Low-Cost Underwater Jetting System

Space and Naval Warfare Systems Command, SPAWAR.

Mechanical Engineering Department
California Polytechnic State University, San Luis Obispo
2017

Carson Bush
carsonbbush@gmail.com
Charles Kleeman
charliekleeman.ck@gmail.com
Daly Sombat
daly.sombat@gmail.com

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

A. Table of Contents

B. Table of Figures

C. Table of Tables

Executive Summary

SPAWAR, a research and development side of the U.S. Navy, needed a way to bury classified payloads below the seafloor in order to anchor the devices. They currently use a jetting system that costs around $20,000 to do it, and they desired a cheaper system capable of performing the same tasks. SPAWAR presented the project to Cal Poly Mechanical Engineers as a senior project in the fall of 2016.

The design team that decided to take on the project was interested in creating the system with two key factors in mind in order to make the device less expensive.

1. Find the minimal water jet pressure and flow rate requirements to allow for a payload to bury itself.
2. Create the system using as inexpensive stock materials as possible without compromising functional requirements.

After creating the system our team was able to test and verify its functionality and found that it was able to successfully bury itself and complete almost every required task. One of the largest issues we ran into was the fact that our Node, or the capsule that holds a payload, was too light and would become buoyant at certain depths.

While analyzing the tests we ran, we were able to create a list of recommendations as to what SPAWAR should do when creating their system in order to make it cost effective and functional. The following report details the design, build, test, and report process that the team underwent to create the functioning Low-Cost Jetting System.

1 Introduction

1.1 Summary

Our objective is to design a one-time use, low-cost, reliable system for Space and Naval Warfare Systems Command (SPAWAR) to bury sensors in the seafloor. Our goals are to design and build a system with the necessary driving mechanism in order to bury a payload with specified dimensions. During this process, we will conduct testings using a test tank and provide SPAWAR with detailed drawings, material selections, instructions on manufacturing, and data collection. Our main critical design challenge will be the complexity of having a functional system working under water. This project has been attempted before with different requirements, but resulting in beneficial data to further improve the design of the mechanism. Our team will be working closely with SPAWAR representatives to these achieve goals.

1.2 Persons Involved

California Polytechnic State University, San Luis Obispo senior mechanical engineering students, Carson Bush, Charles Kleeman and Daly Sombat are members on this team project. SPAWAR is sponsoring the project with Danny Meritt and Bret Thomson as their main representatives. They will assist in firsthand knowledge of the problem, previous and current solutions and the development of possible solutions. Professor Eileen Rossman and Cal Poly Mechanical Engineering Department will provide support and guidance throughout the entire project.

1.3 Problem Statement

SPAWAR needs a way to bury projects with specified dimensions in the seafloor but current standard systems are too expensive. We will provide a one-time use system that is less than $20,000, but still able to withstand the conditions on the ocean floor.

2 Background

2.1 Sponsor Needs and Background

SPAWAR is a government contracted company based out of San Diego with the purpose of integrating military related efforts on land and in the air [1]. In fulfilling these efforts, SPAWAR utilizes an underwater jetting system that buries a specified dimensioned payload into the sea floor. The system they currently use is too costly and requires a large turnaround time. SPAWAR needs a new system built in order to mitigate these two primary needs with the understanding that a lower cost system may take longer to bury the sensor. This system may use a primary driving mechanism that is attached to a subsystem known as the burial device. The burial device needs to simply be built to last one burial, but the driving system would be used for all future burials. SPAWAR will benefit from this system as it will reduce the cost it takes to bury their military grade sensors.

2.2 Existing Burial System

In order to evaluate the existing model, SPAWAR sent our team test results from their current system. This system utilized an off the shelf underwater pump that was connected to a burial device, or Node. While creating the jetting system, SPAWAR had designed three different jetting styles, all of which were located at the bottom of the burial Node.

2.2.1 Design 1

The first design of the jetting system had a singular jet aimed straight downward from the center of the bottom face of the Node. As shown in Figure 1a, the water coming from the Node would blast the sand from the center of the Node down and outward. This would slowly create a cone-shaped hole to allow the Node to sink into the sea floor. Design one was able to make a complete burial in 15 minutes, at a flow rate of 44 gpm, with a pressure of 40 psi at the outlet. The drawback of this design was that the cone-shaped hole was not an efficient way of digging due to the Node's large cross-sectional area. After SPAWAR had evaluated the hole, it was clear that the buried Node had been held up by the walls of the sea floor, as the hole extended 3 feet below the bottom of the Node.

Figure 1a. Depiction of Design 1 currently used by SPAWAR.

2.2.2 Design 2

The second Node design consisted of a 5-hole jetting nozzle as shown in Figure 1b. The initial center jet was modified to include 4 jets that were angled 45 degrees from the vertical axis in order to blast the sand hole outward, and reduce the cone-shaped hole as originally created. This was the most efficient system created, and was capable of burying the Node in 5 minutes. The measured flow rate out of the nozzles was measured at 47 gpm with a pressure of 35 psi. Although a cone-shaped hole was created from the center jet, it was not as large, and only buried the device an additional 2 inches after the pump was turned off.

Figure 1b. Depiction of Design 2 currently used by SPAWAR.

2.2.3 Design 3

A final nozzle designed by SPAWAR was a 4-hole jetting nozzle as shown in Figure 1c. The jets were aimed perpendicular to the vertical axis to simply push the sand outward from the Node. While this system had a little bit longer of a burial time at 8 minutes, it did not dig a hole deeper than desired.

Figure 1c. Depiction of nozzle 3 currently used by Spawar.

2.3 Similar Existing Systems

When looking into designing this system, our team was focused on trying to solve the underlying problem of digging a hole in the sea floor. Below are some useful machines that have been used in performing this task, the scope of driving mechanisms for these devices is expanded beyond existing jetting systems in order to later evaluate which driving mechanism may be most ideal for our design. With each digging system, research into integrating a burial device with the machine is also done to further aid in our future design.

2.3.1 Sea Plow VIII

The company, Tyco Submarine Systems Ltd., developed a subsea cable plow in 1998 that is currently used to bury cables across seafloor [2]. This machine is attached to a boat, which drags it and the cable it is burying to the cable destination. In developing the Sea Plow VIII, the traditional method of burial at the time was to simply use a metal plow, but the company was able to greatly reduce burial time and required tow force by integrating a Jet-Assisted Plowshare. This system would integrate jetting hoses aimed directly downward to breakup the sea floor which would then be plowed by the metal plow as shown in Figure 2a.

Figure 2. Jetting system stationed in front of the plow.

The addition of the jetting system reduced the required towing force by 50% and increased the speed of the plowing machine by over 2 mph. This system used a 250-HP Diesel pump to achieve an operational flow rate at 1800 gpm with a discharge pressure of approximately 90 psi. With the use of the plow it was able to create trenches approximately 3.5’ deep for cable bodies about 16 inch in diameter.

2.3.2 RoboClam

In an experiment performed by Mechanical Engineers at MIT, a robotic version of the Atlantic Razor Clam was created in order to investigate its highly efficient method of burial [4]. The RoboClam is able to dig itself into a hole using a linear actuator that is attached to two pistons. The first piston is located inside the clam and is used to expand and contract the sides of the clam in order to create a void in the sand. This void gets filled with water and sand to create a fluidized zone surrounding the device. The second piston is located above the clam and drives the device downward after the first piston is contracted.

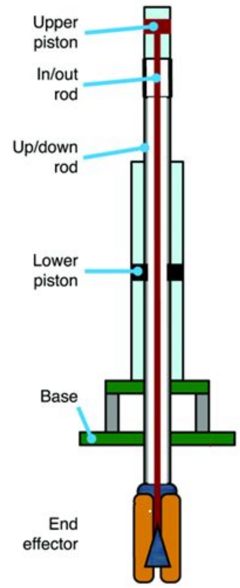


Figure 3a. RoboClam burial mechanism

In Figure 3b below, the burial device is seen through the stages of burial. The grey cloud shows how the fluidization of soil surrounds the burial device after the sides have contracted, it then shows how the device is pushed downward into the mixture.

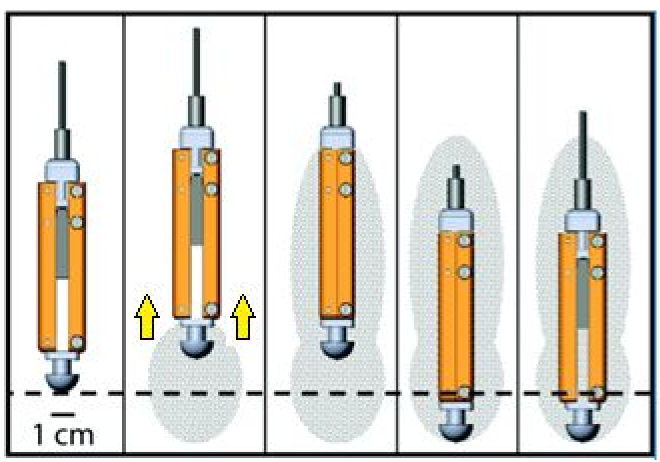


Figure 3b. RoboClam burial method.

The system is so efficient because it is able to create a small vacant space in the sea floor which induces a mixture of sand and water, as opposed to just being pushed into the sand, making movement surrounding the fluidized soil much easier. Energy efficiency was compared using a ratio of energy into the system to depth of burial of the system. This ratio came out to be 1.62 on average, while regular, or blunt-body, digging through static soil is measured to be around 2 or larger.

2.3.3 Autonomous Underwater Array Burial System

A patent idea of Jose M. Andres and Dale N. Jensen is an underwater cable burial mechanism that includes an embodiment of two nozzles at different heights spraying a jet of water for an intended path in the sea floor. In Figure 4, it shows one of the embodiment of the nozzle integrated with the plow blade. The burial mechanism comprises of a plow blade, two nozzles located in the front face of the plow blade, a pump, a cable pack to hold the cable array, at least one ski and thruster to guide it and propel it along the sea floor. The nozzles are angled between 0 degrees to 15 degrees from the vertical towards the plow blade. The first and second nozzles are separated by a vertical distance of 5 inches or less and a horizontal distance of 1.5 inches or less [4].

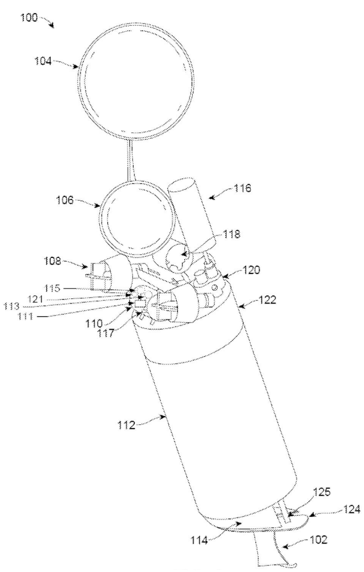


Figure 4. Autonomous Underwater Array Burial System

Testings were conducted changing various variables such as the hydraulic pressure, flow rate, the soil grit, and adding a third nozzle. It resulted that having the hydraulic pressure 60 psi or less, and the flow rate at 14.5 gallons per minute or less were efficient in targeting 4 to 8 inches in burial depth with the different mixture sizes of soil grit. During testing, it was found that increasing the pressure above 60 psi did not increase energy efficiency; in practically, it would be more difficult and expensive to deliver higher pressure. By adding a third nozzle, it showed that it was not necessary for the burial depths from 4 to 8 inches; for deeper burial depths, correlations were seen in increasing the size and flow rate of the two nozzles or adding the third nozzle.

2.3.4 Vector Corporation Mudslinger Hydro-Excavator Vacuum

Vector Corporation manufactures industrial vacuums for surface excavation, septic work and construction applications. We spoke with one of their engineers regarding the feasibility of using vacuum systems to bury the payload instead of high pressure jets. The engineer confirmed that they build systems which could easily dredge the seafloor but that their products cost in excess of $45,000. We also learned that more efficient vacuum systems inject air into the vacuum stream [5].

2.3.5 MD3 Cable Plough

Soil Machine Dynamics Ltd (SMD) designed the MD3 Plough to trench depths from 0 to 10 feet. The burial device consist of passive narrow parallel sided share with repeater burial flaps to temporarily widen trench and a plough share heel water jetting at 1760 gallons per minute at 218 psi. The maximum water depth the device can function in is about 6500 feet. Though very efficient and highly reliable with their integrated control system and monitoring equipment, it is costly, and too large scale for the necessary task.

2.3.6 Pile Installation by Vertical Jets

In an experiment performed by professors at the University of Rio Grande do Sul, a building support pile was driven into the sea floor through the use of a water jetting system [7]. This system utilized the fluidization digging technique similar to the RoboClam, but this version utilized a jet to create the sand/water mixture as shown in Figure 5.

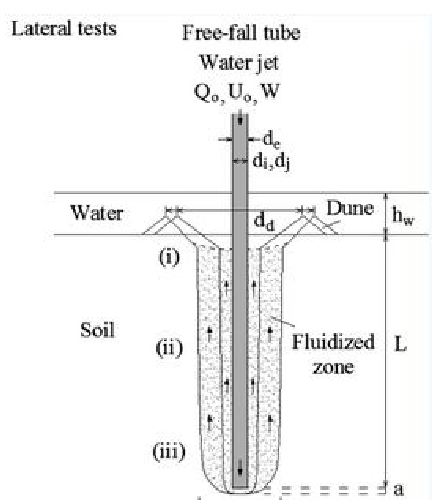


Figure 5. Pile installation by vertical jetting.

This system was able to bury itself due to the weight of the pile. The test results expressed a decrease in burial time after the jetting flow rate was increased in each of the different soil types. Results showed a limitation to this increase however, as the burial rate would not increase after the fluidized field was increased past about two times the diameter of the pile. This limitation to the effectiveness of jetting will be helpful when undergoing the design process as it will give us an idea of where the jetting will reach its maximum potential.

2.3.7 Vibratory Method

Vibratory pile drivers use weights rotating about an eccentric axis to induce vibration in a piling. In granular soils such as sands this effectively liquefies the sand beneath the piling, allowing it to sink into the soil under its own weight. They are often used above ground and typically attached to a crane which has the vibratory hammer attached to it via a dampener to prevent the crane arm from being shaken apart.

2.3.8 Hollow Stem Auger

Hollow stem augers are large screws used to drill into a wide variety of soils which have a hollow shaft meant to house casing for wells. They are used for drilling applications which require large diameter holes to be dug and are offered in stem diameters ranging from less than an inch to greater than a foot. They are attached to large drill rigs which produce 1000s of ft-lbs of torque in order to advance the screw through hard soils such as clays.

3 Objectives

3.1 Statement

We will design and build a system for burying a payload module (as specified by SPAWAR) in the seafloor. This system includes both the undersea burial system and any aboveground equipment required to run the burial system such as a pump. Our goal is to provide SPAWAR with a completed system accompanied by test data by the end of our nine month design period.

3.2 Customer Requirements

We identified three primary customers: our sponsors (SPAWAR), the naval dive team performing the payload installation, and the machine shop technicians responsible for assembling the payload. SPAWAR wants a cost effective method of securing their payload to the seafloor; the divers want a safe and easy installation process; and the machinists want the payload to be simple to fabricate.

With these basic customer needs identified, we developed the complete list of customer requirements:

- Production time: SPAWAR wants to quickly assemble burial devices.
- Cost: SPAWAR wants to reduce the cost of both their above and below water systems.
- Installation Time: SPAWAR is willing to use a burial device, which is significantly slower than their current system.
- Payload Dimensions: The payload must fit the envelope specified by SPAWAR.
- Payload Weight: The burial device weight is not limited by what a single person can lift, as they have the tools and facilities to handle large payloads.
- Implementation: This is a catch-all referring to the ease of payload installation both above the waterline and below. SPAWAR would like the installation process to be as streamlined as possible to facilitate future attempts at automating it.
- One-time Usage: The payload only needs to be secured to the seafloor once, and does not need to be designed for subsequent installations.
- Payload Orientation: The payload should be oriented vertically once secured.
- Power Supply: SPAWAR would prefer that the burial device use power from the surface, though they would like to avoid needing to use expensive and heavy generation or conversion equipment.

- Safety: The device should be safe for divers and other installation personnel to interact with.

3.3 Specifications

To assist in our design selection process, we utilized a procedure known as Quality Function Deployment (QFD), which is shown in Appendix A. QFD aggregates data from benchmarks and technical research with customer needs, which results in a list of customer requirements and technical specifications. As specifications can be interdependent, the top of the QFD diagram displays the relationships between specifications. It also lists the relative importance of each requirement as well as each specification to the requirement in the QFD.

After reviewing the QFD, we listed the specifications that could be quantitatively measured and evaluated. The specifications are listed in Table 1. We have denoted risk using L for Low, M for Medium and H for High risk. Our methods for checking compliance are denoted using I for inspection, A for Analysis and T for Testing.

Table 1. Specification table

Spec #	Parameter Description	Requirement/Target	Tolerance	Risk	Compliance
1	Payload Weight	50 lbs	Min	L	I
2	Payload Outer Diameter	> 12 inches	+ 2”	M	I
3	Payload Length	21 inches	+ 3”	L	I
4	Driving Mechanism Cost	~ $5000	N/A	L	I
5	Burial Depth	24 inches	+ 2”	L	T
6	Burial Diameter	> 12 inches	Min	L	T
7	Burial Time	~ 1 hour	N/A	H	T
8	Post Digging Depth	< 4 inches	Max	M	T
9	Water Depth	0-10 ft	N/A	L	I

The following list details the specifications listed in Table 1.:

- Payload Weight: The weight of the payload. The target payload weight is 50 lbs, which will stand-in for the weight of future payloads that SPAWAR will bury.
- Payload Diameter: The outer diameter of the payload. This is a dummy stand-in for the diameter of future payloads SPAWAR will bury.
- Payload Length: The length of the payload. This is a dummy stand-in for the length of the payload inside of the burial module.
- Driving Mechanism Cost: The cost of whatever driving mechanism (pump/generator/etc) which powers the burial mechanism.
- Burial Depth: The depth beneath the seafloor surface at which the bottom surface of the burial module reaches.
- Burial Diameter: The diameter of the hole which the payload is buried in.
- Burial Time: The time to complete a burial once the burial device reaches the seafloor.
- Post Digging Depth: The additional depth which the burial mechanism buries itself after the driving mechanism has ceased operation.
- Water Depth: The depth of water to the seafloor where the burial mechanism operates.

4 Design Development

4.1 Concepts

4.1.1 Idea Generation

To generate ideas for all possible solutions, our team conducted multiple idea generation sessions. The idea processes that were used were brainsketching, creating a morph table, and using the SCAMPER method.

Brainwriting is similar to the brainstorming method. The session consisted of choosing one function of our project, which we chose “to dig.” Each person in our team sketched as many of their own ideas on a sheet of paper in a time period of about three to five minutes. After the time period was over, we handed our paper to the next person and built off their ideas for another three to five minutes. It continued until the papers circulated back around. With this method, we were able to develop numerous concepts to that function. We were also able to see what each team member was picturing with their ideas but also build off each other’s designs. In Figure 6, one of our brainwriting papers is shown with one team member having written basic things that are able to accomplish the function of digging, and the other team members adding their ideas by creating systems.

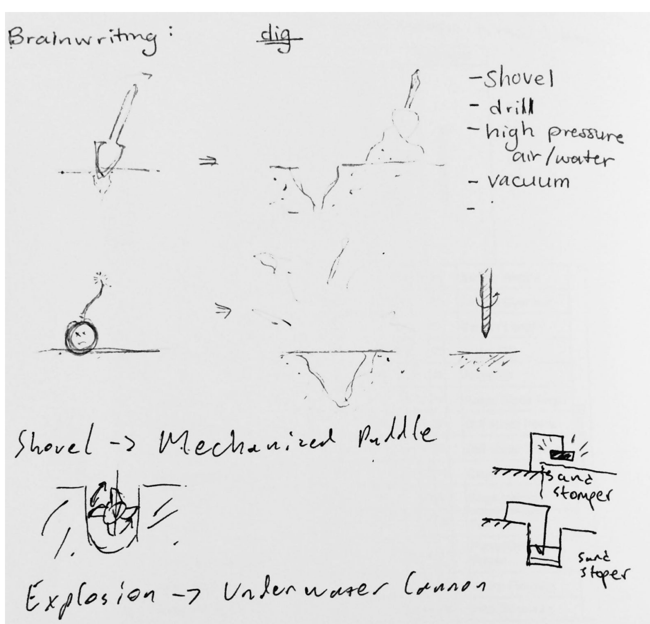


Figure 6. Sketches from brainwriting idea generation session.

The morphological table is a way to find full systems by combining ideas for each function. As shown in Table 2, our team listed all the functions involved in our project with their corresponding possible ways to accomplish that function. Using this method helped with figuring out all the functionalities of our design and listing all plausible to implausible means to those functions. Certain materials and types were chosen based on varying factors that would influence the functions. For instance, we picked materials that would not corrode with salt water for the Node material, and easily detachable but reliable types of connections between the driving mechanism and the Node.

Table 2. Morph table created during one of our idea generation sessions.

Functions:	Means:						
Driving Method	Vacuum	Jetting	Auger	Actuator	TNT		
Node Material	PVC	316 SS	Delrin	Poly-carbonate	HDPE	Aluminum	Fiberglass
Connection of Driving Mechanism and Power	Electricity (line in)	Gas	Solar	Battery	Ocean Tide	Steam	PE Gear System
Sensor Placement	In Node	On Top					
Fastening Styles	Screw	Press Fit	Weld	Glued	Clamps		
Tethering	Rubber Hose	PVC Pipe	Braided Hose				
Driving Mechanism to Node Connect	Screw	Press Fit	Cut Off	Cam Lock			

SCAMPER is a design tool in solving problems, igniting creativity or improving designs during brainstorming meetings. SCAMPER is an acronym for 7 techniques: (S) substitute, (C) combine, (A) adapt, (M) modify, (P) put to another use, (E) eliminate and (R) reverse. For our session, our team chose the technique, modify. Our team listed new possible ways to improve the old system, as shown in Figure 7. We found this method useful by focusing on improving the old system instead of thinking of other mechanisms for a solution. Basing off the existing burial system and research collected, we were able to come up with a few alterations to the old system, such as adding air bubbles to the stream and having an adjustable nozzle that would have different size output holes. Since there were limited information and data on some of these ideas, it inspired us to do some simple initial testings to narrow down our top concept designs.

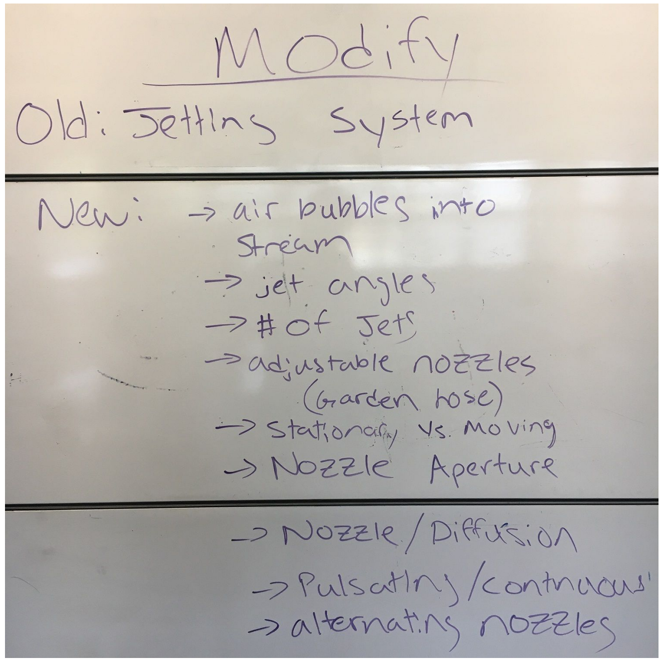


Figure 7. List of ideas using the (M) modify technique in the SCAMPER method to improve old system.

4.1.2 Concept Modeling

The main purpose of this exercise was for idea building and communicating those ideas. It was low-cost and had minimal time investment by using simple materials, such as foam core boards, aluminum foil, tape, straws, etc. to build our models. Our team focused on illustrating how the burial mechanism would be integrated with the Node. The models that we constructed are shown in Figure 8.

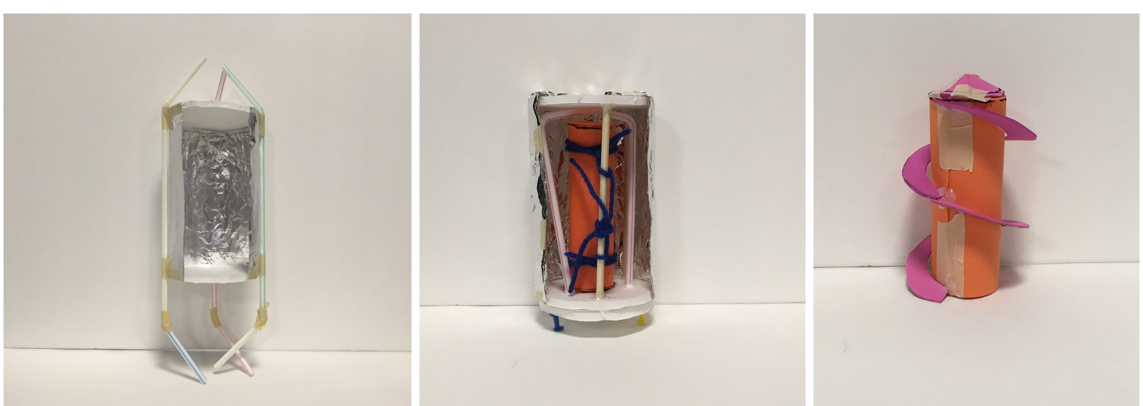


Figure 8. Simple concept models created using household items.

In Figure 8, the picture on the left was to see how the jetting/vacuum tubings would be if it were connected on the outside of the Node and to also show the multiple nozzles at different angles. The picture in the center was to display the opposite in having the jetting nozzles in the inside, and on the bottom of the Node, it would be connected to another section that has numerous output holes. The picture on the right demonstrated the hollow stem auger and the payload would be in the hollow stem section.

With our design specifications in mind, our team was able to analyze, see some of the challenges that we would encounter with building the system and continue narrowing down our selection of designs. One of the challenges that we need to keep in mind was the Node needs to accommodate the specified dimensioned payload with the burial system integrated.

4.1.3 Drawings/Sketches

When we began discussing initial design concepts, we focused on the function, “to dig” and we divided our ideas between systems which use fluid motion to displace sand, such as jetting or vacuuming, or systems which use mechanical motion, such as an auger, to displace the sand. Early design concepts focused more on how to dig sand than to bury the payload as shown in Figure 9. Jetting and vacuum lines were not integrated into a detachable burial mechanism but rather entirely separate from the payload, without any method of preventing sand from flowing back into the hole. This made the auger a more appealing option early on as we realized that we could simply embed the payload in the auger shaft and avoid sand flowing back into the hole.

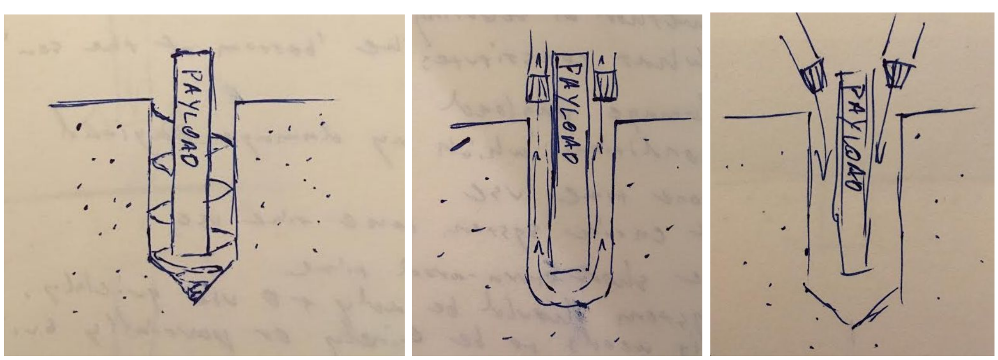


Figure 9. Depiction of three early design concepts: the auger on the left, dredging center, and jetting on the right.

After doing research on alternative burial methods, our team found the RoboClam as well as the Pile Installation methods interesting in their focus towards creating a fluidized zone to allow the burial device to easily fall into the sea floor. In Figure 10, it displays ideas generated surrounding the concept of simply trying to fluidize the sand surrounding the burial Node. Regardless of whether these devices are practical or not, the team attempted to replicate the idea behind simply fluidizing the soil surrounding the burial Node as much as possible. The left sketch in Figure 10 depicts an actuator much like the one used for the RoboClam in order to create a void which would induce fluidization of the soil just below the burial device. The sketch on the right in Figure 10 models the pile driving system. There would be a steady flow of jets around the burial device to induce a steady flow of fluidization from the bottom to the top of the buried Node.

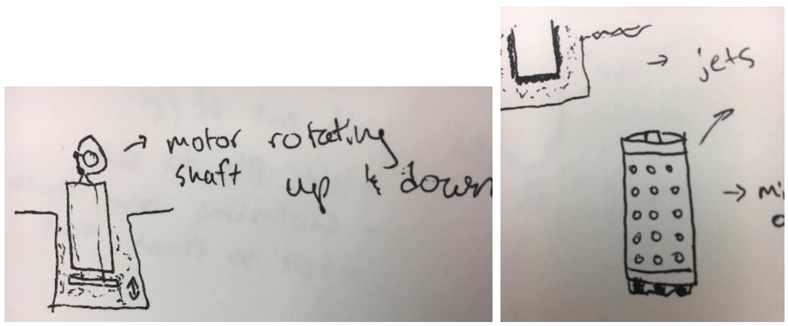


Figure 10. Depiction of design concepts based on research.

4.2 Jetting System Tests

4.2.1 Jetting Model

To help guide the design selection process, our team decided to test several different jetting nozzles to help determine our top concept system. The testing model consisted of a garden hose connected to a plastic hose attachment with five output options as shown below as Figure 11a, and then to a brass hose attachment seen in Figure 11b with three output settings.

Figure 11a. Plastic nozzle attachment. Figure 11b. Brass nozzle attachment.

Our testing tank is shown in Figure 12, which shows a 20” diameter garbage can with a bottom layer of sand approximately 12” in depth and a top layer of water approximately 20” high.

Figure 12. Testing tank (left) sand layer (right) with water.

4.2.2 Testing Results

We performed our tests with the intention of reducing as many variables as possible in order to get a more accurate idea of which nozzle type is best. One of the variables that was observed prior to recording data was that the density of the sand would decrease after a jetting trial had occurred. This happened because the sand had been stirred around in the tank. To mitigate this as much as possible, we shook the tank in order to distribute the sand better, and then waited five minutes for the sand to settle between test trials. With each test, we assumed that the conclusions would be similar when the system was scaled up. To start each test, the hose was turned on so that the valve opening was parallel with the hose. The nozzle attachment was then adjusted to select the nozzle type in question, and then placed against the layer of sand in the test tank in order to start the jetting. When the test was initiated, a timer was used to measure how long it took for the system to reach the bottom of the test tank. In Table 3, the results from each trial of the different flow types in the plastic attachment are listed with a brief description of the flow characteristics.

Table 3. Jetting system test results using the plastic nozzle.

Nozzle Type:	Nozzle Description	Time it Takes to Reach Bottom				
		Run 1	Run 2	Run 3	Run 4	Avg
		[seconds]				
	“Full” Low pressure from one opening	18	23.5*	19	17.5	18.2
	“Shower” jetting from entire bottom face straight downward low pressure	17.5	17	15	14.5	16
	“Center” Multiple streams from one exit point high pressure	15.5	21	11	16	15.9
	“Stream” High pressure from one opening	20.5	14.5	19	18	18
	“Mist” Small streams from one exit high pressure	12.5	11.5	15	14.5	13.4

Based on the results from Table 3, we believe that the most effective system would be one that induces a jetting stream that extends outward as well as downward. The results are not incredibly different from one another; thus we will not base our final design on this test alone, but we do believe this points us in the direction of using a type of wide flow nozzle.

When the jetting model was changed from the plastic to the brass nozzle, the flow rate into the hose needed to be increased in order to create a consistent flow of water when adjusting to each nozzle setting. While this flow rate was different from the plastic nozzle flow rate, it was kept consistent for each of the brass nozzle settings. The results from the brass nozzle tests are shown below in Table 4.

Table 4. Jetting system test results using the brass nozzle.

Nozzle Type:	**Nozzle Description**	**Time it Takes to Reach Bottom**				
		Run 1	**Run 2**	**Run 3**	**Run 4**	**Avg**
		[seconds]				
	Widest flow output	5	4.5	4	4	4.4
	Wide flow	2.5	3	3.5	3	3
	Narrow flow	1	2.5	1	2	1.6

These tests showed different results from the plastic nozzle tests. But after reading into the background research, we believe that the narrow flow stream was so effective because it had the higher flow rate and velocity while the stream diameter was very close to the size of the nozzle diameter. The results from this test were used to support the background section conclusions, which proposed that the effectiveness of jetting increased when the jetting diameter was closer or larger than the burial device diameter.

4.3 Dredging/Vacuum System Tests

4.3.1 Dredging/Vacuum Model

We conducted testing for the dredging system using a 3.5 horsepower shop vac. The shop vac differs from our dredging design concept as it uses a compressor rather than a pump to generate negative gage pressure at the end of the hose, but we deemed that using it to test would be much easier than fabricating our own dredge from scratch. The shop vac used was a RIDGID 6 gallon wet/dry vac (model WD 0671), which is rated at 124 airwatts and 62 cfm of airflow. We converted these values the to suction capacity using the formula below, where P is the power in airwatts, F is the flow rate in cfm and S is the suction capacity in inches of water [8].

$$P = 0.117354 \cdot F \cdot S$$

This yields a vacuum of 17.04 inches of water or 0.616 psia.

Unlike the jetting systems, we did not use alternate nozzle configurations as we were more interested in how the vacuum would perform as a proof of concept than in attempting to optimize the design. During this testing, the vacuum hose was guided solely by hand, which we believe may have introduced error into the times that we recorded. Figure 13 shows the testing of the vacuum system.

Figure 13. The vacuum system being tested.

4.3.2 Testing Results

Testing for the dredging system verified that dredging is viable for seafloor burial. The vacuum did bury itself more quickly than the variable nozzle, but slower than the higher pressure brass nozzle, with an average burial time of 5.87 seconds, as seen in Table 5. It is important to note that direct comparisons between the jetting and dredging tests are not reliable due to the informal and highly variable nature of the testing environment. However, we did accomplish our goal of verifying dredging as a viable option. This allowed us to make more informed decisions when performing our selection process.

Table 5. Dredging system test results.

Time it Takes to Reach Bottom			
Run 1	**Run 2**	**Run 3**	**Average**
[seconds]			
6.1	5.5	6	5.87

It is worth noting that one of the major limitations of the vacuum system is that its flow rate, and thus its performance, is limited by atmospheric pressure and nozzle size, whereas a jetting system can run at as a high velocity and flow rate as the pump permits. Thus, a jetting system is not subject to the same diminishing returns that a dredging system has.

4.4 Idea Selection

Before any testings began, our team created Pugh matrices for the main three components of the system, which were the burial mechanism, the exit flow setup, and the connection from the driving device to the Node. These Pugh matrices are shown in Appendix B. Pugh matrix is a tool in facilitating concept generation and selection. Our team evaluated several concepts according to their strengths and weaknesses against the base concept of the existing design. It was beneficial in evaluating each concept individually with their certain criteria because each concept differed with their function. For instance, the burial mechanism is trying to dig into the seafloor while the connection is trying to secure the attachment between the burial device to the driving mechanism. Based on the criteria of the driving mechanism, our team's highest rated system was vibration and the current and jetting system at a close second; the multiple bottom exit points and the screw fitting were the highest rated for the exit flow setup and connection/attachment respectively. All components were taken into consideration when compiling our decision matrix for our full designed systems.

After narrowing down concepts from the Pugh matrices, we combined the components to have a few full system designs and evaluated those in a decision matrix as shown in Appendix C. Our team chose SPAWAR's requirements of the project as our criteria to evaluate each system. We established that the driving mechanism cost was one of the important objectives of the project, weighed it at 20% compared to the payload weight, burial time and post digging burial at a lower weighted scale of less than 10%. As a team, we discussed and rated each system carefully to ensure we came to our final decision. After calculating the weighted rating, the jetting pump connected to burial Node with a shower nozzle was chosen at a rating of 9.7, and the jetting/dredging system connected to a burial Node coming in second at a rating of 9. After our decision of the system was made, our team wanted to do some initial, prototype testing to see what nozzle configurations would be most efficient with our system, which was discussed in Section 4.2 and 4.3.

While the tests performed were as controlled as possible, we do not believe that they are accurate enough to be the sole rationale behind our design concept. Keeping this in mind, results from the plastic nozzle tests do show a slight advantage towards using a system that jets water in a broad cone that is at least the diameter of the bottom of the burial Node. As seen in Table 3, the average time for the “wide flow” nozzles to reach the bottom of the testing tank was shorter than the more “narrow” flow nozzles. This concept is also validated in section 2.3.6, which showed that the fluidization zone around a pile being inserted into the sea floor was twice the diameter of the pile. With the testing data and background research taken into account, our team believes that a wide flow jetting nozzle should be used in order to best accommodate for the specifications defined by our sponsors. Under the assumption that a wide flow jetting system is more efficient and quicker, we also believe that the burial time would decrease and that a less powerful thus less costly pump would be needed.

The brass nozzle tests gave our team a clear understanding of how an increased flow rate and velocity will cause the jetting system to be much more powerful. While this concept may seem obvious, it was important for us to realize that there is a minimum pressure needed for some nozzles in order to create a consistent flow rate out of the burial system.

Payload dimension specifications that we have been given rely heavily on the connectors used between the pump, burial Node, and nozzle. When constructing the testing model, connecting the pieces was a more difficult process than expected. At the beginning of the test, we believed screw fittings to be the best suited to our needs; however, we realized over the course of our testing that they are not ideal. To conduct our tests, we needed to convert from garden hose thread (GHT) to threaded PVC pipes (NPT) or (BSP). Fittings which couple GHT to NPT were difficult to find and only offered in limited sized at The Home Depot and Miners. While McMaster Carr or other online retailers offers multiple fittings to fit this need, we have decided to look at alternatives that are standardized.

4.5 Top Concept

After testing various jetting styles and a few dredging techniques, we decided on a concept model that we believe most effectively accomplishes the proposed specifications. Using information and knowledge gained from the background section, idea generation sessions, concept modeling, Pugh and decision matrices, and the jetting and dredging tests, jetting was chosen as the best means of driving the burial system. A simple model of our design is shown in Figure 14.

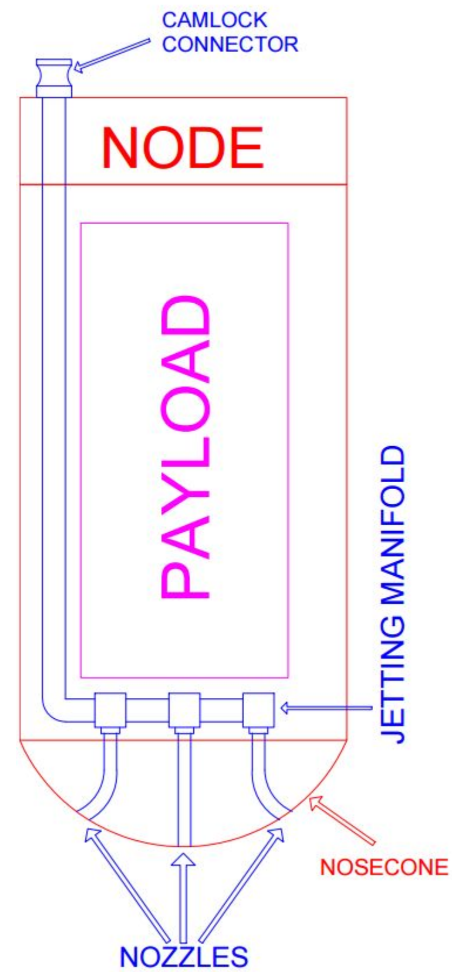


Figure 14. Model of our top design.

4.5.1 Driving System

This system will consist of an electric pump with high pressure polyvinyl chloride (PVC) tubing barbed to the outlet flow. The electric pump requirements, such as flow rate and output pressure, are not completely defined. Our team will have a completed specifications for potential pumps sent to SPAWAR on December 1st, so that it can be ordered and sent to Cal Poly in January, as recommended by our sponsors. High pressure PVC tubing will be used to ensure a large factor of safety even though our pump will most likely induce pressures greater than 100 psi based on the information gathered. PVC tubing is also resistant to corrosion from saltwater and UV light, both of which will be experienced during system use.

4.5.2 Burial Device

The outlet flow of the tubing will be barbed to a plastic camlock fitting. Appendix D gives the type of camlock that will most likely be used as retrieved from Mcmaster Carr. This fitting will allow the PVC to attach and detach with ease and will minimize energy losses. The burial device will have the opposite sex camlock connection on top connected to a cylinder made of PVC. This cylinder will be wide and tall enough to enclose the maximum specified dimensions of the payload, as seen in Figure 14. Additional tubing will be enclosed in the burial Node and attached to an outlet flow nozzle on the bottom of the burial device.

4.5.3 Nozzle

After the tubing is routed around the payload and through the bottom of the burial Node, it will be be attached to a secondary PVC cylinder acting as a nozzle. This cylinder will have the same size diameter as the burial device, but the outlet of the tube will flow into this pressurized cylinder. The bottom casing of the cylinder will have several holes drilled out to act as jet stream exit points. This nozzle will model the same plastic nozzle as used in testing with a shower design to allow for even jetting along the entire bottom of the face with a high pressure and flow rate as will be determined when the electric pump is ordered.

4.6 Safety

One of the other major considerations for the burial mechanism is the ability of divers and other SPAWAR personnel to safely interact with it. The burial mechanism has five major safety hazards: it is heavy enough to cause injury if handled improperly; it runs pressurized fluid when operational; the testing area could likely get wet; the electrical components will be securely enclosed; and people will be interacting with it underwater. A design hazard checklist with planned corrective actions are attached in Appendix E.

4.6.1 Object Weight

The weight of the payload presents a major hazard in the testing phase as we do not have access to the equipment that SPAWAR does. Weight presents two major hazards:

dropping and muscle/joint injury. In order to mitigate these risks, we will try to keep individual components of the burial system at or below the 50 pounds weight recommended by OSHA. Anything larger or heavier will be handled using carts and dollies. We will design the test tank area so that anything over the 50 pound limit does not need to be lifted overhead. Our team will also be wearing closed-toed shoes and hard hats for precautionary measures.

4.6.2 Jetting Water

Pressurized fluid can injure when a bystander stands in the path of the jet or when it causes tubing to rupture. The former can be dealt with by drafting formal testing procedures to ensure that the jet is in position before the burial mechanism is turned on. The latter can be dealt with by using pressure lines rated to pressures greater than what our pump is capable of producing, having an emergency kill switch to stop flow in the event of a rupture, installing pressure gauges to ensure pressures stay at safe levels, and having regular inspections of pressure lines and fittings. These safety hazards are taken into consideration in our final design, and are evaluated in the calculations and justification sections. Team members and those observing testing will also be required to wear safety protective gear such as eye protection throughout the duration of setup and testing of the system.

A wet testing area can be a serious slip and fall hazard. Members of the team will be briefed on how to safely navigate wet floors, and we will keep towels and mops on site to dry floors in the event of a leak or spill.

4.6.3 Electrical Concerns

In using a 230-V, 2 hp pump, our team has taken extra precautions to ensure that the dangers of the high electricity running to the system are greatly reduced. We spoke with Jim Gerhardt, Senior Technician at Cal Poly, regarding our system. He informed us that in order to be able to use the system on Cal Poly grounds, it had to be approved by him after we had consulted a professional electrician. In the process of consulting Aaron Peri, of Sierra Pacific Automation Inc., we were able to decide on a method of connecting our pump to the power source. Our idea was to include a variable frequency drive as a controller, which would be fully enclosed in order to ensure no water would reach the electrical components. Aaron informed us that he had completed plenty of these designs in the past, and that it would be simplified so that all we will need to do is plug in the system. Aaron was will be contracted to create the VFD connection while teaching the team how to safely power and operate the pump and VFD.

Although the electrical work will be contracted, the system is still considered dangerous. Our test procedure will be approved by Jim Gerhardt as well as Tom Moylan, Pier manager, before we undergo testing. We will also perform a dry run for Jim and Tom before beginning testing, as well as each time before beginning to collect data. This will ensure that each team member is aware of their surroundings, their role during testing, and the safety capabilities of the system.

Finally, there are safety considerations for underwater operation. While we will not be interacting with the payload underwater, divers working with SPAWAR will. The major hazard that we can control is designing the burial device to be free of snags or obstructions that could conceivably catch on a diver's equipment.

5 Management Plan

Our team came to the conclusion that we all had wanted to be a part of each aspect of the project. With Carson's knowledge of auger systems and drilling in general, he might have a larger role in developing the driving mechanism and specifying out the pump to be used. Daly and Charles would be more focused on the burial device, including integrating the nozzle and connections with this subsystem. Development of the system will be a team effort, because there will be plenty of tests to better understand and optimize the engineering specifications. The following list shows some major roles of each team member along with Table 6 correlating major milestones of the project with a team lead and date. Appendix F shows a Gantt Chart with a more detailed timeline of the project.

Carson:
- Financial management, purchasing lead
- Driving Mechanism

Charles:
- Main point of contact
- Burial System

Daly:
- Design analyst
- Microsoft Project coordinator
- Burial System

Timeline of Major Project Deliverables:

Table 6. Project Deliverable Timeline

Title	Lead	Date
Project Proposal	Kleeman	10/25
Preliminary Design Review	Sombat	11/18
Critical Design Review	Bush	2/7
Project Update Report	Team	3/16
Project Hardware/Safety Demo	Kleeman	5/2
Project Expo	Team	6/2

6 Final Design Details

6.1 Design Description

6.1.1 Pump

Using SPAWAR's test results from the current system, we researched pumps with similar output abilities. Appendix G shows a list of pumps that we found that we thought would be suitable for our system. After narrowing down the list based on output capabilities, pump makeup, and power sources available, we selected a pump called the Franklin Electric Turf Boss water sprinkler pump. It is a self-priming pump, which means it's designed to lift water from a level below the pump suction without having to fill the suction piping with liquid. The motor requires single-phase 240 volts and two horsepower. Based on the 2 horsepower pump's performance curve as displayed in Figure 15, it can run at a maximum operating pressure of 55 psi and maximum flow rate of 76 gpm, which is a great range of outputs for our testing. The total cost of the pump is $530 (includes taxes and shipping fees), and has a week turnaround time.

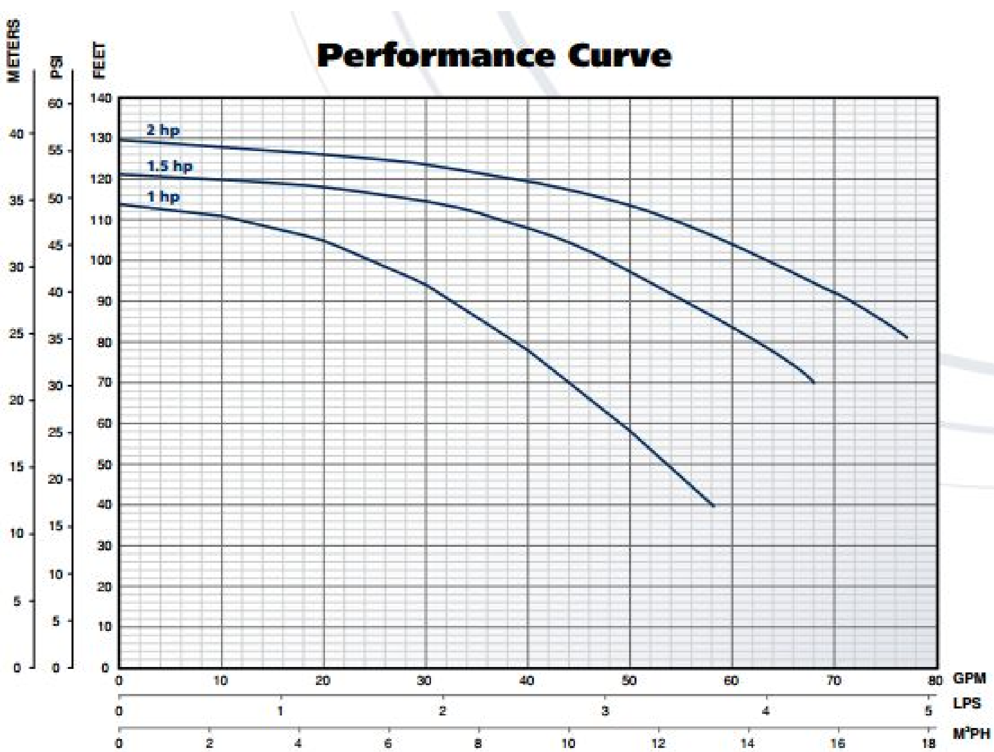


Figure 15. Franklin Electric's pump's performance curve.

A couple of concerns that we had about the pump were that the housing material is cast iron and a control panel or variable frequency drive (VFD) would not be included. Cast iron is corrosive to saltwater, and this can be problematic with our testing because we plan on pumping saltwater from the Cal Poly Pier. After researching the life expectancy of cast iron material with exposure to saltwater, we found an article about cast iron pipes that are often submerged in saltwater due to the high tides; they have a lifespan of about 25 to 30 years [9]. For our case, we plan on testing for a maximum of about 4-8 times in a month, but it will not be continuously pumping saltwater every day. We are prepared to flush it out with fresh water after testing is done for the day to keep it from scale formation, a built up of hard mineral coatings and corrosion deposits.

In order to vary the pressure and flow rate of the pump, a VFD is needed. We researched that VFD's cost a minimum of $350. Although a VFD can be costly, it would be very beneficial in collecting accurate data, which is a large portion of the analysis of our project. We talked with Jim Gerhardt regarding the wiring of the VFD to the pump and then to an external power outlet. He told us that in order to get approval to use the pump on campus property, we needed to consult with a contractor. We were able to meet and work with Aaron Peri of Sierra Pacific Automation to better understand how our pump needed to be configured electronically and how he would make it safe for use on the pier. In Figure 16. Below, an example of our setup is given.

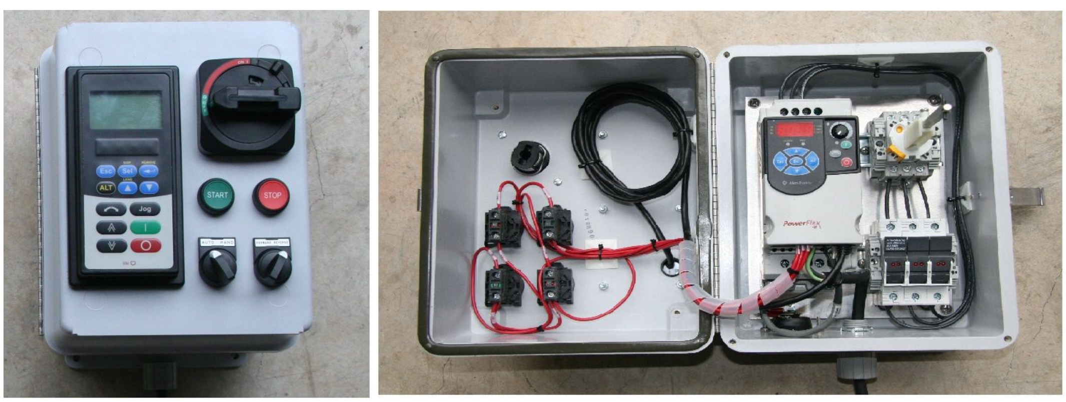


Figure 16. Similar set up of the VFD box.

The VFD will be placed inside a waterproof box and will feature on/off buttons, as well as a dial to vary the power going into the pump. The dial will allow us to manipulate the output of the pump in order to find a minimal pressure and flow rate that will still allow us to jet and bury our payload. Spawar requested that in paying for the contractor, we work alongside Aaron in order to learn more about the wiring of our system.

6.1.2 Test Apparatus

In order to test the system's viability, we designed a test apparatus to raise and lower the Node into a tank representative of the seabed, as well as monitor the flow of water through the system. This apparatus is comprised of three major subsystems: the fluid path, which is the hosing, fittings and instrumentation through which water is pumped; the crane, comprised of an adjustable gantry, clamp and electric winch; and the test tanks, which are a 55-gallon feed tank and a 200-gallon test tank, the latter of which is filled with a 2-foot layer of sand in addition to seawater. The full layout of our testing apparatus can be shown in Appendix H.

The Fluid Path

The water used for jetting starts in a 55-gallon tank. When the pump is turned on, water is sucked from the tank through 1 inch diameter braided PVC hose. The hose connects via a female camlock to a male camlock threaded onto a 1-1 ½ inch National Pipe Threads (NPT) reducer which is threaded into the pump inlet. An identical configuration is used at the pump outlet. We selected braided PVC as the primary pressure line as it would be easier to reconfigure than rigid pipe, an important consideration when the test apparatus footprint is not fully defined and getting everything to fit in our allotted space on the pier could be a challenge.

After exiting the pump, the water travels via more PVC hose to the instrumentation assembly. The assembly is comprised of a pressure gauge, a GPI flowmeter and a pressure relief valve set to open if pressure in the system exceeds 75 psi. All the parts in the assembly are connected via short lengths of PVC pipe with threaded fittings glued on the ends. A male camlock is threaded onto the output of the pressure relief valve. The camlock connects to another run of 1-inch PVC hose which runs water through the Node and out the nozzle into the test tank where excess water will flow out of a discharge valve into the ocean. The full fluid path is shown in Figure 17.

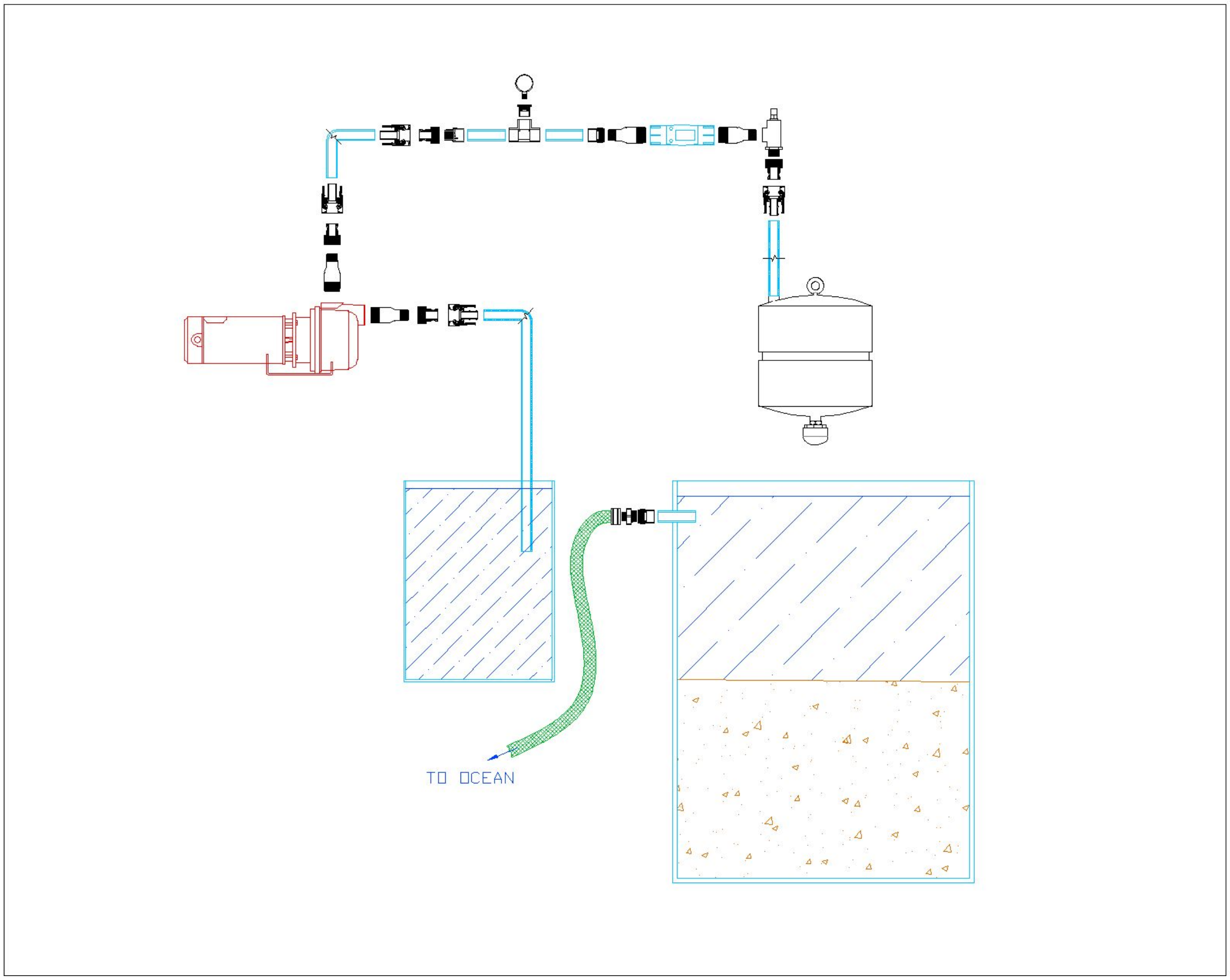


Figure 17. Testing layout of the fluid path from the feeder drum to the ocean.

The Crane

The crane supports the Node and allows us to gradually lower it into the test tank's simulated seabed as we jet. At the top of the Node, an eyebolt will be secured via a nut and washer. This is affixed via cable to a Pullzall electric winch. The winch runs off of 110V AC power and is capable of lifting over 1000 lbs, well in excess of our payload weight. The winch is suspended from a gantry crane using an I-beam clamp and carabineer. A close up of the I-beam clamp and Pullzall winch to Node connection is shown in Figure 18.

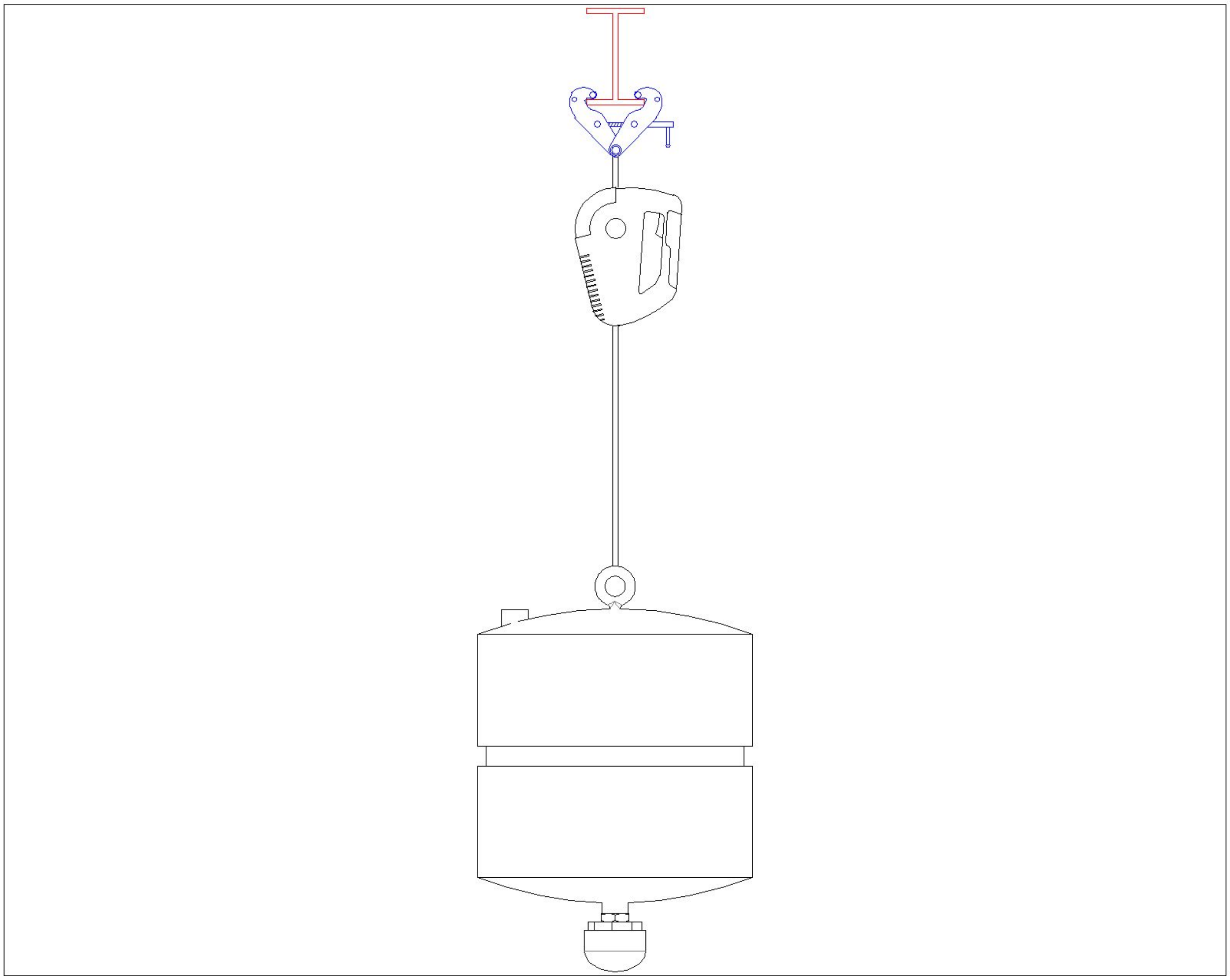


Figure 18. The Pullzall winch connection to the Node.

The Tank

To verify that the Node is able to bury our payload in the seabed, we will use a 3-foot diameter, 4-foot high test tank. The tank will be filled to the brim with seawater as well as approximately 2 feet of medium grain (0.010–0.020 inch diameter) sand. This grain size is common off of the coast of California and should be representative of the conditions in which SPAWAR will operate our system. As the Node is lowered into the tank and jetting commences, we expect that water will rise in the tank. To account for this, a hose is fitted 6 inches below the tank rim to allow excess water to flow into the ocean. The schematic of the testing tank is displayed in Figure 19.

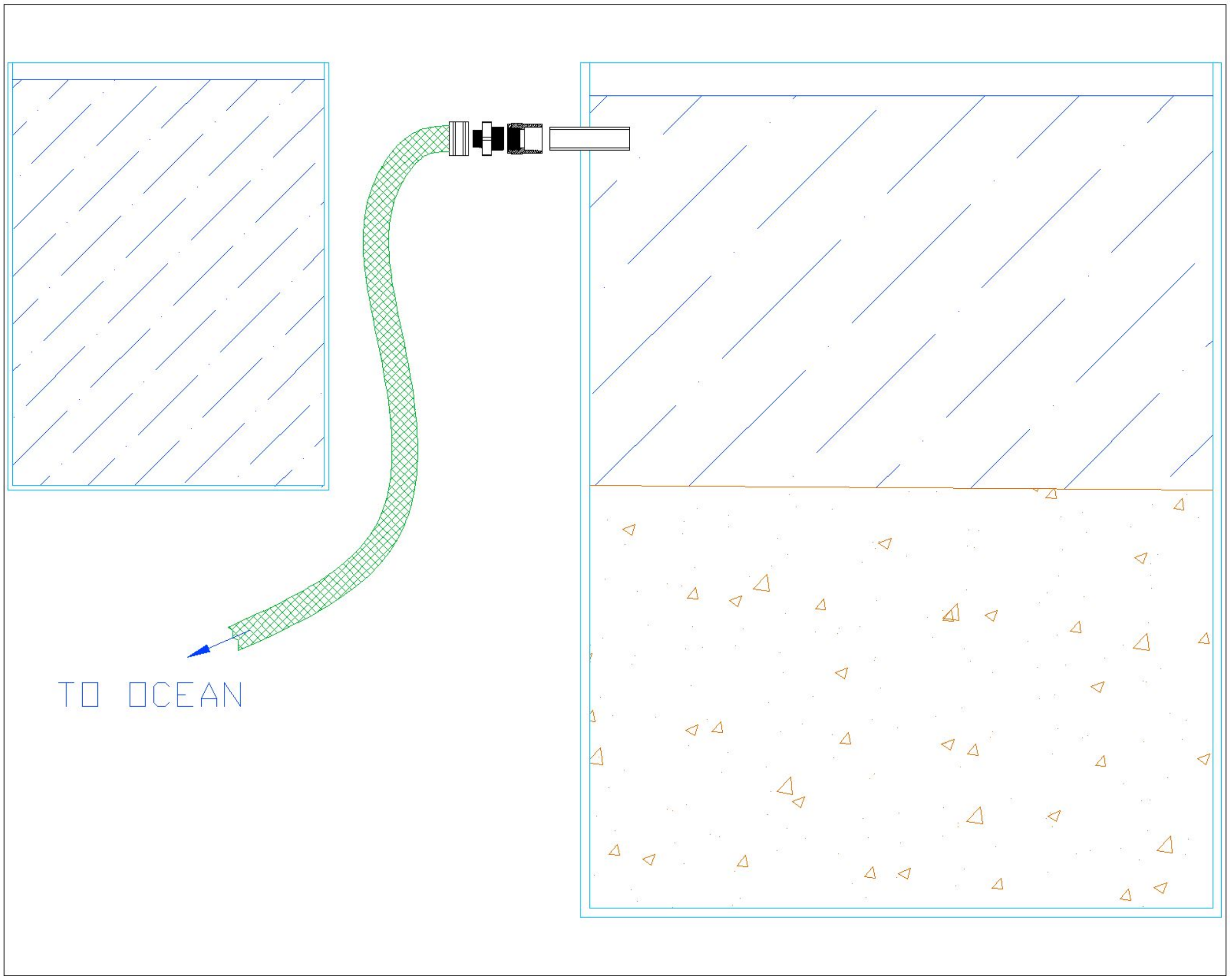


Figure 19. Feeder drum and testing tank with discharge valve.

6.1.3 Node

As previously stated, the function of the Node is to effectively direct the water jet at the seafloor to dig a hole and bury itself while accommodating for a simulated payload. Our final design of the Node is similar to the final concept, with the exception of the interior water hose and nozzle. The Node assembly can be broken into three parts: the frame, the interior hose, and the nozzle connection.

The modification of the interior set up will reduce the number of connections needed, while still allowing for the placement of a payload inside the frame. This more simplistic approach, with fewer connections, will reduce the cost of the system, and hopefully increase the efficiency of the jet. Our nozzle may have been somewhat different during the concept stage, but the new nozzle connection is much more feasible and will likely reduce any backflow as it will not contain multiple break off points. This nozzle will also allow for jetting that is completely perpendicular to the direction of digging, which may be beneficial in the jetting process. The complete Node assembly is displayed in Figure 20. And the final drawings are given in Appendix H. Node Assembly Drawings.

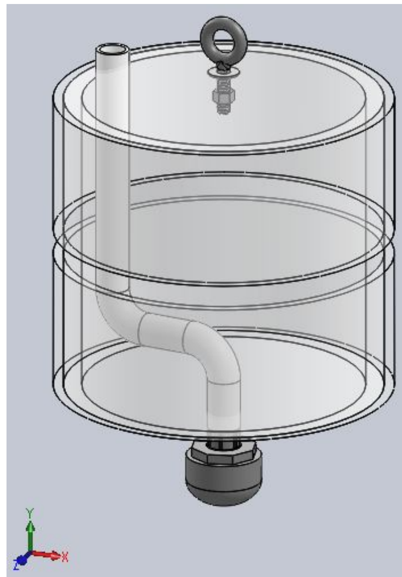


Figure 20. Assembly 10300 Node

Node Frame

As shown below in Figure 21, the Node Frame shows three stock pieces of Schedule 40 PVC ordered from PVC Fittings Online. Schedule 40 PVC is rated for a maximum operating pressure of 79 psi for 12 inch diameter pipes [10]. During testing, the only pressure that this frame will be exposed to is the pressure of the water in the tank, which will not exceed 1 Psi [11]. The function of the Node frame will be to house the payload, interior hose, and nozzle. The Node frame consists of three parts, Outer Pipe, Cap Top, and Cap Bottom.

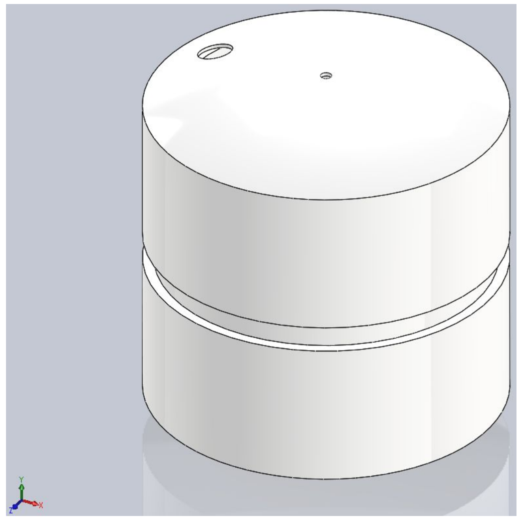


Figure 21. Node Frame

- Node Outer Pipe

The Outer Pipe has a nominal 12 inch diameter and is 12 inches in length. Cut from a 5 foot stock length, a tolerance of ± 0.125 inches is desired in order to best replicate our design.

- Node Cap Top

A 1 inch hole drilled to fit the nominal interior hose as well as a ½ inch hole in the center is shown. An eye bolt with washer and nut will be placed in the center so that the pullzall winch tool system can attach to the Node. The justification behind using the eyebolt is discussed in section 6.2.1 and calculations are shown in Appendix I. Eyebolt Loading Analysis. The entire cap will be glued onto the top of the PVC pipe.

- Node Cap Bottom

A 1 inch hole drilled in the center of the bottom cap will allow the interior tube to connect to the output jetting nozzle. This bottom cap will be held in place using three quick release pins as opposed to PVC glue so that the system can be modified during testing should a problem arise. Calculations for the pins are detailed in section 6.2.1, and are shown in Appendix I. Shear Stress Calculations.

Interior Hose

The function of the hose is to direct the jetting flow in the Node and out of the exit nozzle as modeled in Figure 22. It is the same 1 inch nominal diameter reinforced hose that is used to run water throughout the system which is rated for maximum pressures of 120 Psi. As seen in section 6.1.1, the pump is only able to reach pressures up to 55 Psi, and our pressure relief valve is at 75 psi in order to avoid getting close to the maximum pressure rating of the hose. It will be cut to about 20 inches in order to be bent around a simulated payload. Starting at the top camlock, the hose will run through the Node Cap Top, through the interior of the Node, and out of the center of the Node Cap Bottom.

Nozzle Connection

After running the hose out of the bottom of the Node Frame, the hose will then be connected to a barbed fitting, a schedule 40 PVC reducer, and a 2 inch threaded nozzle made of schedule 80 PVC .

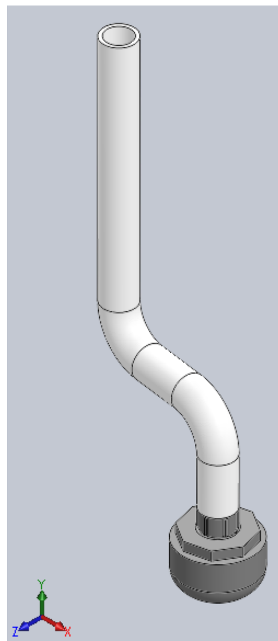


Figure 22. Interior Hose and Nozzle

The purpose of the nozzle connection is to allow us to optimize the jetting process during testing. The nozzle is a threaded end cap that will have drilled holes we plan to drill out, in order to adjust the size and direction of the jetting streams. Multiple nozzles will be ordered and fabricated to test and finalize the ideal nozzle.

6.2 Justification

6.2.1 Calculations

To ensure our design is feasible, engineering analyses were performed. The components that we took into consideration were the pin connections, the eyebolt loading, and the total head loss in the system.

As discussed in section 6.1.3, the bottom cap of the Node will be held in place using three quick release pins so the system in the Node can be modified, if necessary. To secure that three stainless steel quick release pins would be sufficient, shear stress calculations were done based on the material properties of the pin and Node/cap. Assuming the worst case scenario of having our Node flooded with water, the total applied force estimated to about 250 lbs. Using a pin diameter of ½ inch, the average shear stress resulted in a 424.4 psi per pin, which satisfies the condition of being under the ultimate and yield tensile strength of the PVC. Calculations are shown in Appendix I Pin Shear Stress [12 & 13].

Due to the significant difference in the strengths of the pin and Node/cap materials, we predict that the PVC will deform causing the pin to eventually be slanted. To prevent this from happening, we will be adding washers to keep the pins aligned and the PVC from deformation.

As discussed in section 6.1.3, an eyebolt with washer and nut will be threaded in the center of the Node's top cap so that the Pullzall system can attach to the Node. This Pullzall will help us retrieve the Node after burial in a safe manner. Appendix I. Eyebolt Loading Analysis shows a rough estimate of the total applied loading on the bolt to be about 1560 lbs based on the assumption that the Node has been fully engulfed in water and that the sand has settled around the Node completely [14]. This brings up the possibility of the PVC top cap failing during retrieval, but in order to avoid this risk, we will be turning on the jetting system and digging around the Node. We predict that this will unsettle the sand and allow us to assume that the force of the sand on the PVC is negligible. Based on this assumption, we simply calculated if the weight of the Node on the washer would cause the washer to break through the PVC top cap. As shown in Appendix I, the Eyebolt Loading Analysis shows that the normal force of the Node on the washer was not great enough to cause failure of the PVC top cap.

We also generated multiple system curves in EES to try and predict the pump's operating point and help us determine possible nozzle sizes for our test configuration. The EES calculations/codes are in Appendix I. The system curves were generated by calculating the major and minor losses in our system. We used the Hazen-Williams method to calculate major losses in the system, assuming that we were running a total of 25 feet of hose, and that the roughness coefficient of our PVC tubing is 150, equivalent to regular PVC pipe [15]. Minor losses were calculated accounting for a well-rounded inlet, 16 pipe unions, a single blocked off tee, a gradual enlargement and contraction, a rotary water meter, a 90 degree elbow (as a stand in for the pressure relief valve), a sudden expansion for the cap and a sudden contraction for the holes in the cap[16]. We used parametric tables in EES to tabulate the total head loss in the system from 5 to 80 gallons per minute and plotted these results in Excel along with the pump curve. From this figure we estimate that our system will run at approximately 60 gallons per minute and 105 feet of head (Figure 23).

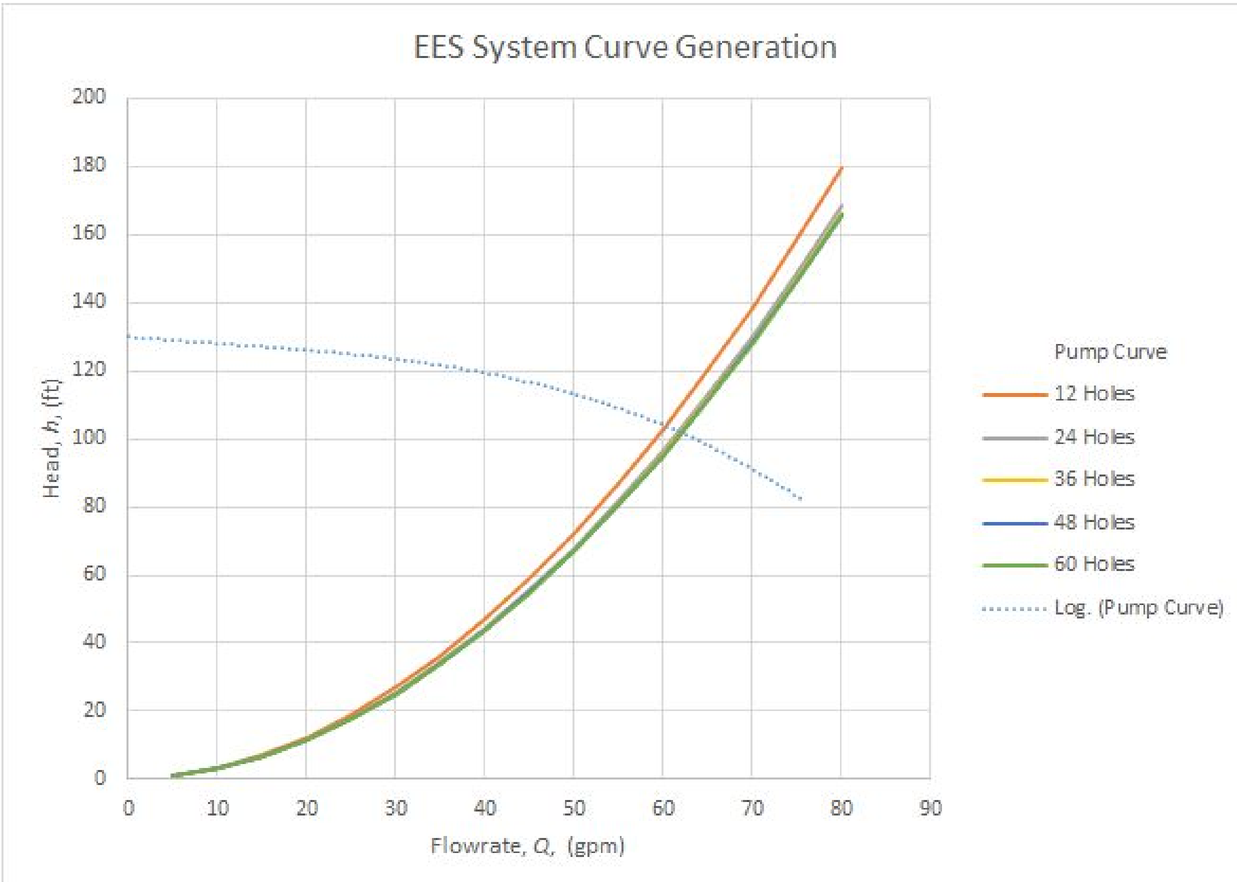


Figure 23. Plot of head versus flow rate based on EES calculations. Note that as the number of holes in the nozzle increases, the curves begin to overlap.

6.2.2 DFMEA & DVP&R

Our team identified failure modes of each function and their potential effects and likely causes in our system, as listed in Appendix J. We ranked each on their severity and occurrence and used the criticality to prioritized design changes and analysis. In one case, we found the possibility of the Node integrity failing due to the breakage of the jetting hose from worn or damaged lines. To prevent this potential problem, we plan performing routine line inspections and also, just making sure all lines are properly secured before running the system. Some actions that have already been addressed and resolved are purchasing materials that will withstand the predetermined loads, purchasing backup parts if the originals fail, and taking calculations and analyses in our final designs. Many of the actions will be taken when we begin initial testings and we will ensure they are checked properly before the system is turned on.

A design verification and test plan has been established to ensure our team accomplishes the SPAWAR's requirements. The Design Verification Plan and Report (DVP&R) is displayed in Appendix K. We have five main specifications that need to be tested: the burial time, post digging depth, vertical burial, burial depth and burial diameter. Each criteria has its acceptance tolerance. As we begin our testing, our data will be reported with our observations.

6.2.3 Bill of Materials (BOM)

With our final designs and testing apparatus analysis, we researched and compiled stock parts to begin the next process of our project: construction. Our Bill of Materials are listed in Appendix L. With the objective of keeping our system as low-cost as possible, most of our parts are stock parts that will be purchased from McMaster Carr. Some materials have been approved and already purchased by SPAWAR to minimize turnaround time and to ensure it is shipped to our team in a timely manner. Each part was chosen based on our design analysis and calculations to ensure that our system operate and function safely. For example, the PVC hosing were rated so they would be able to withstand pressures up to 120 psi, and our system will only run up to a maximum of 55 psi.

7 Project Plan

7.1 Manufacturing Plan

All parts will be constructed on Cal Poly campus in the machine shops, the Hangar and/or Mustang '60. Though most of the parts in the system will be purchased, the parts that are needed to be manufactured are: the nozzle, the Node and the PVC piping.

- Nozzle: The threaded 2-inch diameter PVC caps will need to be drilled for testing a variation of hole sizes, number of holes, and or position of the holes to determine the most efficient design. A hand drill will be used to cut out the holes. If procedure feels unsafe in any way, a drill press or another recommendation from the shop technicians will be used otherwise.

- Node: The two 12-inch diameter PVC caps will need to be drilled for the PVC piping of the pressurized water into the Node from the top and bottom. A drill press will be used to cut out the holes for the piping. Due to the dome-shaped cap, a couple of 45° wood blocks might need to be built to mount down the cap to use the drill press.

- Node: The 12-inch diameter PVC Pipe will need to be cut to 12-inch length from its stock shipping size. A band saw will be used in this process.

- PVC piping: The 1-inch diameter PVC pipes will be bought in long lengths and need to be cut down to smaller lengths for different sections in the testing system. A chop saw or a band saw will be used to cut down the PVC pipes.

7.2 Design Verification Plan

7.1.1 Testing Site

After multiple discussions with Tom Moylan, Marine Operations Manager at the Cal Poly Pier, our testing plans for our project on the pier has been approved. Our team will have to go through a couple of training sessions and demonstrate that our testing system is safe to run before given any keys to access the pier. Once our senior project advisor, Eileen Rossman and senior technician, Jim Gerhardt both approve that our overall system with our planned corrective actions for potential hazards are safe, our team will present our testing system to Thomas Moylan and Jason Felton, Pier Technician, as requested.

The advantages of having our testing apparatus at the pier are the access to the vast quantity of ocean water needed for our jetting system, a closed loop system of discharging excess water from our testing tank straight into the ocean, a 240 volt single-phase outlet, and storage of our heavy testing system.

Transporting the system

With the implementation of camlock connections, the system can be easily broken down for transport. A few of the parts, such as the gantry and pump, are mounted on wheels so they can easily be moved from storage on the pier, to the testing area on the pier. The Node, hose, and flow measuring sections each weigh under 20 pounds and can be moved by hand from storage to the testing area. The heaviest aspect of the testing system is the test tank, which will be kept at the testing area when filled with sand and water. This tank will be transported in a truck bed, and emptied before and after it is moved.

One inconvenience that will interfere with our testing apparatus being at the Cal Poly Pier is their yearly open house, which is an one-day event where they grant the public access to the pier. Due to the limited space, our team will have to break down our testing system and have it moved off the premises to accommodate the expected mass of people.

7.1.2 Testing Procedure

Setting up the system

The system will be set up at Cal Poly according to the test apparatus description and drawings shown in section 6.1.2 and Appendix H . We will show the final setup of the system to Jim Gerhardt where, upon approval, will be then broken down and set up at the Cal Poly Pier under the supervision of Tom Moylan. After the two approvals, we will be able to proceed with testing our system. The setup procedure is as follows and is subject to change by the team or any approving faculty member.

1. Use a wheeled dolly to position both the test tank and the feeder drum on an approved section of pier. Two people should handle the empty 200 gallon tank to ensure safe handling. The tanks should be within 10 feet of each other.
2. Assemble the gantry crane per instructions provided by Northern Tool, ensure that it can be wheeled directly above the test tank then lock the wheels by pressing down on the “on” part of the wheel.
3. Clamp the I-beam clamp to the center of the gantry I-beam.
4. Clip the fixed end of the Pullzall to the I-beam clamp, use a ladder if necessary.
5. Run an extension cord to the Pullzall and plug it in.
6. Using zip ties to secure the extension cord to the gantry to ensure it does not hang over the tank.
7. Unload 50 pound bags of sand and place them next to the test tank. Stack all 20 as neatly as possible and make sure to use proper lifting technique and take frequent breaks.
8. Using a safety knife, cut open a corner of the sand bag then manually tear it open and empty the contents of the bag into the test tank. Repeat until all bags have been emptied into the tank and ensure that empty bags are disposed of properly. *Wear cut proof gloves when performing this step.*
9. Using seawater provided by the pier, fill the test tank to a depth of 3 feet.
10. Wheel the pump into place adjacent to the feeder drum.
11. Set the Node down directly beneath the gantry.
12. Secure PVC hose to the inlet and outlet of the pump using the camlocks.
13. Secure the sensor assembly to the side of the gantry using zip ties.

14. Connect the sensor assembly such that the hose coming out the pump attaches near the pressure gauge and the hose coming out of the Node attaches to the pressure relief valve.
15. Lower the hook of Pullzall and attach it to the top of the Node.
16. Engage the Pullzall to lift the Node above the lip of the tank, have a team member stabilize the Node as it is lifted to keep it from swinging.
17. Unlock the wheels of the gantry and maneuver the Node over the center of the tank.
18. Plug the motor controller into the wall.
19. Screw the garden hose onto the GHT thread on the wall of the test tank and drape it off the edge of the pier.

Testing the system

In order to maintain a safe testing environment, our team has created a testing procedure that will be followed during every future test. Before beginning testing, we will practice a dry run with supervision from both Jim Gerhardt and Tom Moylan. During this supervised practice, we will run through the testing procedure and present our emergency plans in order to get the approval for testing on our own.

Test Procedure

Once the system is set up and the approvals for initiating testing are received, the following steps will be taken in order to test the system.

1. Slowly lower the Node into the water using the chain hoist, until the nozzle rests vertically on the surface of the sand in the tank. The chain hoist holder will allow the Node to be lowered under its own weight.
2. Measure the position of the top of the Node relative to the edge of the tank.
3. Ensure that students and staff are clear of the tank edge.
4. Set controller to desired test settings for the pump output.
5. Press the green “On” button on the controller.

   If the system needs to be stopped for any reason, immediately shut off the pump using the red “Off” button.
6. As the pump is running, monitor and record the system’s pressure and flow rate at 1 minute intervals. The feeder tank will be replenished with water, if necessary.
7. Once the Node has stopped digging in the tank, shut off the pump.
8. Record the depth of the Node.

9. Turn on the pump to loosen up the sand in order for easier Node removal, as per calculations.
10. Engage the Pullzall to retrieve the Node.
11. Once the Node is retrieved replenish sand in the tank. *Note that it will take several test runs to determine the amount of sand needed to replenish the tank.*
12. Let sand in the tank settle until a layer of sand two feet thick forms. If necessary use a wooden board or other flat object to level the sand in the tank.

8 Bill of Materials & Cost Analysis

8.1 Additional Materials

After receiving most of the materials on the BOM, there were a few items that were purchased by our team for convenience, such as the sand from the local store. Some items on the BOM were not used due to unexpected events during assembly and testing, and replaced with various materials. The updated BOM with all the additional materials is shown in Appendix L.

During assembly, we realized the pullzall had to be manually operated on the device to function, which would not work for our testing procedure because of safety concerns. Due to the pullzall being mounted on the steel beam clamp, there is a potential safety concern with having one of our team members leaning over the testing tank to operate the pullzall. Therefore, the pullzall was not used in our testing procedure, and a manual chain hoist was purchased and used instead.

In the course of manufacturing and assembly, we found out from our Cal Poly electrician, Ben Johnson that our pump and VFD were not compatible to be wired. With that, we modified our testing system layout by replacing the VFD, and instead added a tee branch bypass valve to our system so the pressure and flowrate can be varied. This layout is shown in Appendix H.

During testing, we thought that the Node was buoyant after it hit a certain point in the tank even after flooding the Node with water. So, another hole was drilled out on top of the Node cap in order to flood the Node with water and add weights, if needed. To counteract the buoyancy of the Node, we decided adding weights in the Node would be the most convenient solution. Ten pounds of fishing weights were brought at the local fishing docks and were added into the Node, but after a couple of testings, the Node would still be buoyant at a certain depth.

Thirteen pounds of ¼ inch diameter steel bars were purchased at the Cal Poly machine shop and cut down to length to add into the Node, with a total of 23 pounds in the Node.

8.2 Overall Cost

Our spending budget goal for this project was estimated for less than $10,000 with the driving mechanism to be around $5,000. Our total cost in building the jetting system and testing apparatus resulted in about $3,570, in which our team spent about $800 from that cost. Adding the costs of the additional materials and excluding the unused items, the price concluded to about $2,873, which is well under our budget. The highest costs from our BOM came from the gantry, the pump and the flowmeter, while the other materials were reasonable due to the materials being stock parts. All details of the material costs are shown in Appendix L.

9 Product Realization

9.1 System Manufacturing

There were minimal machining in order to keep the cost low. Every stock part was manufactured in the machine shops on Cal Poly campus. The Node, the nozzle, and PVC piping were the only parts in our system that were machined.

- Node: There were a few difficulties we encountered with the Node. A drill press was used to drill out the two 1-inch diameter holes for the top and bottom of the 12-inch diameter PVC caps, but due to the rounded edge of the cap, the PVC caps were not mounted. Instead, it took three people to accomplish drilling the holes out: two to hold it down and the other to operate the drill press. The 12-inch diameter PVC pipe was cut down to a 12-inch length using a hacksaw, which was more work than originally planned. The original intent was to use a bandsaw, but it was too large for the machine in the shop. The pin holes on the side of the Node of the bottom cap were easily drilled out with a hand drill.
- Nozzle: The threaded 2-inch diameter PVC caps were simply drilled using a hand drill. There were three different nozzle configurations. For one nozzle, there were eight ¼” diameter holes drilled straight downward onto the top of the nozzle cap. The second nozzle also had eight ¼” diameter holes drilled out but were angled outward at about 45 degrees. The last one had 12 ¼” diameter holes drilled straight downward and six ¼” diameter holes drilled horizontally outward on the side of the cap.

- PVC piping: The 1-inch diameter PVC pipes and hoses were easily cut to length for different sections of our system by using a vertical band saw.

9.2 Assembly

9.2.1 System Assembly

There were multiple components that needed to be assembled securely in order to create a system that was safe to use. Each threaded connection of piping was reinforced with Teflon tape to avoid leaks in our system. The PVC hoses were connected with camlocks and reinforced with PVC tube clamps to secure the connections. The sensor connection assembly, which contains the pressure gauge, flowmeter, and PVC piping, were glued with the PVC cement. The sensor connection assembly is shown in Figure 24. We found that the pressure relief valve was not needed because our system would only be running at less than 20 psi and the pressure relief valve was rated for 75 psi. The new testing layout can be shown in Appendix H.

Figure 24. Sensor connection assembly, which contains the flowmeter and the pressure gauge (not shown).

Due to the incompatibility of the VFD and the pump, a bypass valve was built into the system to replace the VFD in order to vary the flow rate. A ball valve, a tee, and PVC piping were assembled and connected to the the pump, the sensor connection assembly, and PVC hosing that would be discharged back into the reservoir tank. The bypass valve assembly is shown in Figure 25.

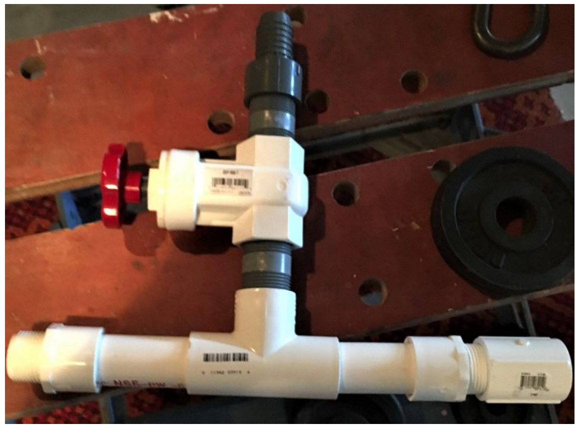


Figure 25. Bypass valve assembly.

9.2.2 Node Assembly

One unexpected concern was that once the body of the Node and the cap were put together (without the PVC glue), it was hard to get the cap off the body of the Node. Our previous thoughts were that if there were any leaks or anything wrong inside the Node, we would be able to release the pins and easily take the bottom cap off. One way we tried to solve this issue was applying marine lubricant to the inside of the cap and the body of the Node, which still failed to slip the bottom cap off the body of the Node. We found that sanding down the outer body of the Node and the inside of the bottom cap helped remove the cap off the body of the Node.

9.4 System Testing

9.4.1 System Setup

Once the safety and hardware dry test run demonstration was approved by Professor Rossman, our system was transported to the Pier. After gaining approval for testing on the Pier from Tom Moylan, our team was ready to set up the system for testing over the course of a month. The gantry was set up according to the packaging instructions and moved in the designated section of the Pier used for testing. The pump was installed by the Cal Poly electricians. All equipment were not moved until the system testing was completed. A picture of the system setup is seen in Figure 26. below.

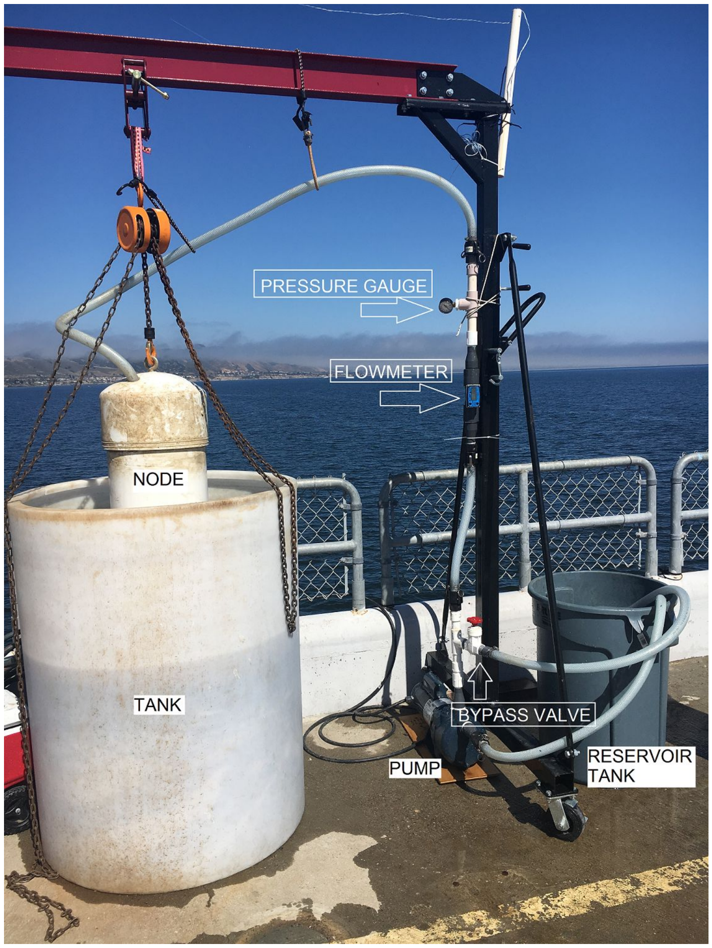


Figure 26. Testing system setup

1. Gantry wheels were locked in place using the wheel locks as well as wooden chucks.
2. Test tank was positioned underneath the center of the gantry and the reservoir tank just on the outside of the gantry.
3. I-beam clamp was hand-tightened onto the center of the support beam of the gantry.
4. Chain hoist was attached to the I-beam clamp using a 1,000lb rated climbing rope.
5. Approximately 21 bags of 15-cubic feet of sand was placed into the testing tank.
6. The test tank was then filled with water so that when the sand was saturated and settled, the water extended one foot above the sand in the test tank.
7. The chain hoist was lowered completely and the Node was attached using the hoist clamp.
8. PVC hose was attached to the inlet of the pump using the camlock, and the other end was inserted into the reservoir tank.

9. The tee-branch and valve were attached to the outlet of the pump using threaded connections and teflon tape.
10. The PVC and camlock were then secured onto the tee-branch with one end going into the reservoir tank and the other going to the sensor assembly.
11. Sensor assembly was attached to the side of the gantry using zip ties.
12. PVC from Node was attached to the other end of the sensor assembly.

9.4.2 Testing Procedure

This procedure was used for each test taken at the Cal Poly Pier, the testing data is shown in Appendix K. and analyzed in 9.4.3. If any safety concern of the equipment arises, reference Appendix M for the operator's manual.

1. Fill the Reservoir tank with water using the Pier water hose.
2. Slowly lower the Node into the test tank using the chain hoist, until the nozzle rests vertically on the surface of the sand in the tank. The person holding the chain will allow the Node to be lowered under its own weight when the test is being performed.
3. Measure the position of the top of the Node relative to the tank.
4. Set valve on the tee-branch to the desired test settings for the pump output.
5. Switch the pump on by selecting the "On" position at the power source and begin the timer.

   If the system needs to be stopped for any reason, immediately shut off the pump by switching to the "Off" button on the power source.
6. As the pump is running, monitor and record the system's pressure and flow rate.
7. If necessary, use the pier water hose while the pump is running to ensure the reservoir tank is filled with enough water to complete the test.
8. Once the Node can no longer bury itself, shut off the pump and stop the timer.
9. Take the slack off the chain and record the depth of the Node as well as the total time to bury.
10. Use the chain hoist to retrieve the Node.
11. Once the Node is retrieved, replenish sand in the test tank and water in the reservoir tank.
12. Rake the sand to get an even surface of sand along the tank.
13. Let sand in the tank settle for approximately 30 minutes or until a layer of sand approximately two feet thick forms.

9.4.3 Testing Data & Analysis

During our testing phase, we were able to accomplish most of our desired goals from vertical burial of the Node, to different burial rates based on the Node input flow. In our DVPR attached as Appendix K., it can be seen that our system passed every test except for the depth test as we were not able to bury the Node 24 inches or greater. The raw data table in Appendix K. displays the information recorded during testing as well as some notes regarding how each jetting trial ran. Figure 27. below displays the burial rates of each nozzle grouped by the valve position. Our data shows that the burial rate increased with the increase in flow rate as we had expected, and the lowest burial depth reached was approximately 21.5 inches.

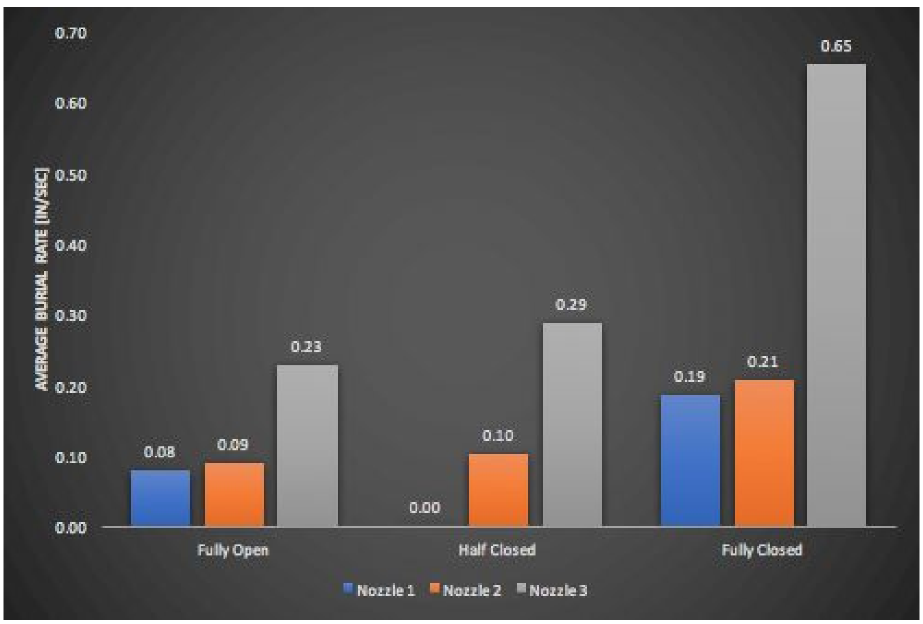


Figure 27. Burial rates with respect to nozzle and flow settings

Our team decided to do some simple calculations to find velocity and pressure of the water jets at the exit of the nozzles based on the values recorded at the pressure gauge and flow meter as seen in Appendix I. These calculations utilize the modified Bernoulli's equation while neglecting head losses, because the length of the jetting tube was so small, to give an estimated pressure and velocity at the exit points [17].

9.4.4 Data Interpretation

Nozzle Type

After testing various nozzles during our preliminary design phase and more notably during the testing phase from the actual system as displayed in Figure 28., our team was able to better understand the way jetting burial works.

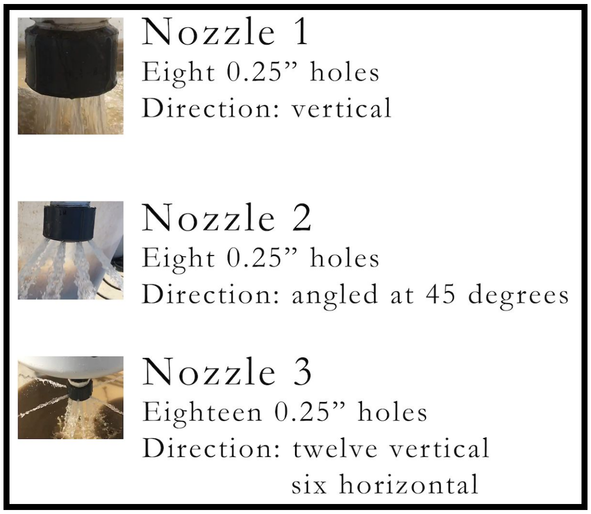


Figure 28. Nozzles used during testing

With our three nozzle types, we noticed that the horizontal and angled jets are more efficient than the vertical jets. We also determined that more holes in a nozzle allows for a higher flowrate and thus a faster burial. This supported our intuition that a wider jetting area would be more conducive to quick burial than a deeper one.

Burial Rate

An interesting phenomena that we observed during testing was a decrease in burial rate once the Node reached a depth of around 12-14 inches. We concluded that the most likely explanation was that that the nozzle was actually coming into contact with the bottom of the tank. The variation in chain length can be accounted for by the lateral movement of the node within the tank during testing. The rate could theoretically be affected by the depth of the payload beneath the surface of the sand as a multiphase fluid comprised of sand and water is more dense than water and thus exerts a nominally greater buoyant force but we did not address this during testing as our measurements only concerned the average burial rate.

10 Recommendations

There are multiple components we would modify in future iterations of the system design, which we found through manufacturing, assembly, and testing. These components should be highly considered when designing the actual system because they are aimed at lowering the cost of the system that is still able to accomplish the task of burying a device in the sea floor.

10.1 Node

As discussed in the Data Interpretation section, our Node would become neutrally buoyant and effectively stop digging after reaching a certain depth. In future iterations of the Node, our team would further increase the weight of the device by placing weights inside the Node surrounding the payload. We also believe that because the specific gravity of PVC is slightly less than that of water, constructing future nodes out of a more dense plastic such as HDPE may aid in burying the device. However, given the relative abundance and low price of PVC pipe and pipe fittings this could prove to be more expensive than simply adding ballast.

10.2 Nozzle

Our results indicated that the third nozzle, one which combined horizontal jetting with a number of vertical jets, was the most effective. We believe that this is due to a combination of factors, the horizontal jets increased the surface area of fluidized sand for the payload to sink into, and the greater number of holes which allowed for a greater flowrate. We believe that future nozzle designs should incorporate at least the 18 ¼-inch holes that we used in the third nozzle design and believe that even better results could be achieved with more holes or the incorporation of holes angled at 45-55 degrees into the nozzle alongside the existing vertical and horizontal holes.

10.3 Pump

During our tests, the same pump was run at full power with different settings for a bypass valve used to simulate different pump outputs to produce water jets of varied pressure and intensity. Even at low output flow, we were able to cause the Node to bury itself. While we were not completely sure as to why burial stopped, though we do strongly suspect that the node had simply reached the bottom of the tank, we noticed that both added weight and an increase in the water jet flowrate assisted in the burial rate.

10.3.1 Pump Type

The pressure recorded during testing remained around 5 psi, or about 12 feet of head, while the maximum was recorded to be 14 psi, or about 32 feet of head. These pressures are significantly lower than the pressures used in the SPAWAR tests of between 35-40 psi. This data, along with our research prior to testing, shows us that a pump, which is able to give a high flow rate at lower pressures, would be just as good for jetting purposes than using a pump with both high flow and high pressure outputs. Since a pump that is not required to output as much head would be more cost effective and energy efficient, we would recommend that SPAWAR use a centrifugal pump that is able to output around 20-30 feet of head at around 20-40 gpm.

10.3.2 Battery Powered System

Because the system would ideally be powered using a battery where electrical power would need to be minimized, two pumps working in parallel would be able to achieve the high flow rates at lower pressures as shown in Figure 29. below.

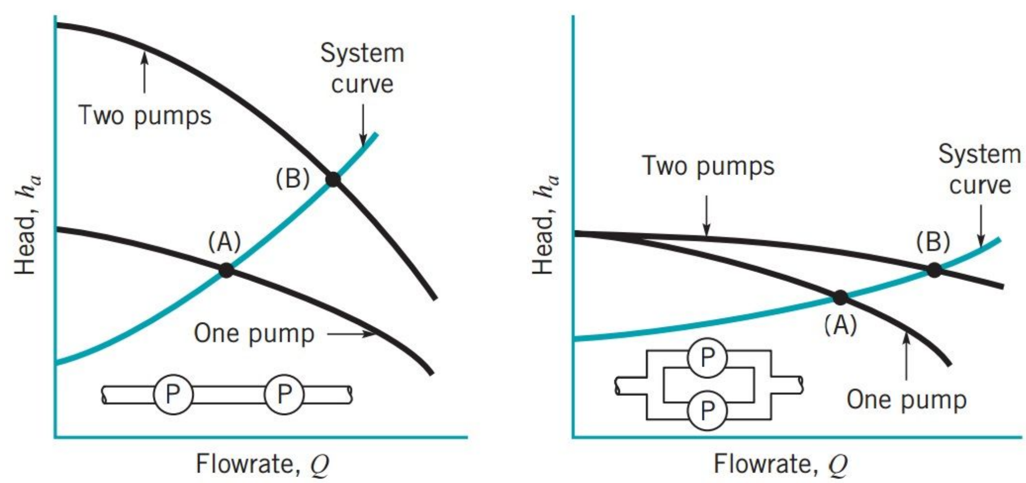


Figure 29. Two pumps in series (left) and two pumps in parallel (right) [17].

Using two pumps in parallel would allow the pumps purchased to be smaller, and would allow for the use of lower voltage pumps, at the expense of the additional weight and cost of multiple pumps. This setup may be more useful in the future if this device were to be automated.

11 References

1. [1] “SPAWAR About Us.” *The Navy’s Information Warfare Systems Command.* United States Navy, n.d. Web. 19 Oct. 2016

2. [2] Messina, Frank D. "Advances in Undersea Cable Burial Technology for the Twenty-First Century." (n.d.): n. pag. Web. 8 Oct. 2016.

3. [3] Winter, Amos G., V, and Monica Isava. "An Experimental Investigation of Digging Via Localized Fluidization, Tested With RoboClam: A Robot Inspired by Atlantic Razor Clams." *Journal of Mechanical Design*. N.p., 8 July 2016. Web. 20 Oct. 2016.

4. [4] Andres, Jose M., and Dale N. Jensen. “Autonomous Underwater Array Burial System.” *Google Patents.* Google, 28 Feb. 2013. Web. 19 Oct. 2016.

5. [5] Vector. "Vector Corp Interview." Telephone interview. 20 Oct. 2016.

6. [6] “SMD Products - MD3 Cable Plough.” *SMD.* Soil Machine Dynamics Ltd, n.d. Web. 20 Oct. 2016.

7. [7] Schnaid, Fernando, and Larissa De Brum Passini. "Experimental Investigation of Pile Installation by Vertical Jet Fluidization in Sand." *Journal of Offshore Mechanics and Arctic Engineering*. Federal University of Rio Grande Do Sul, 16 June 2015. Web. 23 Oct. 2016.

8. [8] ASTM International, ASTM F558 - 13, 2013

9. [9] Wilson, Mike. "Your Building's Drainage System: How It Works & Repair." *Pipelining Technologies*. Pipelining Technologies, Inc, 29 Nov. 2016. Web. 23 Dec. 2016.

10. [10] "PVC Pipes - Pressure Ratings." *PVC Pipes - Pressure Ratings*. N.p., n.d. Web. 04 Feb. 2017.

11. [11] "How Does Pressure Change with Ocean Depth?" *US Department of Commerce, National Oceanic and Atmospheric Administration*. N.p., n.d. Web. 04 Feb. 2017.

12. [12] "Bolt or Pin In Single Shear Equation and Calculator | Engineers Edge." *Bolt or Pin In Single Shear Equation and Calculator | Engineers Edge*. Engineers Edge, LLC, n.d. Web. 29 Jan. 2017.

13. [13] Kerns, Jeff. "What's the Difference Between Bearing, Shear, and Tear-Out Stress?" *Machine Design*. Penton, 1 July 2016. Web. 29 Jan. 2017.

14. [14] Blattenberger, Kirt. "Density of Some Common Building Materials." *Density of Common Building Materials per Cubic Foot - RF Cafe*. RF Cafe, n.d. Web. 29 Jan. 2017.

15. [15] Fox, Robert W., Alan T. McDonald, Philip J. Pritchard, and John W. Mitchell. *Fox and McDonald's Introduction to Fluid Mechanics*. 9th ed. Hoboken, NJ: Wiley, 2015. Print.

16. [16] "Appendix A: Physical Properties of Fluids And Flow Characteristics of Valves, Fittings and Pipe." *Flow of Fluids*. 4th ed. New York City: Crane, 1982. A-26-29. Web.

17. [17] Munson, Bruce Roy, Donald F. Young, and Theodore Hisao Okiishi. *Fundamentals of Fluid Mechanics*. 6th ed. Hoboken, NJ: J. Wiley & Sons, 2006. Print.

12 Appendices

Appendix A: QFD

Legend: ● = High, ○ = Medium, ▽ = Low

		Specifications								
	Requirements	Payload Weight	Payload Diameter	Payload Length	Driving Mechanism Cost	Burial Depth	Burial Diameter	Burial Time	Post Digging Burial	
Customer		A	B	C	D	E		F	G	
SPAWAR	Low cost	▽	▽	▽	●	○	○	●	▽	
	Short turnaround time				▽					
	Burial device made of stock materials	▽	▽	▽		▽	▽	○	▽	
	Production time minimized								○	
	Easy implementation	●	●	●	▽					
	Burial device used once	▽	▽	▽				○		
	Payload orientation vertical		▽	▽		○	○	○	▽	
	Power supplied electric				●				○	
	Safely interact with divers/crew				○	▽	▽		▽	
	Targets	>=50 Lbs	8"	21"	~5,000$	24"	>12"	>~1 Hour	<4"	
	Weighted Importance	3	7	7	6	8	8	4	2	
	% Importance	6.7	15.6	15.6	13.3	17.8	17.8	8.9	4.4	100.0

Appendix B: Pugh Matrices

Exit Flow Setup					
Concept	Current Nozzle	Rotating Nozzle	Bottom Surface Area	Multiple Bottom Exit Points	Side Exit Points
Criteria	1	2	3	4	5
Cost	N/A	-	+	S	-
Flow Rate	N/A	-	-	S	-
Pressure	N/A	-	-	S	-
Surface Area Dispersion	N/A	+	+	+	S
Connections needed	N/A	-	S	S	-
Digging Performance	N/A	+	+	+	+
Constant Flow Direction	N/A	-	S	S	+
Σ +	-	2	3	2	2
Σ -	-	5	2	0	3
Sum	0	-3	1	2	-1

Burial Mechanism						
Concept	Current Soln.	Auger	Jet	Dredge	Jet/Dredge	Vibration
Criteria	1	2	3	4	5	6
Depth	N/A	S	S	S	S	S
Diameter	N/A	-	S	S	S	S
Weight	N/A	-	+	-	-	+
Complexity	N/A	-	S	-	-	+
Reliability	N/A	-	S	S	S	-
Speed	N/A	-	-	-	+	-
Cost	N/A	+	S	+	-	+
Σ +	-	1	1	1	1	3
Σ -	-	5	1	3	3	2
Sum	0	-4	0	-2	-2	1

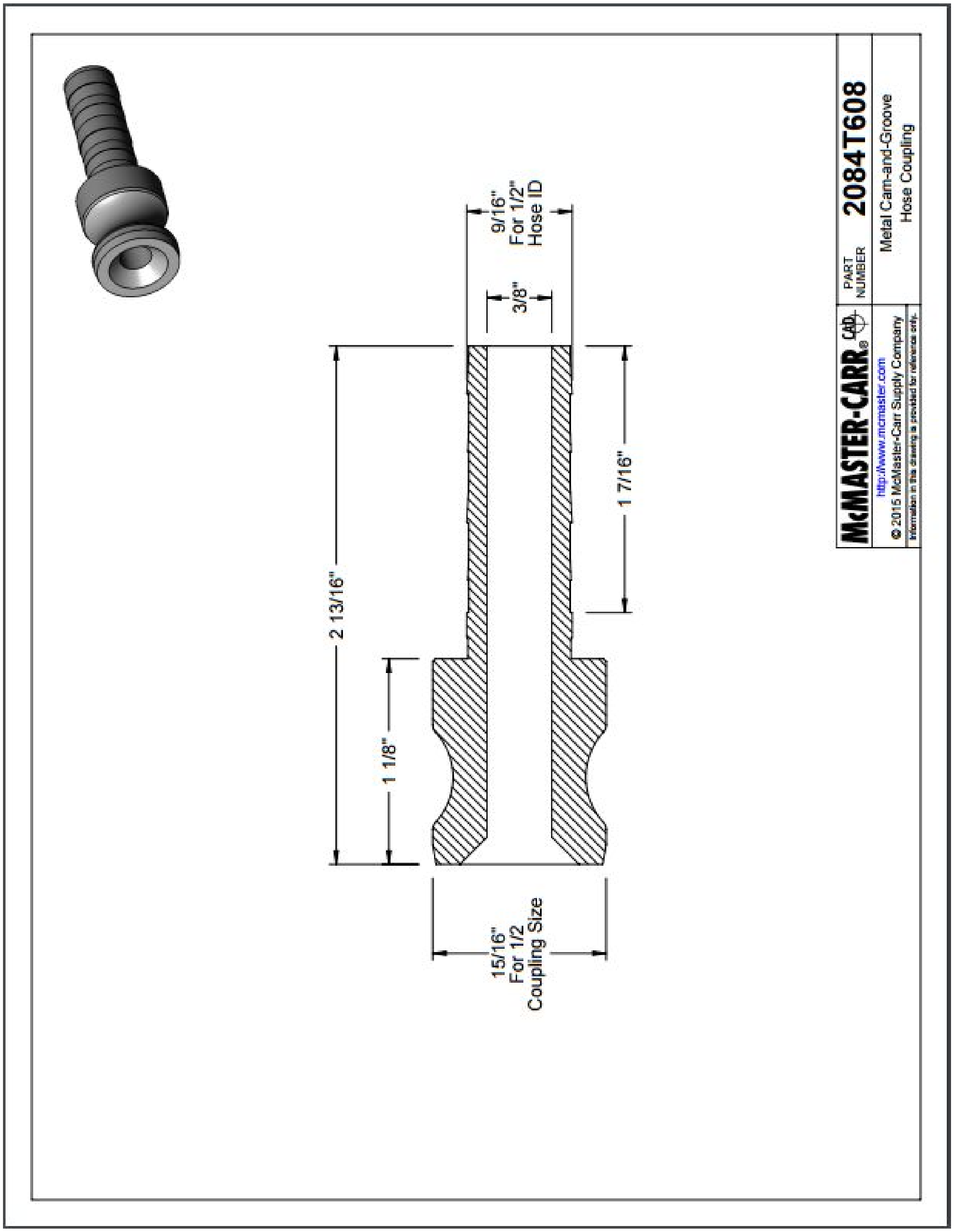
Connection/Attachment								
	Concept	Press Fit	Screw	Weld	Clamps	Valve	Quick Connect	Cam Lock
Criteria		1	2	3	4	5	6	7
Cost		N/A	+	-	S	S	S	S
Manufacturing		N/A	+	+	S	+	S	S
Ease of Installation		N/A	S	-	+	+	+	+
Detachment		N/A	-	-	+	-	S	+
Reliability		N/A	+	+	+	+	+	+
	Σ +	-	3	2	3	3	2	3
	Σ -	-	1	3	0	1	0	0
	Sum	0	2	-1	3	2	2	3

Appendix C: Decision Matrix

Concept		Payload Weight	Payload Diameter	Payload Length	Driving Mechanism Cost	Burial Depth	Burial Diameter	Burial Time	Post Digging Burial	Total
Hollow stem auger with above sea floor drilling rig	**Weight**	10.00%	15.00%	15.00%	20.00%	15.00%	15.00%	5.00%	5.00%	100.00%
	Rating	10	5	10	3	10	5	9	10	--
	Weighted Rating	1	0.75	1.5	0.6	1.5	0.75	0.45	0.5	7.05
Jetting pump connected to burial node with shower nozzle	**Weight**	10.00%	15.00%	15.00%	20.00%	15.00%	15.00%	5.00%	5.00%	100.00%
	Rating	10	10	10	10	10	10	8	6	--
	Weighted Rating	1	1.5	1.5	2	1.5	1.5	0.4	0.3	**9.7**
Vaccum/Dredging system connected to burial node	**Weight**	10.00%	15.00%	15.00%	20.00%	15.00%	15.00%	5.00%	5.00%	100.00%
	Rating	10	7	10	9	10	7	6	8	--
	Weighted Rating	1	1.05	1.5	1.8	1.5	1.05	0.3	0.4	8.6
Vibratory hammer attached to node	**Weight**	10.00%	15.00%	15.00%	20.00%	15.00%	15.00%	5.00%	5.00%	100.00%
	Rating	7	4	7	6	7	4	9	8	--
	Weighted Rating	0.7	0.6	1.05	1.2	1.05	0.6	0.45	0.4	6.05
Jetting/Dredging system connected to burial node	**Weight**	10.00%	15.00%	15.00%	20.00%	15.00%	15.00%	5.00%	5.00%	100.00%
	Rating	10	10	10	6	10	10	10	6	--
	Weighted Rating	1	1.5	1.5	1.2	1.5	1.5	0.5	0.3	9

Appendix D: Anodized Aluminum Cam-and-Groove Hose Coupling

NOTE: Dimensions will depend on pump chosen, below will be edited after pump is purchased.



Appendix E. Design Hazard Checklist

Team: Jetting Advisor: Rossman

Y	N	
☒	☐	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?
☐	☒	2. Can any part of the design undergo high accelerations/decelerations?
☒	☐	3. Will the system have any large moving masses or large forces?
☒	☐	4. Will the system produce a projectile?
☒	☐	5. Would it be possible for the system to fall under gravity creating injury?
☐	☒	6. Will a user be exposed to overhanging weights as part of the design?
☒	☐	7. Will the system have any sharp edges?
☐	☒	8. Will any part of the electrical systems not be grounded?
☒	☐	9. Will there be any large batteries or electrical voltage in the system above 40 V?
☒	☐	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☒	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part the system?
☐	☒	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☒	☐	14. Can the system generate high levels of noise?
☒	☐	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☒	☐	16. Is it possible for the system to be used in an unsafe manner?
☐	☒	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
1. The burial device will involve jetting out pressurized fluid.	The area will be secured before the system is turned on.	5/3/17	5/3/17
3. The payload will be 50 lbs. but the whole system will be greater than 50 lbs.	Anything 50 lbs or greater will be handled by carts, dollies, gantry, etc.	4/25/17	5/3/17
4. The burial device will produce a projectile: pressurized fluid.	The area will be secured before the system is turned on. The projectile will only face the bottom of the test tank during operation.	5/3/17	5/3/17
5. The payload will be 50 lbs. but the whole system will be greater than 50 lbs.	Anything 50 lbs or greater will be handled by carts, dollies, etc. Hard hats will be worn during assembly/disassembly of gantry.	4/18/17	5/3/17
7. There will be possible sharp edges on the Node.	Any sharp edges will be filed down.	4/18/17	4/20/17
9. The pump will run at 220-240 volts.	The system will be correctly setup, and Ben Johnson will have correctly wired the pump before any testings begin.	5/1/17	5/3/17
10. The Node will contain pressurized fluid.	The tubing that will be connected to the Node will have a pressure control valve to monitor and release the pressurized fluid.	5/3/17	5/3/17
14. The pump will make high-level noise when running.	The noise level will be monitor to be at OSHA's permissible exposure limit at 90 dBA (for an 8 hour day).	5/3/17	5/3/17
15. Testing of our system will be located at the Cal Poly pier, so it will be exposed to fog, cold temperatures, salt air, etc.	The system will be designed and built to handle these extreme conditions.	4/25/17	5/3/17
16. The system can be used unsafely by not having the system setup correctly.	Have at least 2 people check if the system is setup correctly before turning on the system.	5/3/17	5/3/17

Appendix F. Gantt Chart

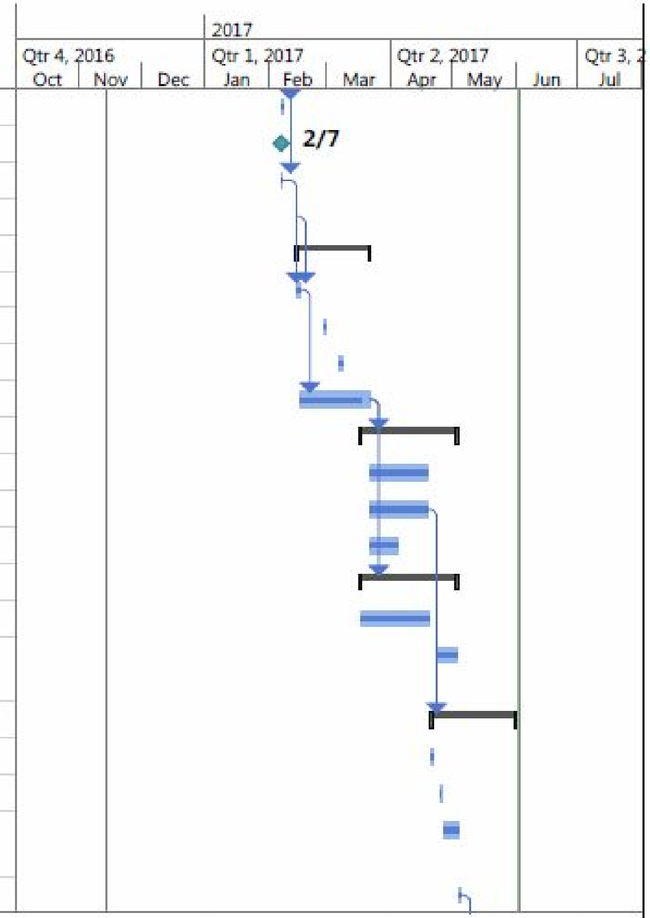
ID	Task Name	Duration	Start	Finish
1	**PDR**	**5.13 days**	**Thu 11/17/16**	**Thu 12/1/16**
2	PDR Report	0 days	Thu 11/17/16	Thu 11/17/16
3	PDR Presentation	1 hr	Thu 12/1/16	Thu 12/1/16
4	**Ordering Pump**	**21 days**	**Fri 12/2/16**	**Mon 1/23/17**
5	Testing (Pressure vs Flowrate)	1 day	Fri 12/2/16	Fri 12/2/16
6	Spec Pump	2.5 wks	Mon 12/5/16	Wed 1/11/17
7	Approval from sponsor	2 days	Wed 1/11/17	Fri 1/13/17
8	Order pump	1 wk	Fri 1/13/17	Mon 1/23/17
9	**Testing Site**	**7 days**	**Mon 1/23/17**	**Wed 2/1/17**
10	Communication through email with Tom	1 wk	Mon 1/23/17	Mon 1/30/17
11	Meeting with Tom (Cal Poly Pier)	1 day	Mon 1/30/17	Tue 1/31/17
12	Approval of Testing Apparatus on Cal Poly pier	1 day	Tue 1/31/17	Wed 2/1/17
13	**CDR**	**38 days**	**Thu 12/1/16**	**Tue 2/14/17**
14	FMEA	4 days	Thu 12/1/16	Tue 12/6/16
15	DVPR	4 days	Thu 12/1/16	Tue 12/6/16
16	Analysis Plan	4 days	Thu 12/1/16	Tue 12/6/16
17	CAD Modeling	2 wks	Fri 1/20/17	Thu 2/2/17
18	Design Analysis	1 wk	Tue 1/31/17	Mon 2/6/17
19	Bill of Materials (BOM)	3 days	Fri 2/3/17	Tue 2/7/17
20	Manufacturing Plans	1 day	Fri 2/3/17	Fri 2/3/17
21	Design Safety/Hazard Checklist	1 day	Wed 2/1/17	Thu 2/2/17
22	Testing Procedure	1 day	Mon 2/6/17	Mon 2/6/17

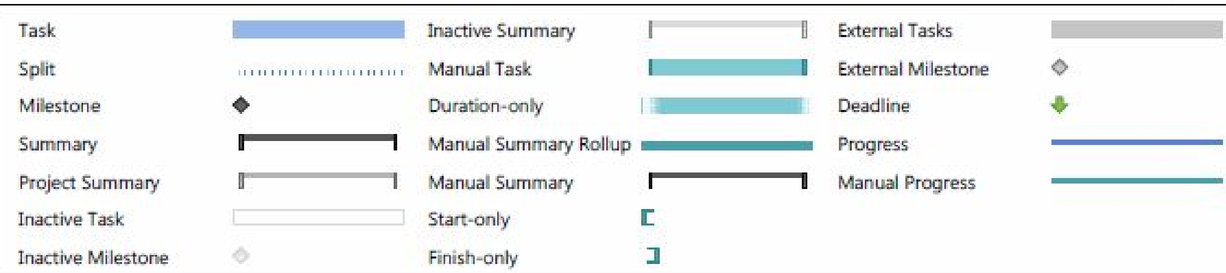
Project: Team 1 Gantt Chart
Date: Fri 6/2/17

Task; Split; Milestone; Summary; Project Summary; Inactive Task; Inactive Milestone; Inactive Summary; Manual Task; Duration-only; Manual Summary Rollup; Manual Summary; Start-only; Finish-only; External Tasks; External Milestone; Deadline; Progress; Manual Progress

Page 1

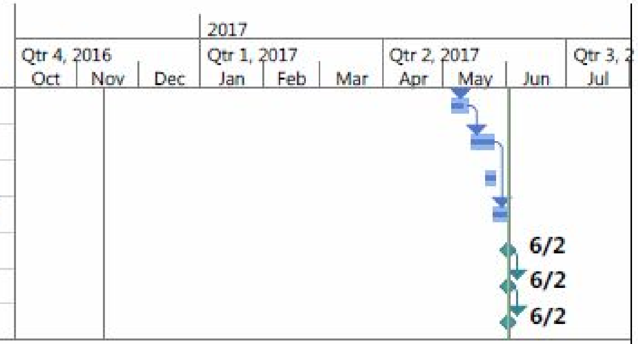
ID	Task Name	Duration	Start	Finish
23	Rough Draft of CDR report	1 day	Tue 2/7/17	Tue 2/7/17
24	CDR Report	0 days	Tue 2/7/17	Tue 2/7/17
25	CDR Presentation	1 hr	Tue 2/7/17	Tue 2/7/17
26	CDR Presentation to Sponsor	2 hrs	Tue 2/14/17	Tue 2/14/17
27	**Order Parts/Approval of Testing Site**	**24.75 days**	**Tue 2/14/17**	**Tue 3/21/17**
28	Bill of Materials (BOM) Finalized	2 days	Tue 2/14/17	Thu 2/16/17
29	Presentation with Tom, Pier manager	1 day	Tue 2/28/17	Tue 2/28/17
30	Operator's Manual	2 days	Tue 3/7/17	Wed 3/8/17
31	Approval from sponsor/Shipping	4.55 wks	Thu 2/16/17	Tue 3/21/17
32	**Manufacturing**	**28.25 days**	**Fri 3/17/17**	**Wed 5/3/17**
33	Nozzle - Caps (Variation)	3 wks	Wed 3/22/17	Tue 4/18/17
34	Node - cut various holes	3 wks	Wed 3/22/17	Tue 4/18/17
35	PVC Pipe cutting	1 wk	Wed 3/22/17	Tue 4/4/17
36	**VFD & Pump**	**28.25 days**	**Fri 3/17/17**	**Wed 5/3/17**
37	Order and Shipping	3.6 wks	Fri 3/17/17	Wed 4/19/17
38	Wiring done by Ben at Pier (just the pump)	1.5 wks	Mon 4/24/17	Wed 5/3/17
39	**Setup & Testing**	**27.5 days**	**Fri 4/21/17**	**Wed 5/31/17**
40	**Project Hardware/Safety Demo**	**1 day**	**Fri 4/21/17**	**Fri 4/21/17**
41	Drop Off Materials/Equipment at Pier	1 day	Tue 4/25/17	Tue 4/25/17
42	Setup at Pier/Safety Demo with Tom/Make Changes	5 days	Thu 4/27/17	Wed 5/3/17
43	Testing Demo for Sponsor	1 day	Thu 5/4/17	Thu 5/4/17





Project: Team 1 Gantt Chart
Date: Fri 6/2/17

ID	Task Name	Duration	Start	Finish
44	Figure out Test Procedure	1.2 wks	Fri 5/5/17	Fri 5/12/17
45	Test Project	1.7 wks	Mon 5/15/17	Thu 5/25/17
46	Expo Poster	1 wk	Mon 5/22/17	Fri 5/26/17
47	Test Review/Analyze Data	3 days	Thu 5/25/17	Wed 5/31/17
48	**FDR Project Expo**	0 days	Fri 6/2/17	Fri 6/2/17
49	**FDR Hardware Handoff**	0 days	Fri 6/2/17	Fri 6/2/17
50	**FDR Report**	0 days	Fri 6/2/17	Fri 6/2/17



Project: Team 1 Gantt Chart
Date: Fri 6/2/17

Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	

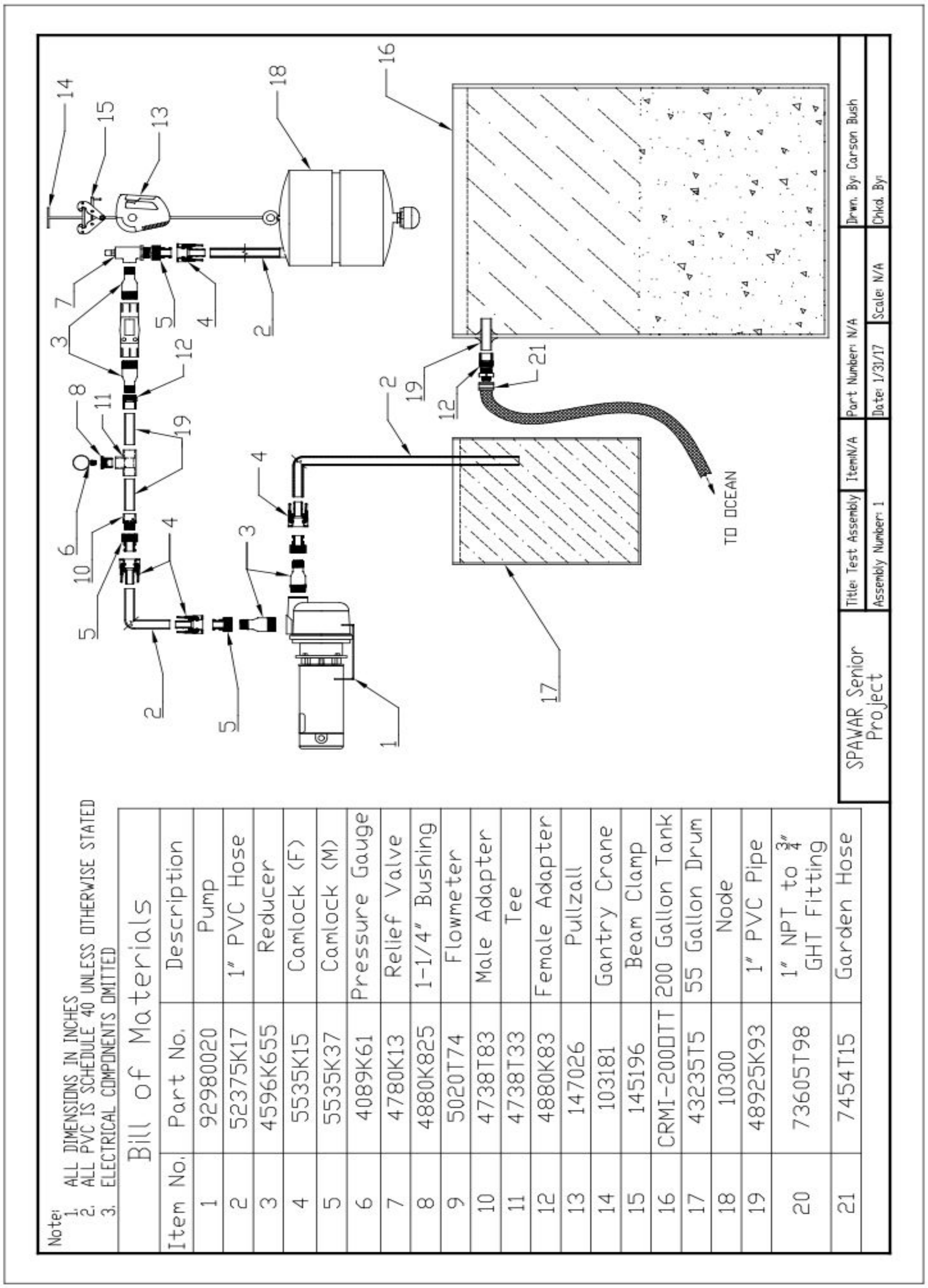
Page 3

Appendix G. Pump Specifications

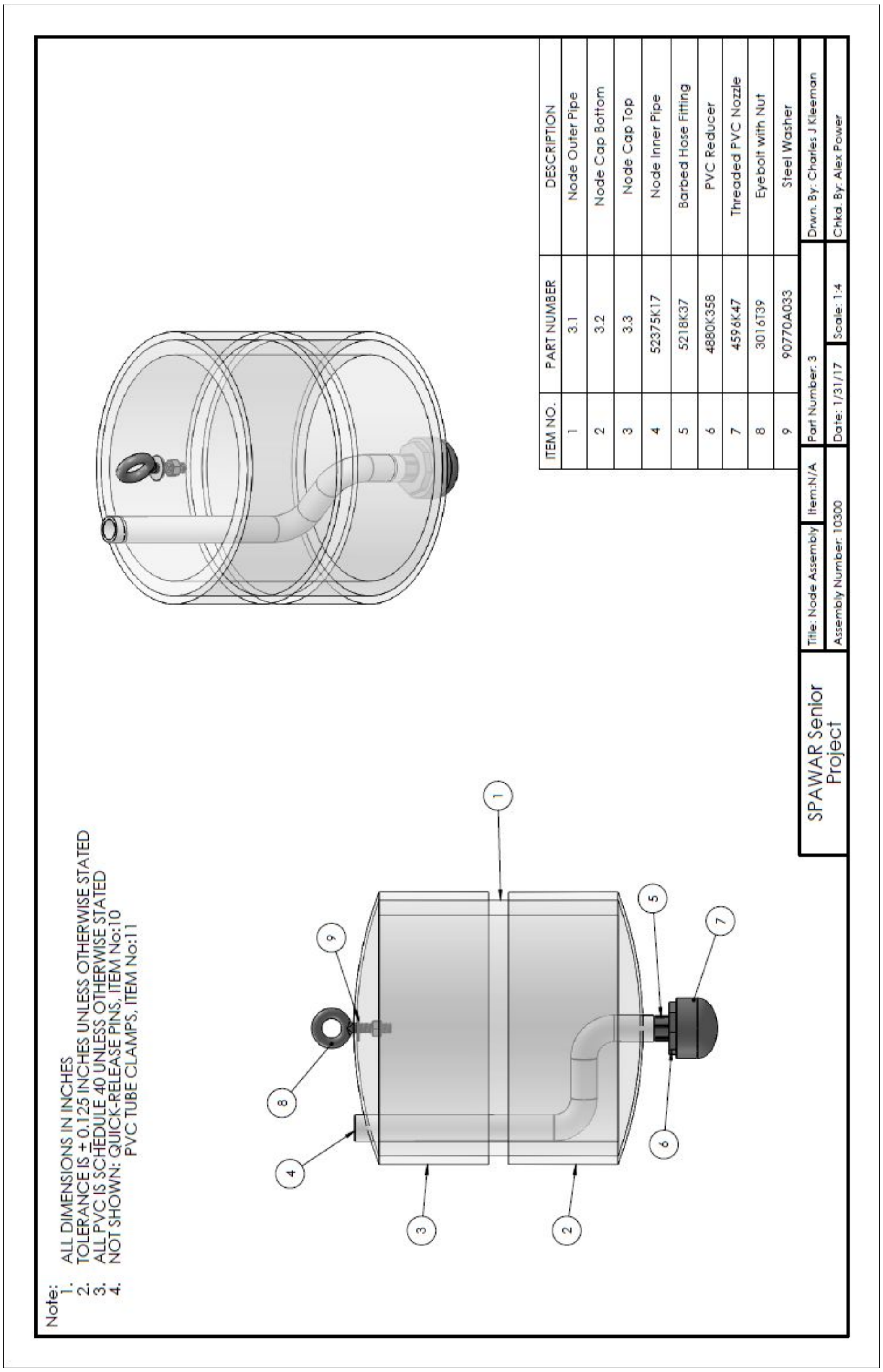
Pump Name	Company	hp	Power	Discharge Pipe Size	Max Pressure [Psi]	Max Flowrate [gpm]	Price	Additional Charts/Notes:
80TM2.2 3	Tsurumi	3	220-460 V (3 phase)	3 in	30	170	$3,075	Needs custom control board - $1400
2ZWU3	Dayton (Grainger)	3/4	208-230/460 (3 phase)	1 inch NPT	23.8	72	$880	
8249K84	McMaster	1.5	120/208-240 (Single Phase)	1 1/4 inch NPTF	26	115	$650	Moderate wear with salt water use
C51CD	MTH	2	208-230 (3 phase)	1 in	50	75	$997	
4320K93	McMaster	3	240 (3 Phase)	1 1/4 inch NPTF	35	135	$906	Not self priming
9929K56	McMaster	3/4	120 (Single Phase)	1 NPTF	25	53	$755	
8256K43	McMaster	2	240 (3 Phase)	1 NPTF	45	56	$860	Moderate wear with salt water use
2763IPT95	IPT	2	230/460 (3 Phase)	2 in	36	125	$600	Self priming
RC2-2	Ampco	1.5						
FTB2CISSIT	Franklin Electric	2	230 (3 Phase)	1 1/2 inch	52	70	$700	Self priming
369E-98	AMT	2	230/460V (3 Phase)	1 inch	28	90	$845	Not self priming; require flooded suction

Appendix H. Drawings

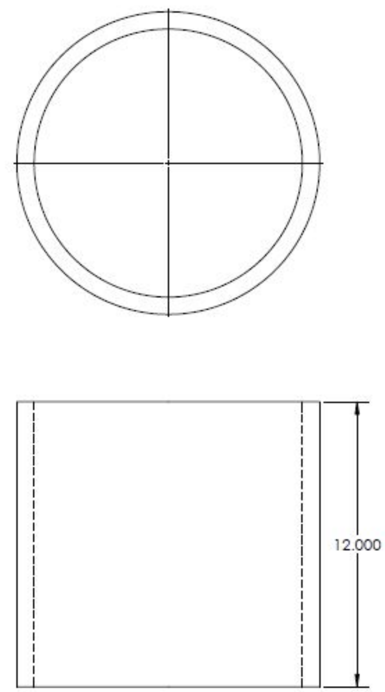
Test Apparatus Drawings



Node Assembly Drawings

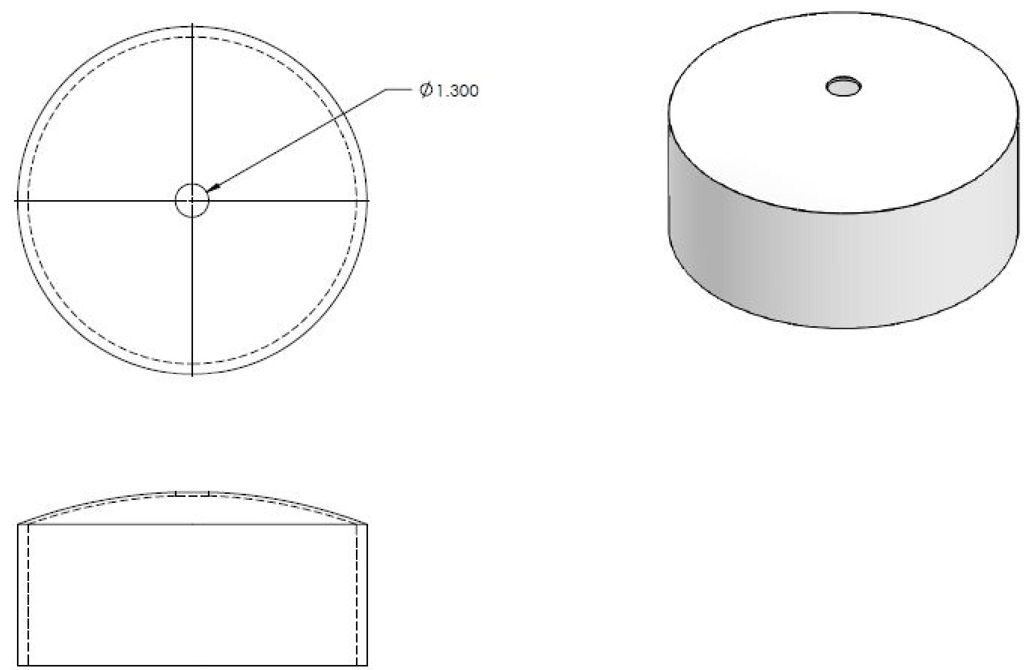


Note:
1. CUT FROM PVC FITTINGS ONLINE PART NUMBER: 4004-120AB



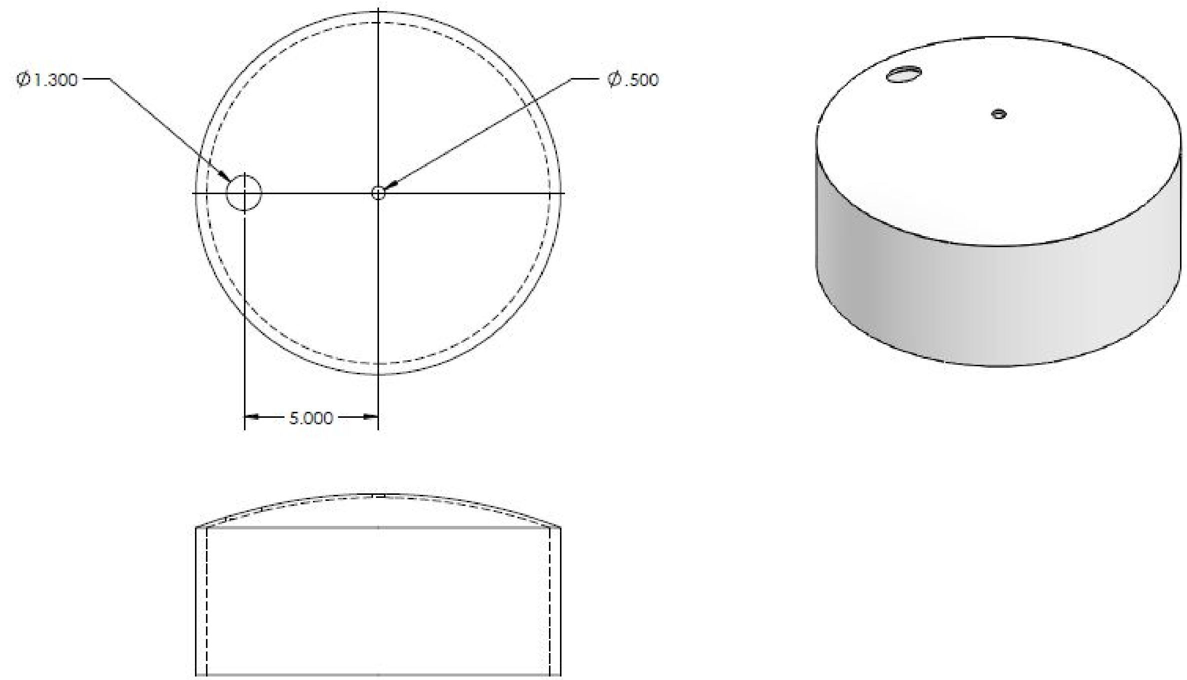
SPAWAR Senior Project	Title: Node Outer Pipe	Item No:1	Part Number: 3.1	Drwn. By: Charles J Kleeman
	Assembly Number: 10300		Date: 1/31/17 / Scale: 1:4	Chkd. By: Alex Power

Note:
1. MACHINED FROM PVC FITTINGS ONLINE PART NUMBER: 447-120

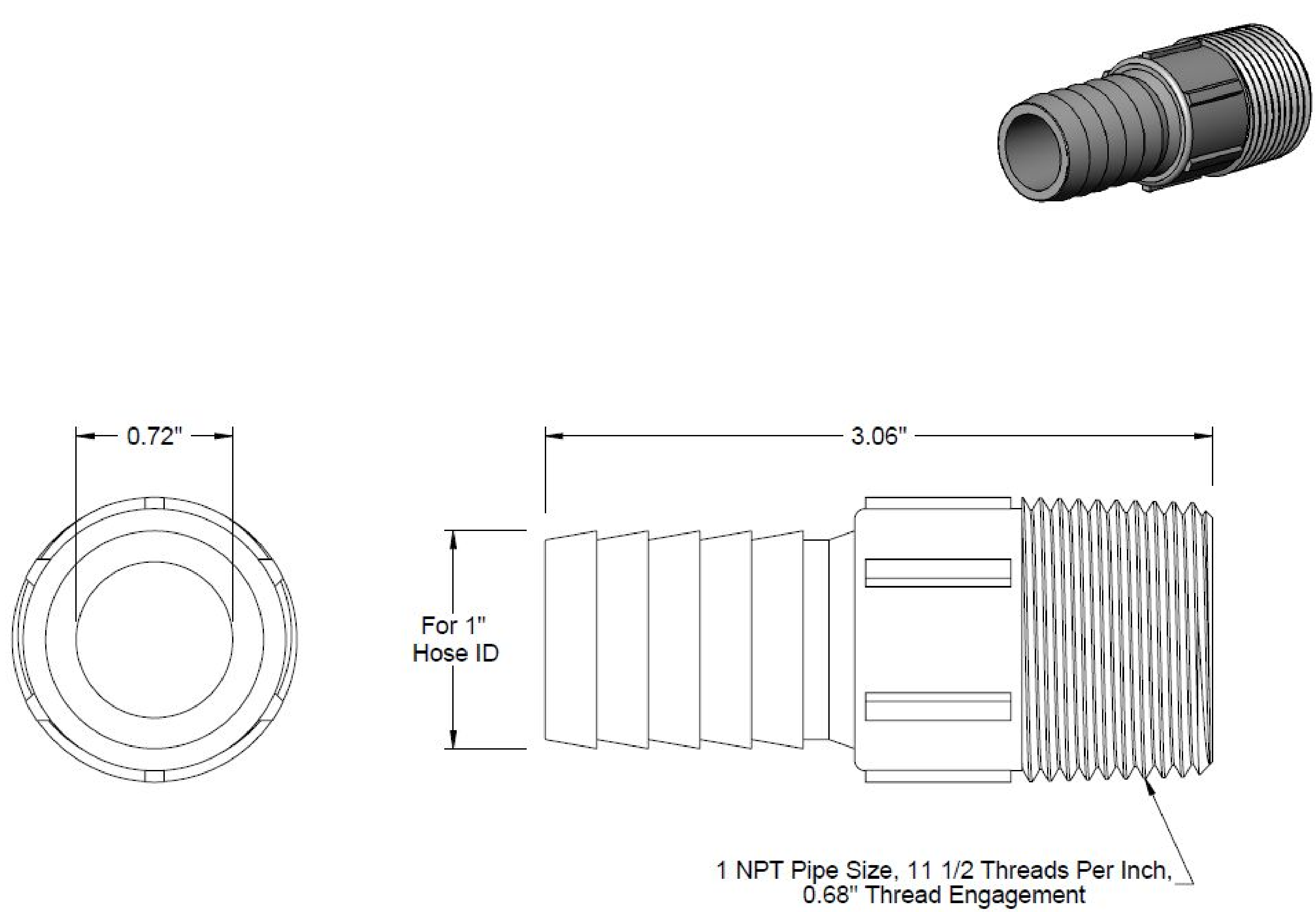


SPAWAR Senior Project	Title: Node Cap Bottom	Item No: 2	Part Number: 3.2		Drwn. By: Charles J Kleeman
	Assembly Number: 10300		Date: 1/31/17	Scale: 1:4	Chkd. By: Alex Power

Note:
1. MACHINED FROM PVC FITTINGS ONLINE PART NUMBER: 447-120



SPAWAR Senior Project	Title: Node Top Cap	Item No: 3	Part Number: 3.3	Drwn. By: Charles J Kleeman
	Assembly Number: 10300		Date: 1/31/17 · Scale: 1:4	Chkd. By: Alex Power

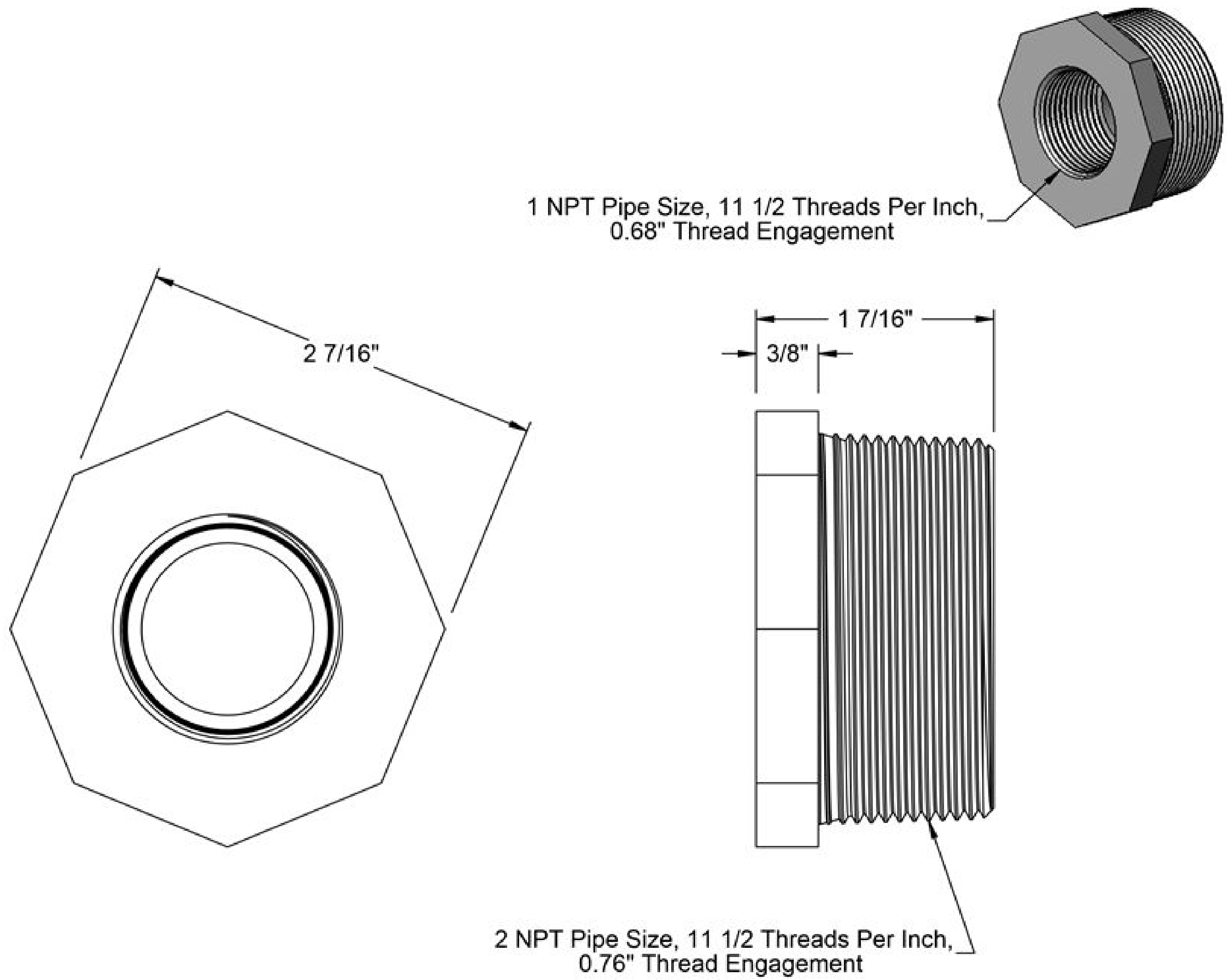


McMASTER-CARR® CAD

PART NUMBER **5218K37**

http://www.mcmaster.com

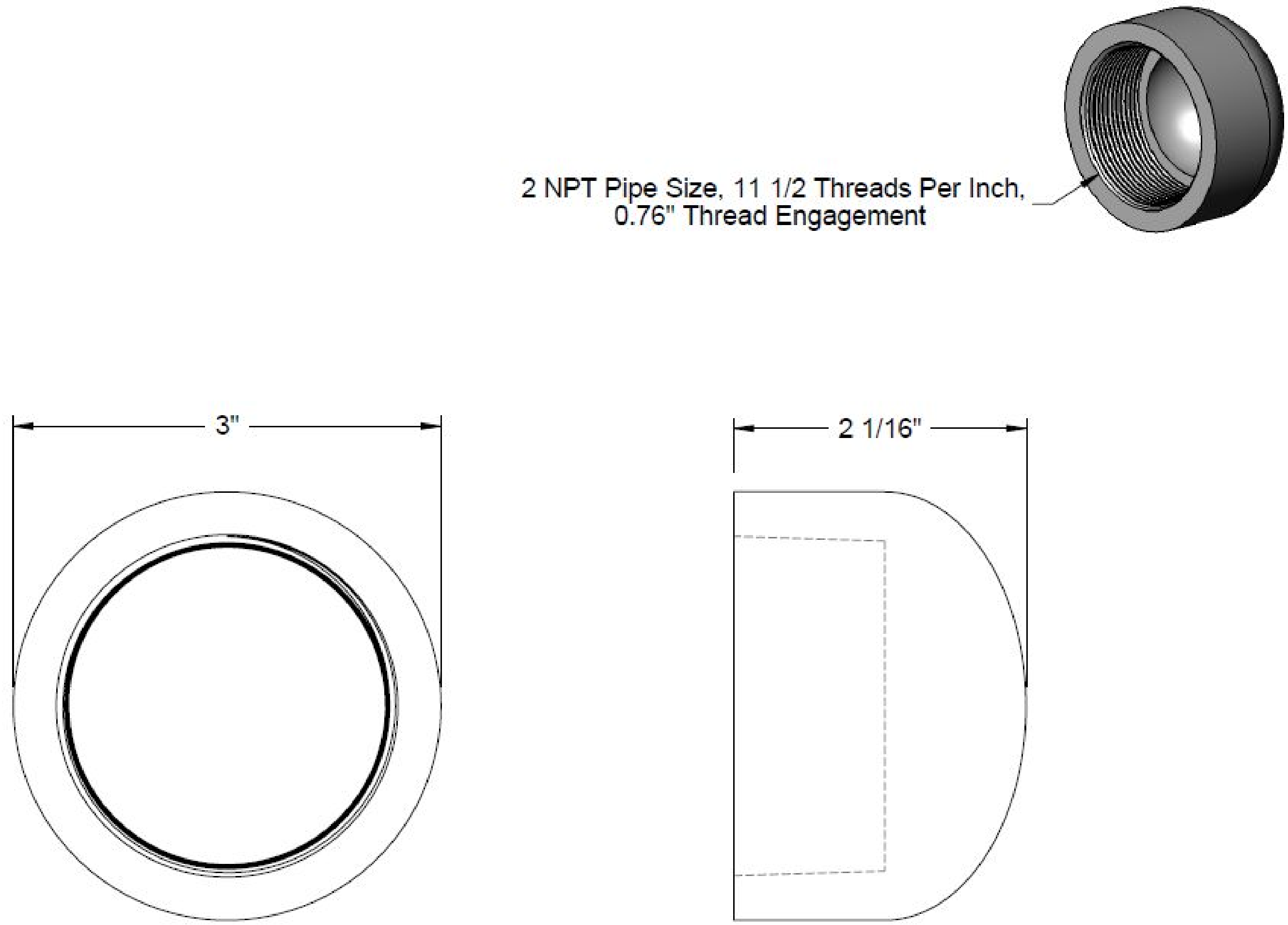
Lightweight Plastic Hose
Male Pipe Adapter



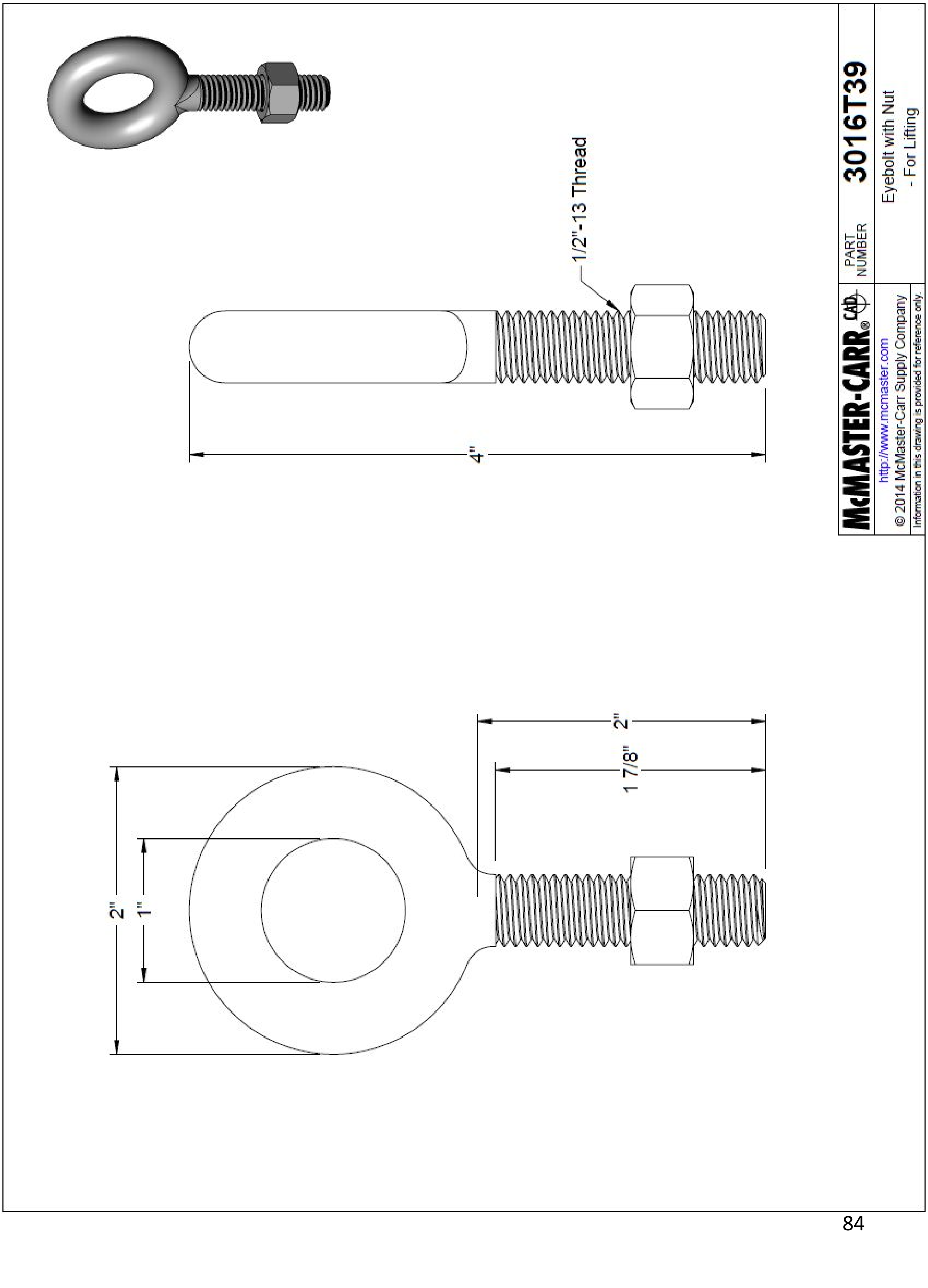
McMASTER-CARR® CAD | PART NUMBER **4880K358**

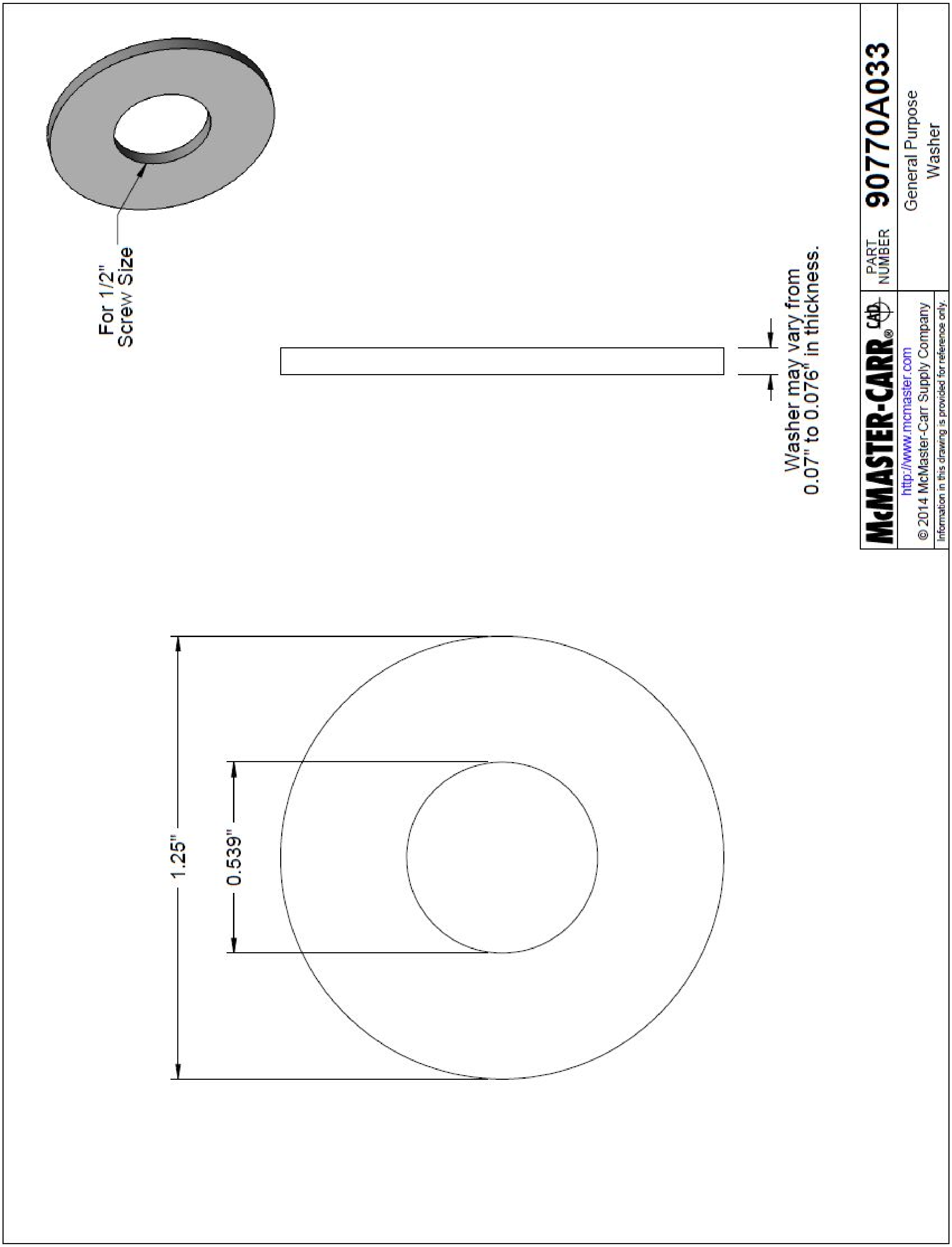
http://www.mcmaster.com

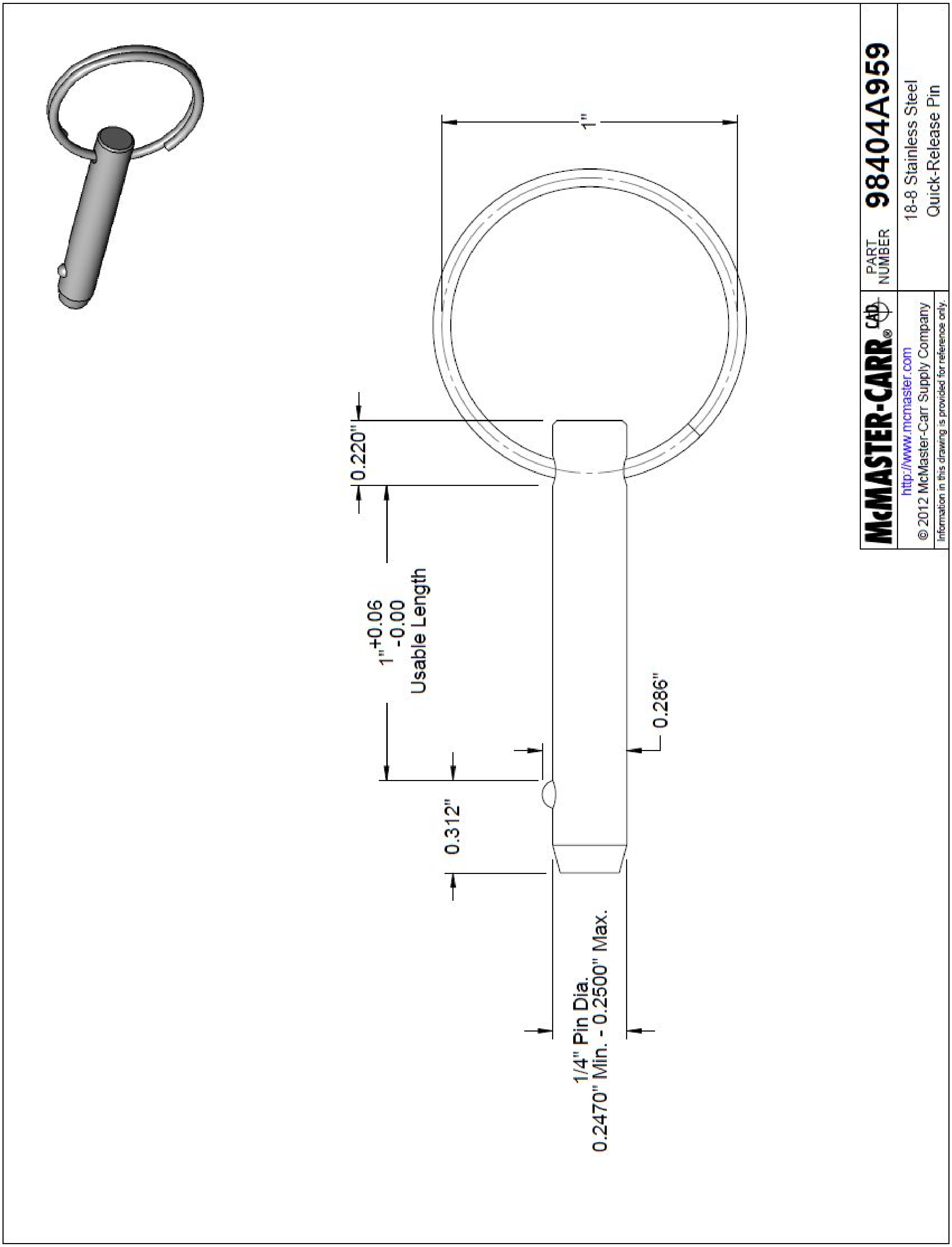
Standard-Wall White PVC
Male x Female Hex Reducing Bushing

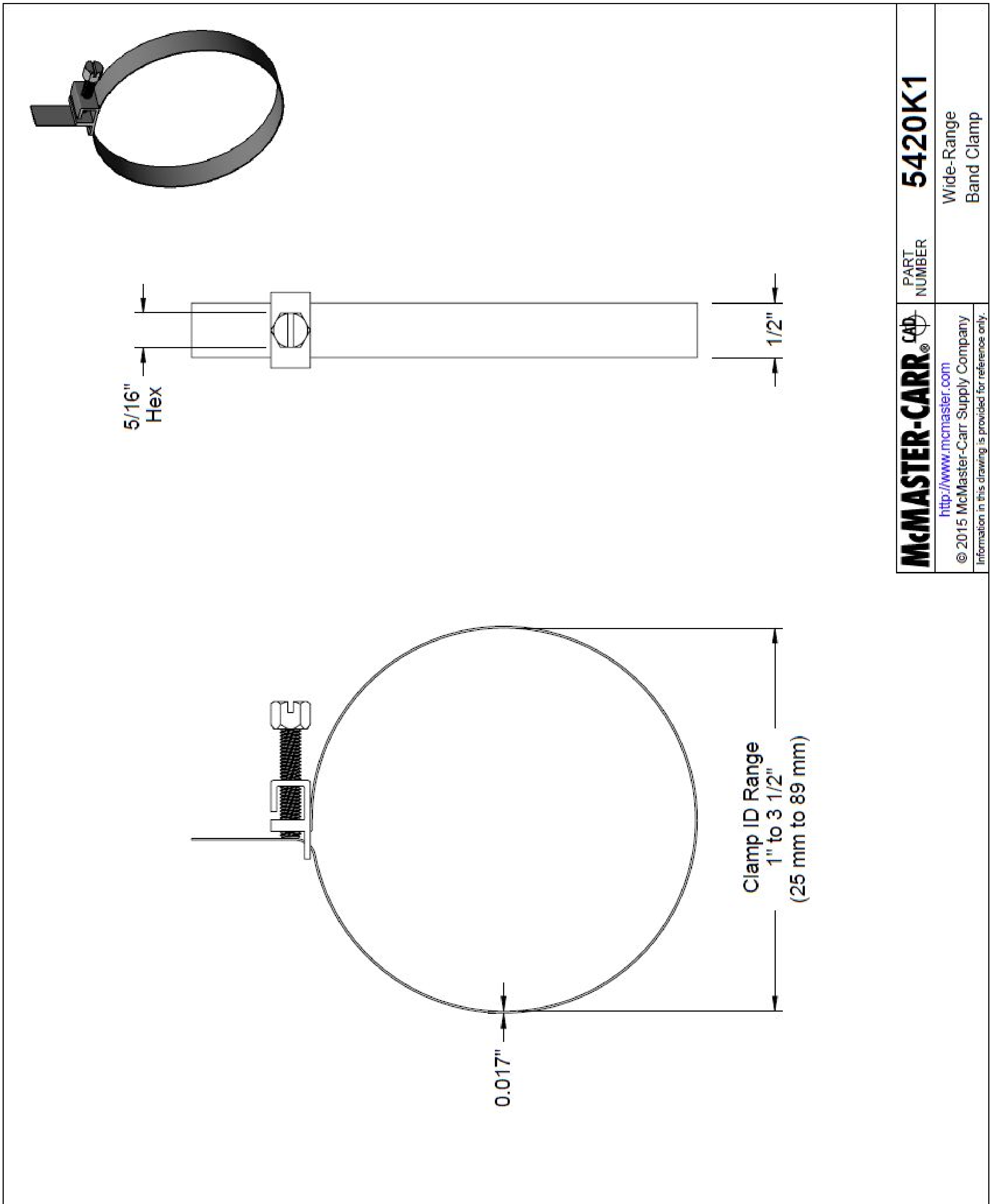


McMASTER-CARR® CAD	PART NUMBER 4596K47
http://www.mcmaster.com © 2013 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Thick-Wall Dark Gray PVC Threaded Cap

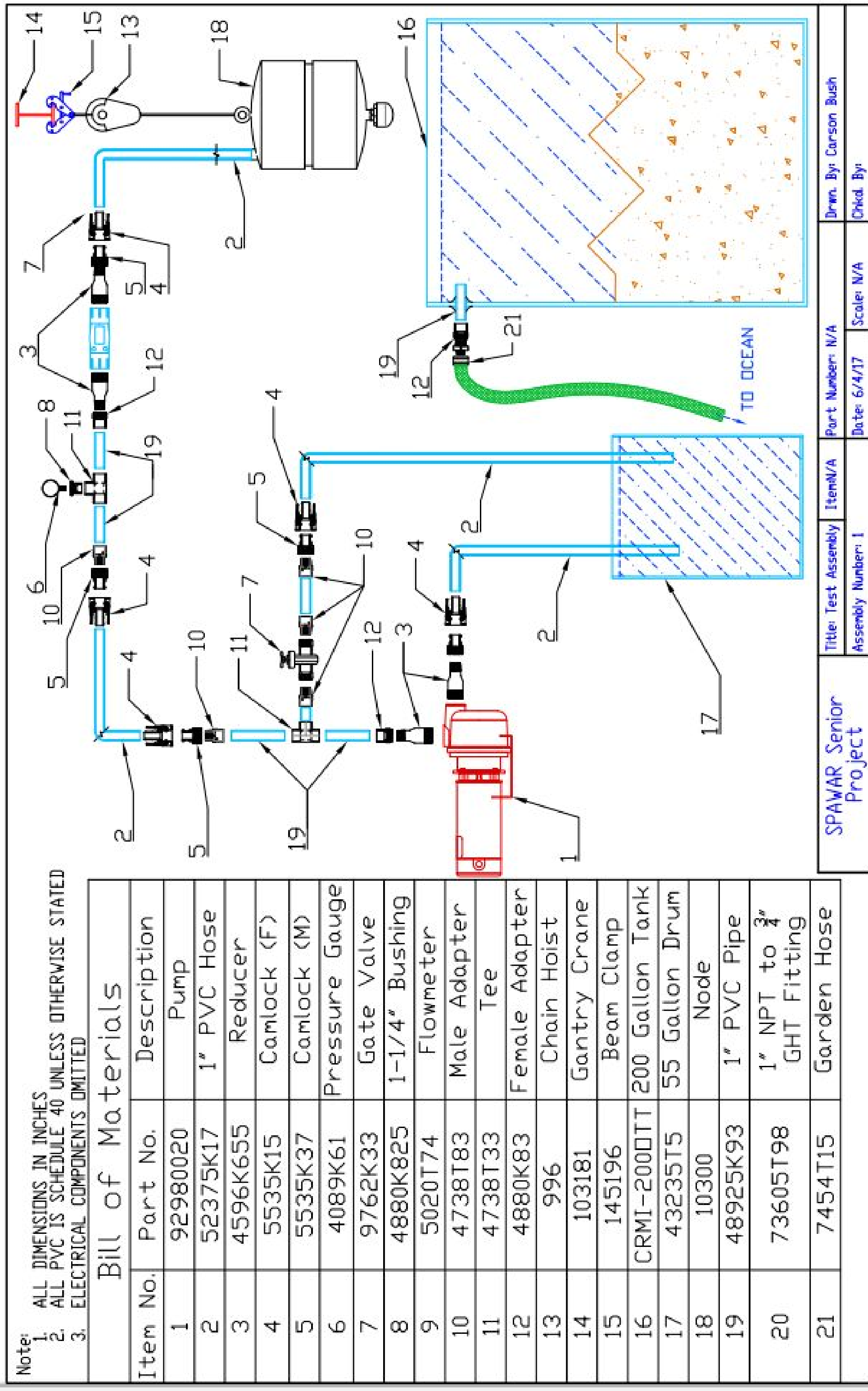

1/2"-13 Thread
4"
2"
1"
2"
1 7/8"
McMASTER-CARR® CAD
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
PART NUMBER
3016T39
Eyebolt with Nut - For Lifting


For 1/2"
Screw Size
Washer may vary from
0.07" to 0.076" in thickness.
1.25"
0.539"
McMASTER-CARR®
CAD
PART NUMBER
90770A033
General Purpose
Washer
http://www.mcmaster.com
© 2014 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.


1"
0.220"
1" +0.06 -0.00
Usable Length
0.286"
0.312"
1/4" Pin Dia.
0.2470" Min. - 0.2500" Max.
McMASTER-CARR® CAD
PART NUMBER
98404A959
http://www.mcmaster.com
© 2012 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
18-8 Stainless Steel
Quick-Release Pin


5/16"
Hex
1/2"
Clamp ID Range
1" to 3 1/2"
(25 mm to 89 mm)
0.017"
McMASTER-CARR®
CAD
PART NUMBER
5420K1
Wide-Range
Band Clamp
http://www.mcmaster.com
© 2015 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.

Modified System Layout



Bill of Materials

Item No.	Part No.	Description
1	92980020	Pump
2	52375K17	1" PVC Hose
3	4596K655	Reducer
4	5535K15	Camlock (F)
5	5535K37	Camlock (M)
6	4089K61	Pressure Gauge
7	9762K33	Gate Valve
8	4880K825	1-1/4" Bushing
9	5020T74	Flowmeter
10	4738T83	Male Adapter
11	4738T33	Tee
12	4880K83	Female Adapter
13	996	Chain Hoist
14	103181	Gantry Crane
15	145196	Beam Clamp
16	CRMI-200□TT	200 Gallon Tank
17	43235T5	55 Gallon Drum
18	10300	Node
19	48925K93	1" PVC Pipe
20	73605T98	1" NPT to 3/4" GHT Fitting
21	7454T15	Garden Hose

Appendix I. Calculations

Shear Stress Calculations

Shear Stress Calculations

PVC Material: (Node + Cap)

Tensile Yield Strength: 8.0×10^3 psi

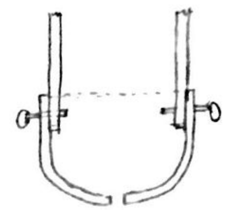
Young's Modulus: 410×10^3 psi

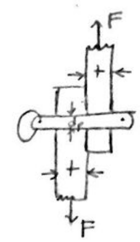
Ultimate Tensile Strength: 7.54×10^3 psi

Stainless Steel (18-8) pins:

Tensile yield Strength: 74.0×10^3 psi

Young's Modulus: 27.6×10^6 psi





Pin: dia, d_p = 0.5 in

PVC (pipe & cap): thickness, $t \approx 0.406$ in

Ave Shear Stress, $\tau_{avg} = \frac{4F}{\pi d^2}$

$$\tau_{avg} = \frac{4(250\text{ lb})}{\pi(0.5\text{ in})^2}$$

$$\tau_{avg} = \frac{1273.2\text{ psi}}{3\text{ pins}}$$

$$\tau_{avg} = 424.4\text{ psi (per pin)}$$

Bearing stress, $\sigma_B = \frac{F}{td}$

$$\sigma_B = \frac{250\text{ lb}}{(0.406\text{ in})(0.5\text{ in})}$$

$$\sigma_B = \frac{1232\text{ psi}}{3\text{ pins}}$$

$$\sigma_B = 410\text{ psi (per pin)}$$

$$\sigma_{allowable} = \frac{\text{Ult. strength}}{\text{F.S.}}$$

$$= \frac{7.54 \times 10^3\text{ psi}}{3}$$

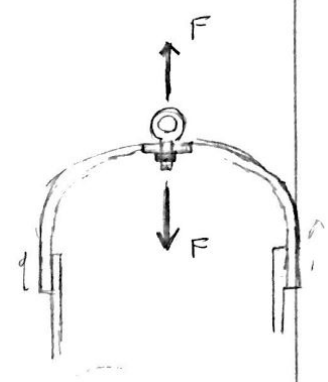
$$\sigma_{allow} = 2513.3\text{ psi}$$

Loadings:
- Node ~ 5.25 lb
- Cap ~ 8.22 x 2 = 16 lb
- Payload ~ 50 lbs
- Piping in system ~ 10-20 lb
- Leaks into Node:
  - dome ~ 5 lb
  - half/full cyl. ~ 50-100 lb

Est. of Total Weight:
135 - 250 lb

Eyebolt Loading Analysis

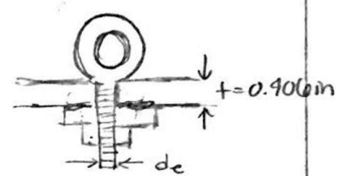
PVC Material:
Tensile yield strength: 8×10^3 psi
Young's Modulus: 410×10^3 psi
Ultimate Tensile strength: 7.54×10^3 psi



Galvanized steel Eyebolt:
Tensile yield strength: 79.8×10^3 psi

Ultimate Tensile strength: 87×10^3 psi

Stainless Steel Washer:
Tensile yield strength: 35×10^3 psi
Ultimate Tensile strength: 90×10^3 psi

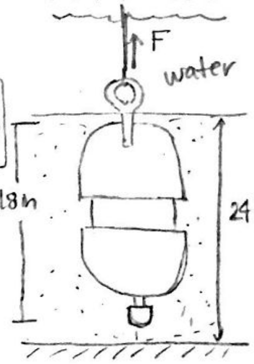


Eyebolt: $d_e = 0.5\text{in}$
$\ell_{threaded} = 1\,7/8\text{ in}$

Washer: $d_{in} = 0.539\text{in}$
$d_{out} = 1.25\text{ in}$

Range of Loading:
· Before burial = 250 lb
· After burial ≈ 1560

$\rho_{bank\ sand} = 92.6 \frac{lbm}{ft^3}$ source [13]



$W_{sand} = \rho g V$

$= \left[92.6 \frac{lbm}{ft^3} \cdot \frac{lbf}{32.174\, lbm \cdot ft/s^2}\right]\left(32.174 \frac{ft}{s^2}\right)\left[\pi (1.5ft)^2 (2ft)\right]$

$W_{sand} \approx 1310\ lbf$

$\tau_{max} = \frac{4}{3}\frac{4F}{\pi d^2} = \frac{4(1560\,lb)}{\pi(0.5in)^2} \cdot \frac{4}{3}$

$\tau_{max} = 10,593.4\,psi$

$\sigma_b = \frac{F}{td} = \frac{1560\,lb}{(0.406in)(0.5in)}$

$\sigma_b = 7,684.7\ psi$

Eyebolt Loading Analysis (continued)

Assumption:
→ Force of Sand on Node Negligible

given: $\rho_{water} = 62.42\ lbm/ft^3$
Source [12]

$r_{Node} = 6''$
$h_{Node} = 12''$

Analysis:

$V_{cylinder} = \pi r^2 h$

$V_c = \pi (6in)^2 (12in)$

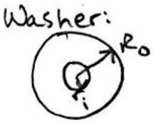
$V_c = 1357.2\ in^3$

$W_{water} = \left(62.42 \frac{lbm}{ft^3}\right)\left(\frac{1\ lbf}{32.174\ \frac{lbm\,ft}{s^2}}\right)\left(32.174 \frac{ft}{s^2}\right)\left(1357.2 in^3\right)\left(\frac{1 ft^3}{1728 in^3}\right)$

$W_{water} = 49.03\ lbf$

$\sigma = \frac{P}{A}$

Washer:



$R_o = 0.625''$
$r_i = 0.2695''$

$A = \pi R_o^2 - \pi r_i^2$

$A = 0.999\ in^2$

$\sigma = \frac{49\ lbf}{0.999\ in^2}$

$\sigma = 49\ psi << 7.54 \cdot 10^3\ psi$

Total Head Loss Calculations (EES Codes)

```
"System Curve for Node"

 "Flowrate"
{Q = 50 [gpm]}
Q_ft = Q*0.0022280093

"Major Losses"
C = 150
k = 1.318
L = 25 [ft]
D_1 = 1 [inch]
A_1 = pi*(D_1/12)^2/4
D_2 = 1.5 [inch]
A_2 = pi*(D_2/12)^2/4
C_1 = pi*(D_1/12)
R = A_1/C_1
V_1 = Q_ft/A_1
V_2 = Q_ft/A_2
V_exit = Q_ft/A_exit

V_1 = k*C*(R^0.63)*(S^0.54)
h_l_maj = S*L

"Minor Losses"
g = 32.174 [ft/s^2]
h_l_min = (k_inlet+16*k_union+k_tee+k_enl+k_valve)*V_1^2/(2*g)  + (k_cont+k_meter)*V_2^2/(2*g) + (k_exit)*V_exit^2/(2*g)
h_l_m1 = (k_inlet+16*k_union+k_tee+k_enl+k_valve)*V_1^2/(2*g)
h_l_m15 = (k_cont+k_meter)*V_2^2/(2*g)
h_l_mexit = (k_exit)*V_exit^2/(2*g)

"Inlet"
k_inlet = 0.04

"Theaded/Camlock Unions"
k_union = 0.04

"Tee"
k_tee = 0.40

"Enlargement"
beta_1 = 0.957/1.5
k_enl = (1-beta_1^2)^2/beta_1^4

"Contraction"
beta_2 = 1.5/0.957
theta = 50.68 [degrees]
k_cont = 0.5*(1 - beta_2^2)*sin(theta/2)^(1/2)/beta_2^4

"Water Meter"
k_meter = 6

"Pressure Relief Valve"
k_valve = 0.69

"Cap"
D_cap = 2 [in]
A_cap = pi*(D_cap/12)^2/4
k_cap = (1 - A_1/A_cap)^2

"Exit"
D_exit = 0.25 [in]
{n_exit = 12}
A_exit = n_exit*pi*(D_exit/12)^2/4

k_exit = 0.5*(1 - (A_exit/A_cap)^2)^2

"Total Losses"
h_l_tot = h_l_maj + h_l_min
```

System Curve for Node

Flowrate

$Q_{ft} = Q \cdot 0.0022280093$

Major Losses

$C = 150$

$k = 1.318$

$L = 25$ [ft]

$D_1 = 1$ [inch]

$$A_1 = \pi \cdot \frac{\left[\frac{D_1}{12}\right]^2}{4}$$

$D_2 = 1.5$ [inch]

$$A_2 = \pi \cdot \frac{\left[\frac{D_2}{12}\right]^2}{4}$$

$$C_1 = \pi \cdot \frac{D_1}{12}$$

$$R = \frac{A_1}{C_1}$$

$$V_1 = \frac{Q_{ft}}{A_1}$$

$$V_2 = \frac{Q_{ft}}{A_2}$$

$$V_{exit} = \frac{Q_{ft}}{A_{exit}}$$

$$V_1 = k \cdot C \cdot R^{0.63} \cdot S^{0.54}$$

$$h_{l,maj} = S \cdot L$$

Minor Losses

$g = 32.174$ [ft/s^2]

$$h_{l,min} = \left[k_{inlet} + 16 \cdot k_{union} + k_{tee} + k_{enl} + k_{valve}\right] \cdot \frac{V_1^{\,2}}{2 \cdot g} + \left[k_{cont} + k_{meter}\right] \cdot \frac{V_2^{\,2}}{2 \cdot g} + k_{exit} \cdot \frac{V_{exit}^{\,2}}{2 \cdot g}$$

$$h_{l,m1} = \left[k_{inlet} + 16 \cdot k_{union} + k_{tee} + k_{enl} + k_{valve}\right] \cdot \frac{V_1^{\,2}}{2 \cdot g}$$

$$h_{l,m15} = \left[k_{cont} + k_{meter}\right] \cdot \frac{V_2^{\,2}}{2 \cdot g}$$

$$h_{l,mexit} = k_{exit} \cdot \frac{V_{exit}^{\,2}}{2 \cdot g}$$

Inlet

$k_{inlet} = 0.04$

Theaded/Camlock Unions

$k_{union} = 0.04$

Tee

$k_{tee} = 0.4$

Enlargement

$$\beta_1 = \frac{0.957}{1.5}$$

$$k_{enl} = \frac{\left[1 - \beta_1^{\,2}\right]^2}{\beta_1^{\,4}}$$

Contraction

$$\beta_2 = \frac{1.5}{0.957}$$

$\theta = 50.68$ [Degrees]

$$k_{cont} = 0.5 \cdot \left[1 - \beta_2^{\,2}\right] \cdot \frac{\sin^{[1/2]}\left[\frac{\theta}{2}\right]}{\beta_2^{\,4}}$$

Water Meter

$k_{meter} = 6$

Pressure Relief Valve

$k_{valve} = 0.69$

Cap

$$D_{cap} = 2 \quad [in]$$

$$A_{cap} = \pi \cdot \frac{\left[\frac{D_{cap}}{12}\right]^2}{4}$$

$$k_{cap} = \left[1 - \frac{A_1}{A_{cap}}\right]^2$$

Exit

$$D_{exit} = 0.25 \quad [in]$$

$$A_{exit} = n_{exit} \cdot \pi \cdot \frac{\left[\frac{D_{exit}}{12}\right]^2}{4}$$

$$k_{exit} = 0.5 \cdot \left[1 - \left(\frac{A_{exit}}{A_{cap}}\right)^2\right]^2$$

Total Losses

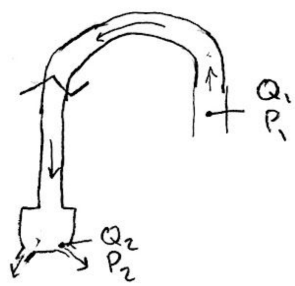
$$h_{l,tot} = h_{l,maj} + h_{l,min}$$

Sample Calculations

Charles Kleeman

Pressure & Flow rate Calculations

Use the modified Bernoulli's Equation to determine pressure and flow rate at the nozzle based on the sensor readings.



Assumptions

- Water incompressible
- Steady state
- constant streamline effects
- inviscid flow

Equation

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_L$$

- initial assume no losses

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2$$

$\Delta z = 3$ feet

$P_1 = 10$ psi (Test full open nozzle 2)

$Q_1 = \sum_{n=2}^{9} Q_n$

$Q_1 = 29$ gpm

$Q_1 = V_1 A_1$

$V_1 = \left(29 \frac{gal}{min}\right)\left(\frac{1 min}{60 sec}\right)\left(\frac{1 ft^3}{7.48 gal}\right) / \left(\frac{0.5 in}{12 \frac{in}{ft}}\right)^2 \pi$

$V_1 = 11.85$ ft/sec

$Q_2 = Q_{3-9} = 3.625$ gpm

$V_2 = \left(3.625 \frac{gal}{min}\right)\left(\frac{1 min}{60 sec}\right)\left(\frac{1 ft^3}{7.48 gal}\right) / \left(\frac{.125 in}{12 \frac{in}{ft}}\right)^2 \pi$

$V_2 = 23.69$ ft/sec

$\gamma = 62.4 \frac{lbf}{ft^3}$

$$\frac{1440 \frac{lb}{ft^2}}{62.4 \frac{lb}{ft^3}} + \frac{(11.85 \, ft/sec)^2}{2(32.2 \, ft/sec^2)} + 3 ft = \frac{P_2}{62.4 \frac{lb}{ft^3}} + \frac{(1.48 \frac{ft}{sec})^2}{2 \cdot (32.2 \, ft/s^2)}$$

$P_2 = 8.47$ psi

Appendix J. Design Failure Modes and Effects Analysis (DFMEA)

									Action Results	Testing		
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurence	Criticality	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Dig Hole	Too Deep	Non reachable connection	7	Jetting system on too long	2	14	Establish burial times in testing	Team 5/3/17		1	0	0
			2	Node burial post digging	5	10	Establish burial post digging in testing	Team 5/3/17				
	Too Shallow	Not fully Buried	6	Jetting system shut off too soon	2	12	Establish burial times in testing	Team 5/3/17		8	19	152
		Non vertical orientation	5	Line rupture	3	15	Use high pressure lines/fitting, perform routine line inspections	Team 2/6/17	PVC pipes are able to handle a range of high pressures.			
	Too Narrow	Node does not fit	8	Improper jet angle	2	16	Establish proper jet angle in testing	Team 5/3/17		10	0	0
		Longer dig time	1	Pump too weak	4	4	Establish proper pump power in testing	Team 5/3/17				
	Too Wide	Difficult to bury	4	Improper jet angle	2	8	Establish proper jet angle in testing	Team 5/3/17		1	0	0
		Sideways orientation	5	Pump too powerful	6	30	Establish proper pump power in testing	Team 5/3/17				
Bury Payload	Node gets caught	Incomplete burial	7	Soil obstruction	1	7	Survey area before burial	Team 5/27/17		7	0	0
		Longer dig time	1	Diver snagged	2	2	Establish SOP for divers/eliminate sharp surfaces and corners	Team 4/29/17	No areas of system getting caught			
	Node integrity failure	Payload damaged	9	Overpressured lines	2	18	Use high pressure lines/fitting, perform routine line inspections	Team 2/6/17	PVC pipes are able to handle a range of high pressures.	8	0	0
		Jetting hose break	8	Worn/damaged lines	5	40	Perform routine line inspections	Team 5/27/17				
		Nozzle misalignment	4	Unsecured camlocks	6	24	Use locking camlocks	Team 2/6/17	Locking camlocks are on our BOM			
Retain Payload	Water ingress	Payload damaged	9	Sharp surface in soil	1	9	Survey area before burial	Team 5/27/17		1	19	19
		Heavier node	1	Poor seals	4	4	Perform routine line inspections	Team 5/27/17				
	Sand ingress	Payload damaged	9	Internal line rupture	3	27	Perform routine line inspections	Team 5/27/17		2	19	38
		Heavier node	1	Sand in nozzle	1	1	Run jet before node touches the seafloor	Team 5/27/17				
		Internal node damage	1	Sand in pump intake	3	3	Do not recycle water from testing tank	Team 5/3/17				
	Hose Burst	Digging stops	2	Overpressured lines	2	4	Use high pressure lines/fittings	Team 2/6/17	PVC pipes are able to handle a range of high pressures.	5	0	0
		Payload damaged	9	Unsecured camlocks	5	45	Use locking camlocks	Team 2/6/17	Locking camlocks are on our BOM			
	Payload does not fit	Payload cannot be buried	10	Incorrect measurements	1	10	Design analysis calculations	Team 2/6/17	Final designs are reviewed on testing layout.	9	0	0
	Connection break	Pump cannot connect underwater	9	Defects in manufacturing parts	1	9	Order a few extra	Team 3/17/17	Extras are accounted for in our BOM	4	0	

									Action Results	Testing		
Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Occurence	Criticality	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Node-Pump Connection	Connection break	Pump cannot connect above water	3	Defects in manufacturing parts	1	3	Order a few extra	Team 3/17/17	Extras are accounted for in our BOM	4	0	0
	Jammed connection	Pump cannot be disconnected	9	Pressure built up in lines	2	18	Cut pressure lines once burial is complete	Team 5/27/17		8	0	
		Clogged jetting line	6	Water does not flow correctly	6	36	Eliminate corners and bends in lines where possible	Team 2/6/17	Final designs have minimal corners and bends in lines.	7	0	0
	Seal leakage	Longer dig time	1	Loss of pressure	5	5	Perform routine line/seal inspections	Team 5/27/17		6	0	
			1	Loss of flowrate	5	5	Perform routine line/seal inspections	Team 5/27/17		7	0	0
	Connection fitting incorrect	Burial device does not function	10	Incorrect measurements	1	10	Design analysis calculations	Team 2/6/17	Fittings are reviewed on testing layout and on BOM	10	0	

Appendix K. Design Verification Plan & Report (DVP&R)

ME428 DVP&R Format

Report Date: 5/3/17 | Sponsor: SPAWAR | REPORTING ENGINEER: Kleeman

TEST PLAN						TEST REPORT								
						SAMPLES TESTED		TIMING		TEST RESULTS				
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	NOTES
1	Burial Efficiency	How long it takes to bury the node. We will vary the node flowrate using the valve as well as vary each nozzle fitting (1-5)	1. Node is buried 2. Node uses minimum pump power	Team	Test Tank	5 nozzles each at 3 different flowrates	B	5/3/17	5/20/17	Pass	20	2	First two tests Node was filled with air and was too bouyant to bury itself
2	Post Digging Depth	How deep the node is buried after the pump is turned off	Max 4 inches	Charlie	Test Tank		C	5/3/17	5/20/17	Pass	All	None	Node did not sink after Pump was turned off
3	Vertical Burial	Device needs to be buried in a vertical orientation	10° Deflection from vertical	Carson	Test Tank		C	5/3/17	5/20/17	Pass	All	None	Node was aligned using the chain hoist
4	Burial Depth	Observe that the node is buried as deep as necessary	24 inches	Daly	Test Tank	1	C	5/3/17	5/20/17	Fail	None	All	We were never able to bury the Node lower than 21.5 inches due to Node bouyancy or Node hitting the bottom of the tank.
5	Burial Diameter	Observe that the node is buried as wide as necessary	Min 12 inches	Charlie	Test Tank	1	C	5/3/17	5/20/17	Pass	All	None	Node would bury itself then sand would settle around it

Raw Data Table

					Time = 1 min		Time = 2 min		Average						
Valve Position	Nozzle	Trial	Test # for the day	Starting Chain Length [in]	Pressure [psi]	Flowrate [gpm]	Pressure [psi]	Flowrate [gpm]	Pressure [psi]	Flowrate [gpm]	Ending Chain Length [in]	Delta Chain Length [in]	Burial Time [sec]	Burial Rate [in/sec]	Notes:
Fully Open	1	1	1	18.5	5	13.3	5	13.3	5	13.3	N/A	N/A	105	N/A	Reservoir tank went empty before Node could finish burial
		2	2	14.75	5	12.1	5	12.1	5	12.1	N/A	N/A	200	N/A	More sand added to tank, Node was in the process of burial but after a certain depth was too boyant and would not sink
		3	3	15	5	12.2	5	12.2	5	12.2	32	17	230	0.0739	Added 10 pounds of weight, Burial was somewhat diagonal, we assume that the chain length chain is the distance it was buried.
		4	4	20	5	9.3	5	12.1	5	10.7	29	9	105	0.0857	
	2	1	1	23.5	5	16	N/A	N/A	5	16	32	8.5	77	0.1104	13 lbs added, future weight of all tests totals 26lbs
		2	2	21.5	5	15	5	13.4	5	14.2	34	12.5	179	0.0698	1:30 is when the burnial rate slowed down; Had to stop due to low water level in reservoir tank.
	3	1	2	20.5	3	17	5	15.5	4	16.25	33	12.5	39	0.3205	
		2	3	18	3	16	3	15.5	3	15.75	28	10	47	0.2128	
		3	3	12.5	5	17	5	14.92	5	12	29.75	17.25	115	0.1500	Sand added to the tank and 17lbs added to Node; tests at these conditions are marked in light grey
Half Closed	2	1	1	21.5	5	12.4	5	9.33	5	10.865	33	11.5	158	0.0728	
		2	2	18	5	13.68	5	10.98	5	12.33	33	15	112	0.1339	
	3	1	4	18.5	5	19	5	20.26	5	19.63	31.5	13	77	0.1688	Stopped mid way then turned pump back on because we needed to fill the Node with water
		2	5	18	4	20.24	5	19.86	4.5	20.05	34	16	31	0.5161	
		3	2	13	5	20.12	5	20.4			28	15	84	0.1786	Sand added to the tank and 17lbs added to Node; tests at these conditions are marked in light grey
Fully Closed	1	1	1	22	N/A	N/A	N/A	N/A	N/A	N/A	32	10	48	0.2083	Added 13 more pounds; 26 seconds but had to stop because water started overflowing in tank (couldn't build a siphon) and reservoir tank was low (had to turn up water line); did not want to ruin pump/started back up and ended at 48.62 seconds; Started floating at the end due to the jetting; difficult to do with just 2 people (especially at high speed); we didn't even get the chance to read for the pressure and flowrate
	2	1	3	20	10	31	10	27	10	29	32	12	58	0.2069	
		2	1	21	10	12	10	32	10	22	31	10	52	0.1923	
	3	1	6	18	14	41.12	13	40.3	13.5	40.71	34	16	21	0.7619	
		2	7	19	12	38.48	13	N/A	12.5	38.48	35	16	21	0.7619	
		3	1	8	10	26	13	41	11.5	33.5	29.5	21.5	49	0.4388	Burial slowed down greatly after reaching around 16"
															Unless otherwise stated, test was stopped becuase Node would no longer bury itself

Appendix L. Bill Of Materials (BOM)

Bill of Materials								
Assembly Number	Item Number	Part Number	Description: Assembly	Description: Sub-Assembly	Vendor	Quantity	Cost	Total Cost
10000	1	92980020	Primary Pump		Water Pumps Direct	1	$530.00	$530.00
10000	2			Dolly (15x25 in)	ULine	1	$62.00	$62.00
10000	3			Wiring Pump	Cal Poly	1	$826.00	$826.00
10000	2	1	Test Assembly					
10100	1	52375K17		Hose 1" ID	McMaster Carr	50	$2.45	$122.50
10100	2	4596K655		PVC Reducer	McMaster Carr	4	$6.50	$26.00
10100	3	5535K15		Camlock (Female)	McMaster Carr	6	$6.78	$40.68
10100	4	5535K37		Camlock (Male)	McMaster Carr	6	$2.59	$15.54
10100	5	4089K61		Pressure Guage	McMaster Carr	1	$9.95	$9.95
10100	6	4780K13		Pressure Relief Valve	McMaster Carr	1	$106.88	$106.88
10100	7	4880K825		1-1/4" NPT Hex Bushing	McMaster Carr	1	$0.99	$0.99
10100	8	5020T74		Flowmeter	McMaster Carr	1	$405.64	$405.64
10100	9	4738T83		1" Male to Unthreaded Socket Adapter	McMaster Carr	1	$3.00	$3.00
10100	10	4738T33		1" Tee	McMaster Carr	1	$6.30	$6.30
10100	11	4880K83		1" Female to Unthreaded Socket Adapter	McMaster Carr	2	$0.50	$1.00
10100	12	147026		WARN Pullzall 120 V	Northern Tool	1	$189.99	$189.99
10100	13	103181		2000 lb Adjustable Gantry Crane	Northern Tool	1	$548.99	$548.99
10100	14	145196		1-Ton Steel Beam Clamp	Northern Tool	1	$49.99	$49.99
10100	15	CRMI-200OTT		200 Gallon Tank	The Tank Depot	1	$231.99	$231.99
10100	16	1.1		55 Gallon Plastic Trashcan	N/A	1	N/A	N/A
10100	17	48925K93		1" PVC Pipe (5 ft sch 40)	McMaster Carr	1	$4.92	$4.92
10100	19	73605T98		1" NPT to 3/4" GHT Adapter	McMaster Carr	1	$14.68	$14.68
10100	20	7454T15		25' Garden Hose	N/A	0	N/A	N/A
10100	21	111351		Sand	Home Depot	25	$5.70/$2.97	$106.46
10100	22	25A-A8P0N104		VFD PowerFlex 523 AC (plus shipping)	One Source	1	$486.09	$504.94
10100	23			Manual Chain Hoist	Harbor Freight Tools	1	$59.25	$59.25
10100	24			Tee Branch Valve Connection	Home Depot	1	$29.86	$29.86
10000	3	3	Node					
10300	1	3.1		12" Schedule 40 White PVC Pipe	PVC Fittings Online	1	$109.86	$109.86
10300	2	3.2		PVC Bottom Cap 12"D S40	PVC Fittings Online	2	$57.63	$115.26
10300	3	3.3		PVC Top Cap 12"D S40	PVC Fittings Online	1	$57.63	$57.63
10300	4	5218K37		Barbed Hose Fitting	McMaster Carr	1	$1.94	$1.94
10300	5	4880K358		PVC Reducer	McMaster Carr	1	$2.41	$2.41
10300	6	4596K47		Threaded PVC Nozzle	McMaster Carr	5	$9.63	$48.15
10300	7	3016T39		Eyebolt with Nut	McMaster Carr	1	$6.86	$6.86
10300	8	90770A033		Steel Washer	McMaster Carr	1	$4.20	$4.20
10300	9	98404A959		Quick-Release Pins	McMaster Carr	3	$5.80	$17.40
10300	10	5420K1		PVC Tube Clamp	McMaster Carr	13	$1.21	$15.73
10300	11			Fishing Weights	Port San Luis Boat Yard	10	$5.00	$50.94
10300	12			Steel bars	Cal Poly Mustang 60	13	$2.00	$26.00
10000		2	Adhesives					
10200	1	74605A15		PVC Glue (16 oz)	McMaster Carr	1	$9.99	$9.99
10200	2	8277		J-B Weld Waterweld	The Home Depot	1	$5.77	$5.77
10200	3			Marine Lubricant	The Home Depot	1	$23.97	$23.97
							Total:	$4,393.66
			(pink)	Purchased by Team	Total (not including unused items):			$3,698.73
			(green)	Purchased by SPAWAR	Total needed from SPAWAR:			$801.42

Appendix M. Operator’s Manual

Jetting System Operator’s Manual

Table of Contents

1. System Overview

The system is capable of jetting high pressure water at a range of flow rates operated by a specified pump. Our model of the pump is listed in Appendix A. The pump used in operation will be connected to SPAWAR's automation system. The following steps should be used for the newly chosen pump.

1.1 System Configuration

The parts of the system that SPAWAR will use in their automated system are the pump, the camlocks connecting the pump to the PVC hosing of the system, the Node and nozzle. Due to a high voltage of 230 volts, it is advised that the electrical wiring is handled with extreme caution, or have an electrician handle the wiring to the pump. Note that all wiring must meet National Electrical Code (NEC) and local codes. The pump will be connected to the PVC hosing by camlocks, as shown in Figure 1. For this specified pump, PVC reducers are connected to the pump to ensure uniform flow throughout the system.

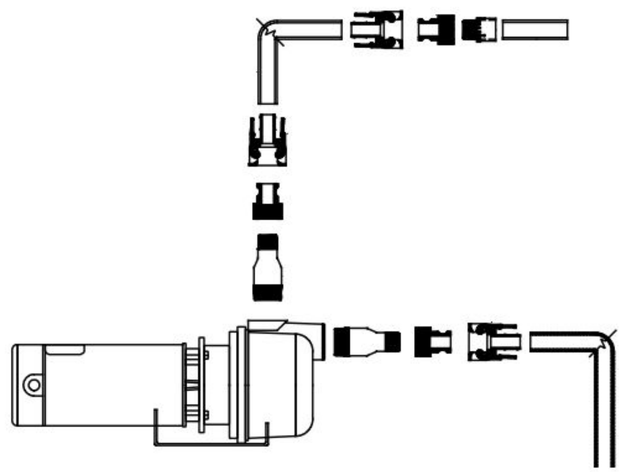


Figure 1. Schematic of the connection of the pump to the PVC hosing with camlocks. Note that there are PVC reducers fastened to the pump before the camlock connections.

The PVC hosing will connect into the Node, which will contain the payload. The nozzle will be attached at the bottom of the Node as a NPT threaded PVC end cap, as shown in Figure 2. The nozzle will have specified hole configurations, where the high pressured water will jet out.

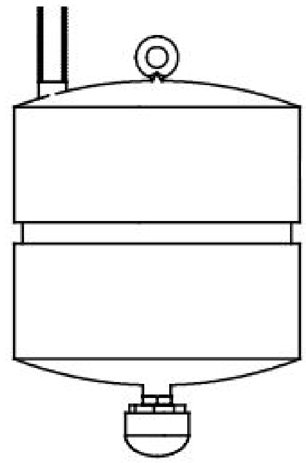


Figure 2. Schematic of the Node and nozzle. Note that the nozzle does not show the detail of the hole configurations.

2. Node Operation

2.1 CAUTION:

- Before using the Node, ensure that the area in which operation will occur is clear of obstructions or debris which could cause injury

2.2 Introduction:

The Node shall be used to insert a payload below the seafloor. This manual, along with the procedure, can be used to successfully install and operate the Node. All parts used in the manufacture of the Node should be consistent with the Bill of Materials (BOM). Alternate parts should match or exceed the factor of safety of those used in the BOM.

2.3 Inspection:

2.3.1 Nozzle:

- Ensure that the outlet ports are unobstructed
- Verify that the threads on the nozzle are clean and undamaged

2.3.2 Node:

- Ensure the PVC hose is free of cracks, punctures, or kinks
- The Node caps should both be secured such that they cannot be shaken loose
- Ensure payload is not loose inside the Node

2.4 Connection:

Attach the cam and groove coupling protruding from the top of the Node to the hose coming out of the pump by pressing the male fitting of the cam and coupling into the female fitting such that the gasket in the female coupling is properly seated. Then push the cam arms down so that they lock themselves against the side of the female coupling. *Ensure that the gasket in the female coupling has not fallen out or fouled before making the attachment.*

2. Troubleshooting

Problem	Possible Cause	Remedy
Water not exiting Node	a) Pump not turned on b) Hose clogged c) Nozzle clogged	a) Turn on pump b) Disconnect nozzle and flush hose with water c) Disconnect nozzle and flush threads and outlet holes with water
Low water pressure out of Node	a) Kink in hose b) Crack in hose	a) Stretch out hose a) Reposition payload inside Node b) Replace PVC hose where broken

Appendix A. Pump Operator's Manual

The link below can be used to access the Franklin Electric Turf Boss 2 HP Self-Priming Cast Iron Sprinkler Pump.

https://www.waterpumpsdirect.com/manuals/106258101_Turf_Boss_Owners_Manual_R4_01-14_WEB.pdf