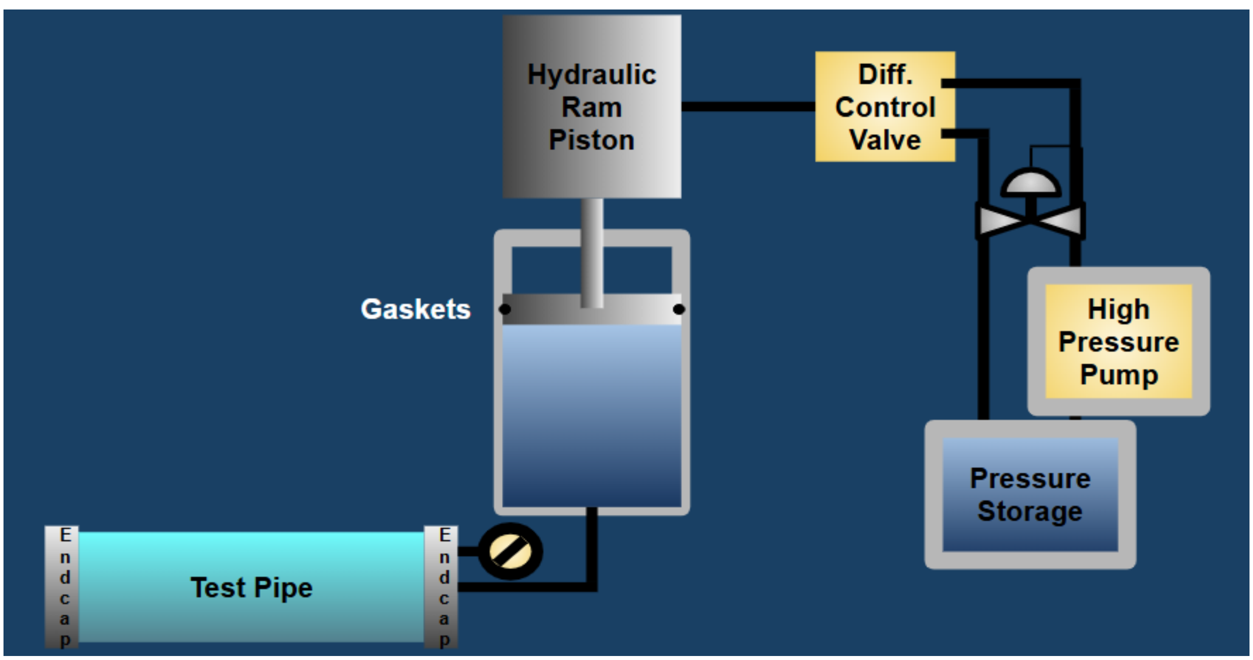

Figure 16

Design D: This design uses a positive displacement pump coupled with an accumulator tank to directly change the pressure in the water. With a PLC and electronic monitoring system, the RPM of the pump and the valve opening and closing the accumulator can be changed over time to create the required pressure curves and the loss in volume in the event of a failure can be tracked to keep the pump from unnecessary cycling during a pipe failure.

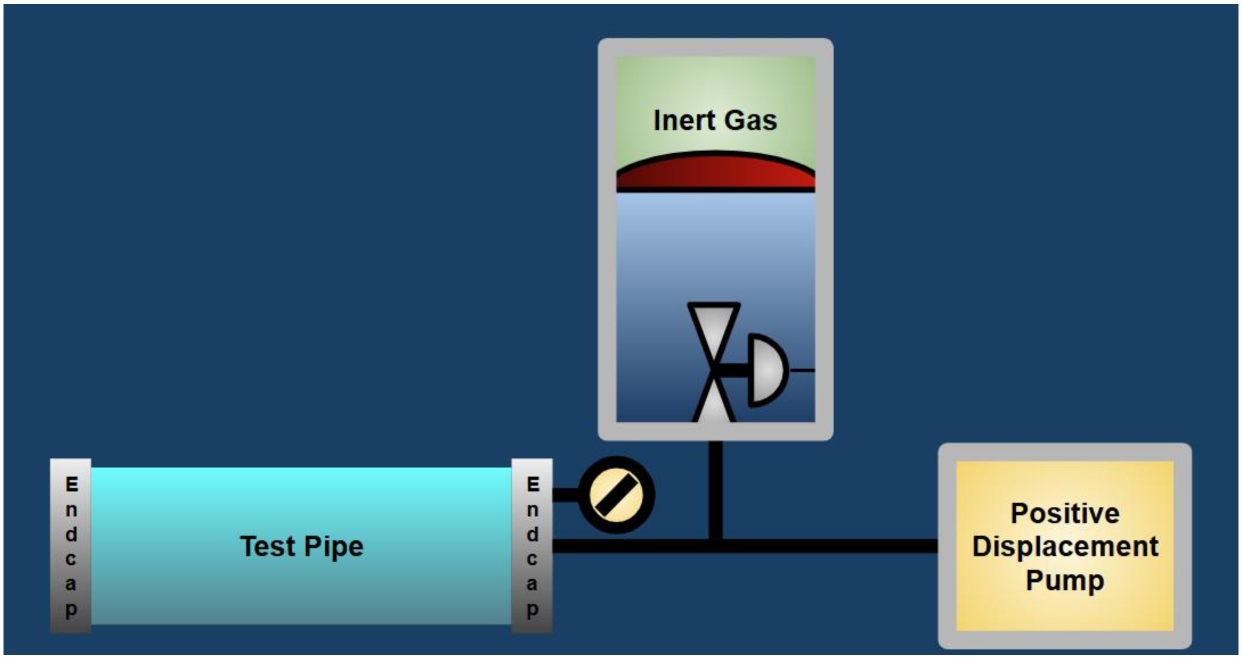

Figure 17

<u>*Accumulator Validation*</u>

Toward the end of the spring semester, we made substantial progress in our prototyping process. We constructed our first, and most simple prototype which successfully demonstrated the pneumatic pressure generation concept both with and without a bladder. In the area of electronic control and instrumentation, we have continued the development of our initial raspberry-pi and python concept as well as development of an initial PLC prototype for our digital control and data acquisition platform using ladder logic programming. PLCs offer a native ability to read and output a variety of analog and digital signals such as 0-5V, PWM, 4-20mA to name a few. Currently, ladder logic programming is being constructed using the free ABB Automation Builder software.

In our physical prototyping, we achieved a working prototype of a bladder accumulator. In order to construct this, we inserted a bike tire's schrader valve into a pressure rated soda cap and sealed it by forcing superglue through the threads with the application of pressure. After partially filling the bottle, we sealed it with the cap and placed the bottle behind a concrete wall. We raised the pressure to 35 psi and marked the change in water level as seen in fig. 1. After depressurizing, we added water to completely fill the bottle and added the balloon to the interior opening of the schrader valve. We repeated the experiment this time with the balloon and noted a lower volume increase for the same air pressure, which we attribute to the elastic tension in the rubber balloon imbalancing the water and air pressure. Moving forward, we intend to integrate a water filled PVC test pipe with more direct measurement devices through an added valve on the bottle.

We chose this to prototype this accumulator both with and without a boundary because of the low barriers to entry in creating an accumulator and its use in multiple of our designs. We were able to put this simple proof of concept together using household materials that we could find or source very cheaply.

Prototype accumulator shown depressurized(left) and pressurized(right)

Figure 18

Design Refinement

FMEA

Process Step / Input	Potential Failure Mode	Potential Failure Effects	SEVERITY	Potential Causes	OCCURENCE	Current Controls	DETECTION	RPN	Recommended Action
What is the process step and input under investigation?	In what ways does the key input go wrong?	What is the impact on the key output variables (Customer Requirements)?		What causes the key input to go wrong?		What are the existing controls and procedures (inspection and test) that prevent either the cause or the failure mode?			Action recommended to mitigate failure modes. Address RPN > 9 or SEV 4-5
Bladder Tank Structural Integrity	Explosion due to material failure	Test Ends, Property Damage, Loss of Safety	5	Blockage in test pipe hose, valve or regulator failure	3	Built in regulator on accumulator, high thickness walls, ductile construction	2	30	Add redundant regulators to ensure pressures remain within safe operating levels. Monitor strain in accumulator using gages.
Pressure Transducer	Reads False Low Pressure	Dubious Test Results, Unsafe Pressure Buildup in Pipe	3	Random error and loss of calibration over 1mil cycles	3	Manual pressure monitor for operator monitoring. Only accounts for errors that occur while operator is actively watching	3	27	Manufacturer specs ensure calibration well over test life. Recalibration by testing staff between each test.
Solenoid Valve	Valve gating the high pressure storage tank loses ability to form a seal, quickly raising pressure above max working conditions.	Unsafe Pressure Buildup in Pipe and accumulator, Test Halted	3	Operational wear, contaminants in air supply	4	None	3	36	Parts will be replaced between each test to minimize wear.
Solenoid Valve	Valve gating the 100 psi regulator fails such that it is stuck in the closed position, leading to loss in ability to change pressure.	Test Halted	1	Operational wear, contaminants in air supply	4	None	3	12	Parts will be replaced between each test to minimize wear.
Pressure Regulator	100 psi regulator ball loses ability to form a seal, quickly lowering pressure down to atmospheric.	Test Halted, Extra Strain on Test Pipe	2	Operational wear, contaminants in air supply	4	Elimination of high pressure supply in favor of as needed pressure generation.	3	24	Parts will be replaced between each test to minimize wear. Redundancy works to reduce chance of pressure buildup in case of single failure.
Control Program	Control program terminates an otherwise succesful test before required cycle count is reached	Unnecessary Test Failure	1	Random error in measurements, faulty leak detection.	3	None	5	15	In the event of test end, program will check number of proper cycles, current pressure and assess whether to stop or restart.
Water Filling System	Air enters the section below the diaphragm leading to shatter potential of the test pipe.	Air left below diaphragm could shatter test pipe	5	Human error to leave enough air that it could enter the pipe	2	Operator Vigilance and Training	3	30	Add floater system similar to boilers that trigger shut off if water level below diaphragm is below an acceptable level

Table 3

An essential aspect of ensuring design reliability and safety is the systematic evaluation of potential failure modes and their effects. This process, known as Failure Modes and Effects Analysis (FMEA), is a structured approach used to identify, prioritize, and mitigate risks throughout the design and development phases. The three key measures in FMEA are severity, occurrence, and detection. Severity refers to the potential impact or seriousness of a failure mode on the system, ranging from minor inconveniences (scored as 1) to critical safety hazards (scored as 5). Occurrence assesses the likelihood or frequency of a failure mode occurring during the system's lifecycle, considering factors such as component reliability. Detection evaluates the effectiveness of current controls or mechanisms in place to detect and mitigate the effects of a failure mode. These elements are qualitatively assessed and are multiplied together to calculate the Risk Priority Number (RPN), which provides a numerical ranking to prioritize actions for risk reduction based on the severity, occurrence, and detection ratings of identified failure modes. The comprehensive Failure Modes and Effects Analysis (FMEA) conducted on our design helped guide our focus regarding redundancy implementation and design refinement. By systematically identifying potential failure modes and assessing their impacts, we gained valuable insights into areas where additional redundancy measures are necessary to enhance system reliability and safety. The FMEA process has highlighted the specific components and subsystems that require extra attention and consideration during the design revision phase.

Finite Element Analysis

Last semester we did some initial finite element analysis of the internally restrained joint in Ansys. Our results were inconclusive at the time and unfortunately we were unable to get a functioning ansys model despite help from multiple professors, some grad students, and Roy Dean, our main contact at westlake. Supports were added to the ends of the pipe in order for the simulation to run smoothly but this does not accurately model the stresses that the pipe we will see in the cyclical testing because this eliminated the longitudinal force that we want to see. We tried again during the second semester but were still unsuccessful. Our inconclusive Ansys results can be seen in figure 19.

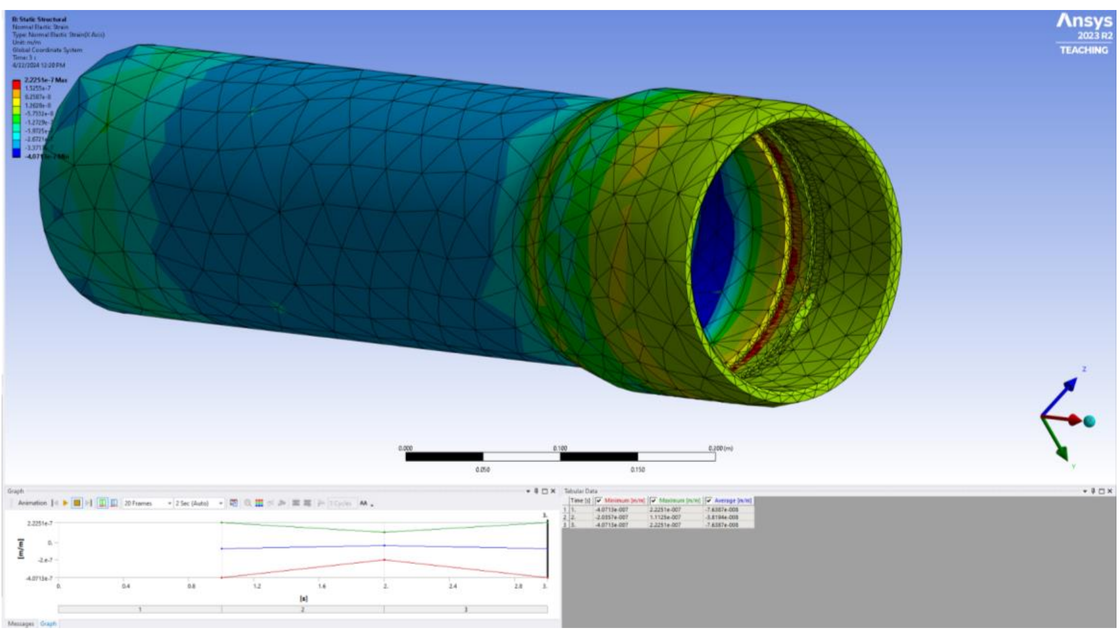

Figure 19

After having a discussion with Roy at Westlake, we were able to construct a fully functional, two dimensional, axi-semetric FEA model using SolidWorks simulation (figure 20). This gave us the result we were expecting, seeing the spline that holds the two pieces together, rotate in its groove and put excessive outward force on the bell. This is where creep can enter the system at the points of high stress and lead to a failure.

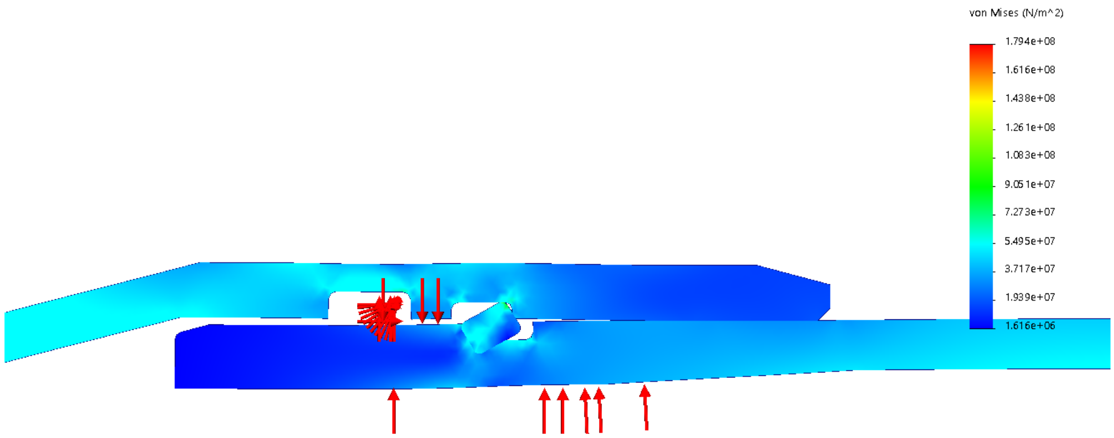

Figure 20

Final Design Testing

Regulator configuration change

As testing progressed, it was clear that our regulators were not functioning as we expected. After discussions with our contacts at Westlake, we were able to reconfigure our testing apparatus in a way we expected to successfully create a pressure cycle as the design required. With this change we were able to conduct a final run of tests to more accurately validate our design.

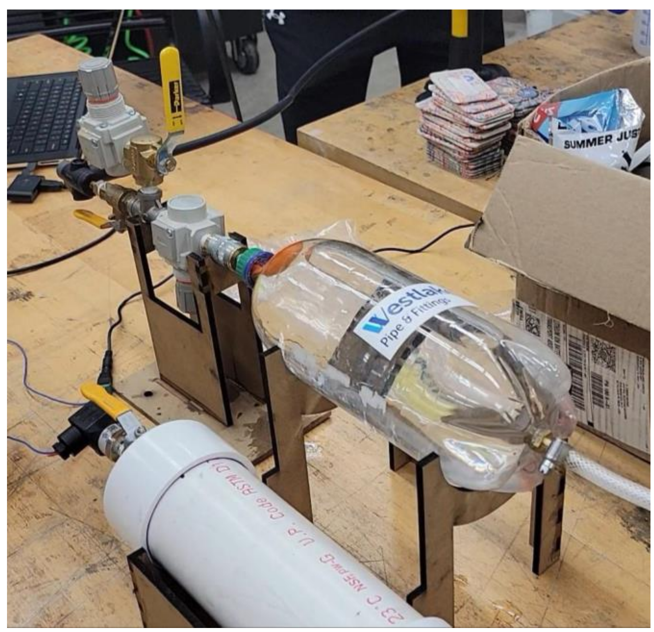

Figure 21

Results

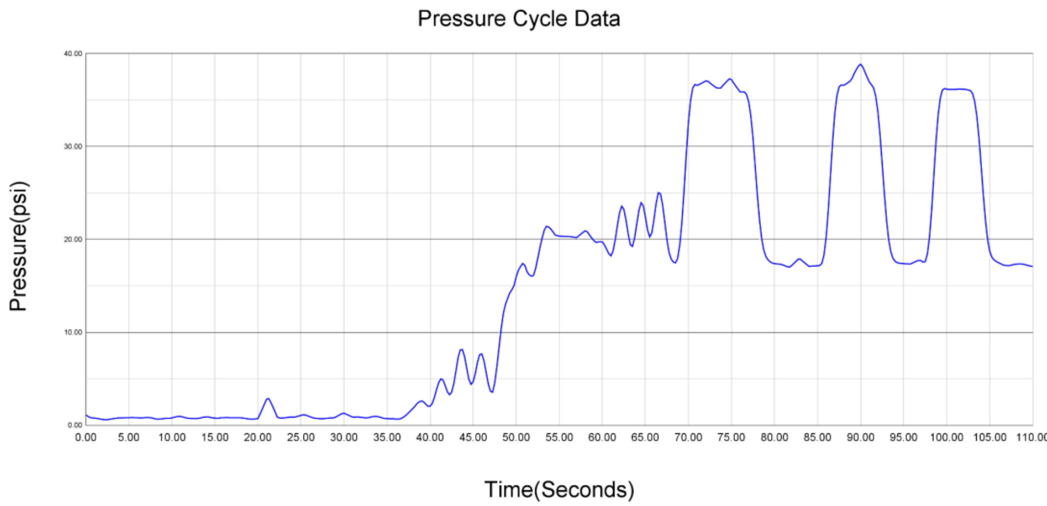

Figure 22

After receiving and graphing the data from the Arduino, we found that after the initial setup and first pressurization of the system, the pressure curve behaved as hoped and created clear control of the base and peak pressure levels using only the control of an on/off valve.

Next Steps

Due to time and logistical constraints, our final design consisted of a working manal prototype. For this apparatus to achieve functionality, all processes need to be reliably automated. This would require the replacement of some parts compared to our final design.

Automation

Solenoid Valves: Replacing the manual valves with current controlled solenoid valves would allow automation and accuracy of the flow of compressed air through the regulating system and the pipe.

Digital Regulator: An air regulator with a digitally controlled pressure would replace the need for the second solenoid valve

Programmable Logic Controller: Though we were able to encode our apparatus' logic into a PLC, we were unable to fully integrate it without the functionality of the other automatic actuators. The PLC would allow for robustly controlled pressure cycles using the feedback of a pressure transducer through the digitally controlled regulator.

Integration

The next steps in the project involve integrating all components of the testing apparatus into a cohesive system and fine-tuning the control system for optimal performance. A user-friendly interface would be designed to ensure accessibility and ease of operation. Full-scale testing would be conducted to validate cycle times and pressure consistency, both with new pipes and those that have undergone fatigue. These steps will ensure the apparatus achieves its intended reliability and functionality under real-world conditions.

Conclusion

The Westlake Pipe & Fittings capstone project culminated in the development of a functional, semi-automated testing apparatus capable of replicating high-cycle fatigue conditions for RJIB pipe joints. Despite the complexity and multifaceted challenges, the constructed prototype represents a substantial step forward toward the fully automated high pressure design.

Crucially, the project has established a strong foundation for continued improvement. Lessons learned from the initial design and testing, combined with the FMEA, and thorough research set the stage for future teams or Westlake to refine the apparatus. By systematically addressing the identified shortcomings, improving fittings, electronics, calibration routines, and automation controls, subsequent iterations can evolve into a highly reliable and industry-standardized testing solution.

In the broader context, this project contributes to safer, more efficient water infrastructure by ensuring that pipes and fittings perform reliably under the stresses they will encounter in service. As global investment in infrastructure grows, the importance of validated, data-driven design improvements cannot be overstated. The work completed here provides a strong foundation for developing testing to ensure the next generation of efficient, reliable, and robust water distribution systems.

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