Department of Mechanical Engineering
Northern Arizona University
Flagstaff, AZ 86011

Navy Precision Optical Interferometer

To: Jim Clark & Steve Winchester

From: Amelia Fuller, Wyatt Huling, & Scott Ryan

Date: 04/18/2013

Re: Nitrogen Supply Distribution Project Final Report

The NAU Capstone project for the Nitrogen Supply and Distribution for NPOI site has come to a closure with our final design, prototype and testing. We are presenting our final report that will cover our project in its entirety. The goal of this project was to provide an improved nitrogen distribution system that requires less maintenance and lower cost than the current system at the NPOI site.

The final design for this nitrogen system is built around a 1000L liquid nitrogen Dewar with ½in copper supply tubing along each 250m arm. A tee will be soldered in at each location and provide nitrogen to ¼in polyvinyl hose that will feed each device with its appropriate pressure. A 5-gallon reservoir tank will be installed near each gate valve station to help accommodate for the high flow required by the gate valves.

A proof of concept prototype was created that implemented a 100 ft. section of the west arm at the NPOI site. This section includes one of each of the astrometric hut, gate valves, and an imaging station. In order to help simulate the length of an entire arm, a 100ft copper coil of tubing is added in line to the prototype design. A 3-gallon reservoir tank was installed for the gate valves due to its availability.

Testing was done on the prototype to assist in predicting the pressure drop of the final system. The error in calculation of pressure drop in the prototype was 36%. Scaling this value up for the total system gives a predicted pressure drop of 3.22PSI from the supply tank to the final imaging station of each arm. The predicted cost saving of using the 1000L Dewar over the current system is 66%. After performing numerous calculations and tests, it is safe to say that this proposed design would save the staff at NPOI both time and money in the long term.

NPOI Nitrogen Distribution

By
Amelia Fuller, Wyatt Huling, Scott Ryan
Team 16

Final Report
Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Spring 2014

Department of Mechanical Engineering
Northern Arizona University
Flagstaff, AZ 86011

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Nomenclature

Q= Volumetric flow rate [m^3/s] or [CFH]
C= Flow coefficient through orifice
ρ= Density [kg/m^3]
ΔP= Pressure drop [Pa]
V= Volume [m^3]
A= Area [m^2]
L= Length [m]
t= Time [s]
K= Loss coefficient in pipe component
D= Diameter [m] or [in]
f= Friction factor
v= Velocity [m/s^2]
α= Coefficient of thermal expansion [$^oF^{-1}$]
ΔL = Change in length [ft.]
T = Temperature [^oF] or [^oC]

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Chapter 1. Introduction

1.1 NPOI Description

The U.S. Naval Observatory (USNO) does research for the Naval Research Laboratory in providing astrometric positioning which is used for navigation and timing for the U.S. Department of Defense. Most military and GPS navigation is still based on the position of the stars and the process of orienteering. Stars are always moving relative to the earth and the other stars, so the U.S Navy is required to continuously map the location of these stars. The Navy accomplishes this by the use of the Navy Precision Optical Interferometer (NPOI). Our sponsor, the operators of the NPOI, work under the USNO. The NPOI is located 16 miles southeast of Flagstaff, AZ on Anderson Mesa. The research done in this facility involves precise observations of the astronomy needed for navigation use.

The NPOI is considered an array telescope. It consists of three 300meter arms that have observatory like mirrors along each arm. By utilizing an array, the optical surface being studied is effectively the diameter of the whole facility. Using the mirrors at the ends of the array has an equivalent effect of employing the use of a 600meter diameter solid mirror. These mirrors are used to direct optical light, the visible light spectrum, into a lab facility that further studies the image.

To operate and manage this system of mirrors, each station is equipped with a gaseous nitrogen supply. Nitrogen is used rather than compressed air for several reasons. The biggest factor is that nitrogen contains no moisture in it that can freeze and affect the mirror surface or cause an obstruction in a tube. Also, nitrogen is less affected by changes in temperature, so the pressure does not vary as much in the lines as compressed air would. The current nitrogen system at NPOI consists of a 150lb rented nitrogen tank at each of the 11 stations on each of the three arms, as well as the fourth astrometric hut that is near the center of the array. The gaseous nitrogen is used to accomplish two tasks. The first is to purge the mirrors of any moisture buildup that may ruin the mirrors. Nitrogen is pumped directly onto the mirror surface whenever the array is not in use, which keeps water from accumulating on the very delicate reflective surface. Aside from this, the nitrogen is also used for a series of pneumatic actuators. Surrounding the very expensive mirrors are housings and flaps for protection. In order to open these flaps to let light through for observation, nitrogen is sent to a pneumatic system that opens the coverings with no vibration due to water in the line or any debris. Pneumatic actuators are also used to operate gate valves that are placed inside the vacuum tubes that direct light into the facility. If one of these vacuum tubes were to be punctured in any way, the sudden pressurization to atmospheric pressure would cause stirring of dust that would ruin all of the mirrors in the system. Gate valves are installed in each arm to prevent the damage from spreading to all of the arms in the array costing the NPOI several hundred thousand dollars.

On behalf of NPOI, our clients Jim Clark and Steve Winchester have requested an improved Nitrogen Supply system.

Chapter 2. Problem Formulation

2.1 Needs Identification

Navy Precision Optical Interferometer (NPOI) has approached the NAU mechanical engineering program with this project in pursuit of improving their nitrogen supply system. It is currently a cumbersome system that involves more work than intended for our client. In order to provide an improvement, our client gave us some specific requirements to meet their needs. These requests include:

- One single supply station
- Flow time to stay within time constraint to prevent a waste in nitrogen
- Intermittent high flow rate at 40PSI for a short time period
- Continuous flow at a flow rate of 3CFH at 10PSI in each arm
- Nitrogen compatible tubing that is corrosion resistant
- Tubing that handles potential temperature drops within cable trays where thermal expansion can occur
- Tubing strong enough to prevent failure from vibrations within cable tray

Based on these needs, we have concluded that our client needs an easily operable nitrogen supply system that is not labor intensive without spending an excessive amount of money.

2.2 Project Goal

The goal of this project is to design the nitrogen distribution with one supply station to replace the several smaller tanks that are currently in use and to have a system that prevents a waste in nitrogen gas. In order to prevent any further waste, the improved design must have the supply to the mirror purges shut off when not in use. There are currently 11 supply stations along each of the three 250 meter length arrays, and another supply station at the fourth astrometric hut. Within each station there are supply tanks that are routinely refilled to maintain nitrogen levels.

Our client has emphasized that the waste in nitrogen affects the cost of supply and renting of the supply tanks itself. Site operators themselves refill each station with nitrogen tanks manually, which is labor intensive.

2.3 Objectives

When creating this system, three runs of nitrogen compatible tubing are connected to a large supply tank. This tubing must be of a diameter that is large enough to handle the necessary flow rate, but small enough to fit inside the cable tray. Since the system will undergo a large change in temperature, the tubing must have a small enough thermal expansion coefficient that it does not induce a large amount of stress on the tubing or brackets. Any vibrations that affect the tubing must be of a low enough amplitude that an infinite amount of cycles will not reduce the life of the system. Although there is no budget for the finalized system, it is also important that cost be kept as low as possible.

Table 2.1: Table of Quantifiable Objectives

Objective	**Measurement Basis**	**Units**
Inexpensive	Cost	$
Tubing size	Diameter	m
No significant change in size (Thermal expansion)	Length	m
Vibration resistant	Cycle life	# of cycles

2.4 Operating Environment

The NOPI site is located in a high elevation environment. It is located in this area for the advancement of their research. However, the effects of the environment place constraints of what material and how it can be supplied efficiently throughout the site. The location of the facility must take into account the exposed system to rain, snow, ice, UV light and potential wildlife interfering with its operating environment. There is a temperature gradient that creates a concerning factor for moisture and thermal expansion. The supply system must be able to operate between the temperatures of -20ᵒF to 120ᵒF.

The supply of nitrogen is dispersed to each station by means of nitrogen tubing along cable trays. The cable trays are run along the stations and are exposed to the atmosphere as well as with other machine operating cables. These cable trays vibrate and therefore require that the nitrogen lines have a life cycle high enough to prevent fatigue and damage in their line.

2.5 Constraints

To meet the needs of the clients, each of the three runs must be 300m long with 11 supply stations on each. These supply stations will provide nitrogen to one regulator per item, since each device requires a different line pressure. The regulators will be used to ensure that the mirror cover purge receives 9psi, the lizard head actuator receives 40psi, and the gate valves receive a minimum of 40psi. Rather than allowing the nitrogen to flow all night when the mirror cover is removed, a solenoid will be put in place to stop flow if the cover is not in place. The client also requested that a valve be put in place before each manifold to allow the flow to be manually shutoff. Since the instrumentation at NPOI is extremely delicate, the employees do not want to add another fragile item to the workplace. Therefore, the nitrogen system should be tough enough that the employees do not have to go out of their way to ensure that they are extremely careful with all of the lines, fittings, regulators, etc.

Chapter 3. Proposed Design

3.1 Material Selection

To reach each station along the 250-meter length arrays, a main supply tubing system needed to be chosen. For this choice, many different materials of tubing were considered. Options such as rubbers, plastics and metals were all considered. Tubing made of plastics included polypropylene and polyethylene. The latter of these two comes very cheap but is not rated for extended outdoor use. Polypropylene boasts a high UV rating but proved to be very expensive and not practical for long lengths. A vinyl option was considered and is very popular in other applications. This would consist of a UV rated polyvinyl chloride, or PVC. Unfortunately under the pressures of the system and the temperatures experienced by the supply line this option is not practical.

The material that was selected for the supply tubing is clean and capped copper. This tubing is used in many commercial refrigeration applications so it is relatively cheap and is guaranteed to be free of any debris that could potential harm one of the devices in the system. Copper rolls come with a soft temper, which makes it easy to install through the curved channels of the cable trays where they will be placed. Connections are done using female fittings that fit snugly over the tube and soldered in place. The soldering is relatively simple to do using plumbing solder and a handheld torch. Unfortunately, because the copper is so soft and easy to work with it is also susceptible to wearing due to mechanical vibrations and general abrasions. Additional caution will be taken when installing the tubing in the cable tray to help compensated for this.

However, due to the extreme flexibility and easy removal of fittings, UV-resistant polyvinyl hose will be used between the copper supply line and each device. If copper were used all the way to the device, a solder joint would have to cut out and resoldered every time an employee performed maintenance on a station. This would not only time consuming, but also expensive due to the cost of the soldering disposables and solder couplings.

Figure 3.1- Cleaned and capped copper tubing [10]

One of the requirements for this system is to have a manual shutoff at each station. There are several different valves that would be suitable for this application, each having special characteristics. Gate valves rely on a threaded stopper that raise/lower into the flow to restrict it. This allows for variable flow rates at the risk of increased loss coefficient and pressure drop. Another option is the angle valve, which has a 90º built into the body of the valve. Unfortunately, this causes an even larger pressure drop than a gate valve, which makes it quite inefficient. A third option, which was ultimately selected for this project is the ball valve. Ball valves rely on a single level that rotates 90º to allow a sphere containing a hole the same size in diameter as the inlet and outlet to be parallel to the flow when open, and perpendicular to the flow when closed. This valve style is extremely efficient (small pressure drop) and simple to use since it only requires a 90º rotation to go from fully closed to open.

Figure 3.2- Brass ball valve [8].

3.2 Distribution System

Originally, the group intended on using small aluminum manifolds at each locations, with a regulator for each individual device. The inspiration came from the staff at NPOI discussing plans to install two additional actuators in the dome of each imaging station and lack of knowledge regarding the gate valve station. However, this plan has changed so the use of a manifold would be wasteful. Instead, at the astrometric huts a single valve and regulator will be installed shortly after the tee. The 9PSI flow coming out of the regulator will pass through a ¼in barb tee to allow for both mirror purges to connect to one regulator.

Figure 3.3- Astrometric hut distribution system.

At the gate valves, it was believed that a tube was connected to each valve in the station so a 3-port manifold was required. This was later disproven thanks to a common plenum that requires only one inlet to supply all three valves. Therefore, a single valve and regulator set to 40PSI is all that will be attached to the reservoir tank dedicated to the gate valves.

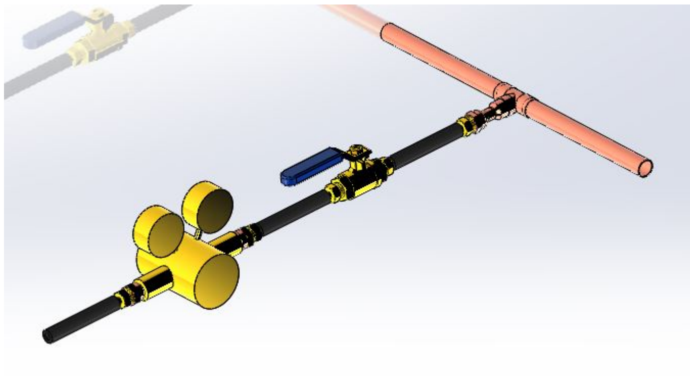


Figure 3.4- Gate valve distribution system.

The most complicated distribution system, although still relatively simple, is located at each imaging station. Due to the high and low pressure requirements of the actuators and mirror purges, a barb tee will be installed after the valve to supply line pressure to two separate regulators. The high pressure regulator will be set to 40PSI and supply a single line that distributes flow to the three pneumatic actuators. The low pressure regulator will be set to 9PSI and will feed the mirror purges located in the dome.

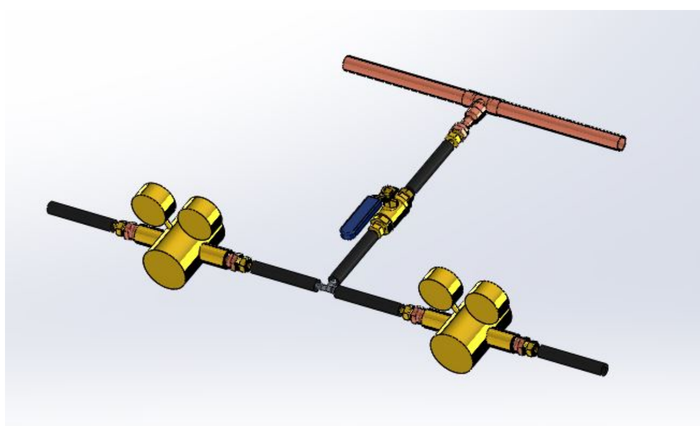


Figure 3.5- Imaging station distribution system.

Although manifolds will no longer be installed at each station, a large 3-port manifold will still be required at the center of the array to distribute flow between the three separate arms. This manifold will be black anodized aluminum with ½in NPT inlet and 3/8in NPT outlets. NPT to tube adapters will then be installed on each port, with the inlet attached to the 1000L Dewar and one outlet going to each arm in the array. A small coil will be bent prior to the inlet to allow for movement in the system without affecting the rigidly mounted manifold.

Figure 3.6- 3-port anodized aluminum manifold.

At the branch of each tee, brass fittings will be used to convert the ½in tube to ¼in hose. To make this conversion, ½in NPT tube to $^{1}/_{4}$in female NPT fittings will be soldered into a small ~2in piece of tube that is soldered into the tee. A ¼in brass barb fitting with $^{1}/_{4}$in male NPT threads will then be installed with Teflon tape to create an airtight seal. The ¼in polyvinyl hose easily secures to the barb fittings using a stainless steel hose clamp at each location. The ball valves and regulators will also use ¼in barb fittings and hose clamps at each inlet and outlet.

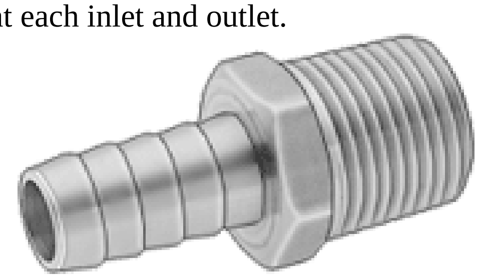


Figure 3.7- Male NPT to hose barb fitting.

Figure 3.8- Female tube to female NPT fitting.

3.3 Supply Calculations

Each arm of the NPOI array consists of one astrometric hut, ten imaging stations, and a set of three gate valves. However, there will only be two imaging stations in use on each arm at one time due to the design of the interferometer. There is also another astrometric hut that will be fed by a separate, smaller run from the supply tank. All of the previously listed components must be accounted for when calculating the necessary nitrogen flow rate on each arm, as well as the whole system.

The astrometric huts contain several different precision instruments, but the only items that require nitrogen are the siderostat mirrors. Each mirror requires a cover with a nitrogen purge that will keep the mirror clean and dry. Each purge consists of a 0.004in orifice at 9PSI line pressure. Since the purge is releasing into the atmospheric air, the pressure drop across the orifice can be assumed to be the line pressure. However, the drop will actually be lower than this so this calculation will be an underestimate. The flow coefficient, C for a square edged orifice plate is equal to 0.75. The calculation for the flow rate on each purge is shown below [1]:

$$Q = CA_o\sqrt{\frac{2\Delta P}{\rho}}$$

Where:

D_o= 0.004in= 0.1016mm

$A_o = \left(\pi/_4\right) \times {D_o}^2 = \left(\pi/_4\right) \times (0.1016)^2 = 0.008107mm^2 = 8.1073E^{-9}m^2$

C= Flow coefficient= 0.75

$\Delta P = P_{line}$= 9PSI= 62052.6Pa

$\rho = Density\ of\ nitrogen = 1.25\ ^{kg}/_{m^3}$

$$Q = 0.75 \times 8.1073E^{-9}\sqrt{\frac{2 \times 62052.6}{1.25}} = 1.9158E^{-6}\ ^{m^3}/_{s}$$

$$Q = 1.9158E^{-6} \times 35.3147 \times 3600 = 0.2436CFH$$

While this value seems logical, the staff at NPOI stated that the flow rate had been calculated as 0.5CFH. This inaccuracy can be due to an underestimate of pressure drop, turbulence through the orifice, and the compressibility of nitrogen gas (the above equation assumes the fluid is incompressible).

At each imaging station there are three pneumatic cylinders that are used to open the hoods covering the "lizard head" and there will soon be two pneumatic cylinders at each camera dome. There is also a siderostat mirror inside the lizard head and the dome, with a purge identical to those located in the astrometric huts. These cylinders operate at an ideal gauge pressure of 40PSI. The pneumatic cylinders have a 1in bore with a 5in stroke. The volume calculation for the cylinder is shown below:

$$V = L \times A$$

Where:
$A = \left({}^{\pi}/_{4}\right) \times D^2$
D= bore= 1in
L= stroke= 5in

$$V = 5 \times \frac{\pi}{4} \times (1)^2 = 3.927in^3$$

Due to the dual actuation of these cylinders, both tubes that are attached to the cylinder must be filled on each actuation. These tubes are $^3/_8$in diameter and approximately 10ft in length. The volume calculation of these tubes is shown below:

$$V = 2 \times 10 \times \frac{12}{1} \times \left(\frac{\pi}{4}\right) * (0.375)^2 = 26.507in^3$$

Now that we have the volume that must be filled to actuate these cylinders, we must convert this to the flow rate that it will be pulling from this system. Since pneumatic cylinders are not 100% efficient, the volume required to extend the rod is not exactly equal to the length times the area, and nitrogen is a compressible fluid, the equation for the flow rate of a pneumatic cylinder is shown below [3].

$$Q = \frac{V \times P_{abs}}{28.8 \times t \times P_{atm}} \left[\frac{in^3}{s}\right]$$

Since the absolute and atmospheric pressures are required, it must be noted that atmospheric pressure at 7000ft is 11.3PSI rather than 14.696PSI like it is at sea level [4]. The time, t is the time required to complete the actuation which is 2 seconds for this application. To convert to the required units of CFH, in^3 must be converted to ft^3 and seconds must be converted to hours:

$$Q\left[\frac{in^3}{s}\right] \times 3600 \left[\frac{s}{hr}\right] \times \frac{1}{12^3}\left[\frac{ft^3}{in^3}\right] = Q \times \frac{25}{12}\ CFH$$

$V = V_{cylinder} + V_{tubes} = 3.927 + 26.507 = 30.434in^3$
t= 2s
P_{abs}= 40+11.3= 51.3PSI

$$Q = \frac{30.434 \times 51.3}{28.8 \times 2 \times 11.3} \times \frac{25}{12} = 5.484 \rightarrow 6CFH$$

Figure 3.9 – Pneumatic cylinder [5]

After the sixth imaging station on each run, there are large gate valves installed in the vacuum tubes that carry the beams of light into the processing station. These tubes are 8 inches in diameter and contain a long series of very expensive mirrors that reflect light at precise angles. If one of these tubes gets damaged, dust and abrasive particles will enter the system and wreak havoc on all of these mirrors. This would cause hundreds of thousands of dollars worth of damage if it were not contained. To prevent this catastrophe, the staff at NPOI installed gate valves that will block any flow in the case of emergency. There are 3 gate valves on each location and each one is actuated with a dual actuation pneumatic cylinder with a 3 inch bore, 15 inch stroke, and 5 feet of tubing attached to each port. The volume calculations for the cylinder and tubes are shown below:

$$V_{cylinder} = L \times A = 15 \times \frac{\pi}{4} \times (3)^2 = 106.03in^3$$

$$V_{tubes} = 2 \times 5 \times \frac{12}{1} \times \left(\frac{\pi}{4}\right) \times (0.375)^2 = 13.254in^3$$

$$V = 106.03 + 13.254 = 119.282in^3$$

$$Q = \frac{119.282 \times 51.3}{28.8 \times 2 \times 11.3} \times \frac{25}{12} = 21.495 \rightarrow 22CFH$$

Figure 3.10 – VAT 8-inch pneumatic gate valve [6]

While the actuators that open the hoods and actuate the gate valves are used intermittently, the purges must flow constantly. The only time that these purges will not flow is when the covers are removed for the astronomers to perform their nightly image capturing. Due to the design of the system, the gate valves will never actuate at the same time that one of the hoods is being opened or closed. Therefore, the maximum flow rate in each arm is shown below:

$$Q = 22 + 6 \times 0.5 = 25CFH \text{ for 6 seconds}$$

This flow rate must be followed by a constant flow rate of 3CFH to continue feeding the mirror purges. While 25CFH is the maximum flow rate that will be seen by each arm, the other situations should also be analyzed.

The hoods on each of the active imaging stations will be opened every night and closed every morning, but will sometimes be opened more frequently. As was previously stated, there are three actuators in each lizard head, and there will be two more in the camera domes. The three cylinders in the lizard head will be operated simultaneously and roughly thirty seconds later, the two other cylinders will operate simultaneously. The flow rate as seen by the supply line is equal to three simultaneous cylinders followed by two simultaneous cylinders all while the mirror purges are flowing. There will be several minutes between each imaging station being operated, so there will be plenty of time for the lines to recover before another large amount of nitrogen is pulled from the system.

$$Q_{open} = 3 \times 6 + 6 \times 0.5 = 21CFH \text{ for 4 seconds}$$

The reason that it is calculated for 4 seconds is because it will take two seconds to open the lizard head, and two seconds to open the camera dome. It is unlikely that these two will be opened consecutively, but since there is a chance that it will happen, it is best to account for it. Since the potential use of storage tanks will affect the tubing size, the calculation for the supply line tubing size will be discussed after the storage tanks.

3.4 Tank Implementation

In order to reduce the load on the main supply line, storage tanks could be installed in series with the supply line near the gate valves. The use of these tanks would allow a smaller tubing size to be used, because rather than the allowable pressure drop being across the entire length of each arm, it would only be across $^1/_3$ of that for the total flow rate and $^2/_3$ of the length for the flow rate that is required by the imaging stations after the gate valves. Considering the availability and low cost of 5-gallon air tanks, this size is the most likely to be used. A 5-gallon tank is equal to $0.6684ft^3$ so it will allow a large amount of nitrogen to be used without instantly affecting the main supply line.

Figure 3.11 – 5 gallon air tank with multiple ports [7]

Shown below is the calculation for the length of ½in (0.55in ID) tubing that would be evacuated if a tank were not used:

$$L = \frac{V}{A} = \frac{0.6684}{\left(\pi/_4 \times (0.55 \times (1/_{12}))^2\right)} = 405.123\text{ft}$$

The equivalent length of $^5/_8$in tubing (0.68in ID) is shown below:

$$L = \frac{0.6684}{\left(\pi/_4 \times (0.68 \times (1/_{12})^2\right)} = 265.0277ft$$

The fact that a tank can play the role of more than 1/3 the length of the supply line would be extremely helpful in an emergency situation that requires the gate valves to be closed instantaneously. It would also be helpful when one active imaging station is near the center, and the second one is at or near the end. Rather than nitrogen having to travel down several hundred feet of tubing, it would be readily available in the 5-gallon reservoir tank.

3.5 Tubing Size

In order to calculate the required tubing size for this application, the total length of tubing must first be calculated. The total length of each arm must account for the ~985ft length between the center and the final station as well as the ten 180º bends and several smaller 45º bends. The calculation below will account for the lengths and bends, but it is likely that there are slight bends in the cable tray that are not included. For this reason, a small length will be added to reduce the risk of underestimating the pressure drop in the line.

$$L = L_{straight} + N[(\pi \times R) - (R \times 2)] + M(\pi \times R)$$

Where:
$L_{straight}$= Unobstructed cable tray length= 820ft
N= Number of 180º bends= 10
R= Radius of curvature of cable tray= 3ft
M= Number of 45º bends= 10

$$L = 820 + 10(\pi \times 3 - 3 \times 2) + 10(\pi \times 3) = 948.496ft \rightarrow 950ft$$

If no tank is used, the pressure drop must be calculated across this whole length for a flow rate that can feed two imaging stations, one astrometric hut, and the set of gate valves (25CFH). For cleaned and capped copper tubing, $^5/_8$in tubing has an inner diameter of 0.68in, ½in tubing has an inner diameter of 0.555in, and $^3/_8$in tubing has an inner diameter of 0.436in. Since the fluid must pass by every connection, the equivalent length is affected by 11 line flow tees, and goes through one tee in branch flow.

In order to calculate the pressure drop and equivalent length for a given tube, a MATLAB code was created. These calculations are done after accounting for any losses due to tees, valves, bends, or curves. To ensure that the tank is usable under the largest operating range, the goal is to keep total pressure drop in the system below 5PSI. The following equations are at the heart of the MATLAB code to calculate the equivalent length and pressure drop:

$$L_{eq} = \frac{KD}{f}$$

Where:
K= loss coefficient (dependent on fitting style and found in table) [2].
D= Flow diameter
f= Friction factor (Dependent on Reynolds number and relative roughness)

$$Re = \frac{\rho V D}{\mu}$$

Where:
ρ= Density of nitrogen= 1.1651$^{kg}/_{m^3}$
V= Fluid velocity= $^{Q}/_{A}$
D= Flow diameter
μ= Dynamic viscosity= 1.755E^{-5}P$a \cdot s$

$$\Delta P = f \frac{L_{eq}}{D} \frac{V^2}{2}$$

The output of the code gives the equivalent length in units of meters, the diameter in inches, and the pressure drop in PSI. The units are all converted to SI units prior to calculation in the MATLAB code, and then converted back to the desired units before being displayed. The pressure drop is calculated for $^3/_8$, ½, and $^5/_8$in tubing:

>> Tubingsizetank
What is diameter?0.436

How many tees?10
How many branch tees?1
How many valves?1
Line length [m]?300
Flowrate [CFH]?21
Equivalent length=
300.9206
Total Pressure Drop=
5.9174

This pressure drop is very large, considering the goal for allowable pressure drop in the whole system is 5PSI.

>> Tubingsizetank
What is diameter?0.55
Flowrate [CFH]?21
Equivalent length=
301.0659
Total Pressure Drop=
1.9474
>> Tubingsizetank
What is diameter?0.68
Flowrate [CFH]?25
Equivalent length=
301.2015
Total Pressure Drop
0.7670

Although the extremely small pressure drop that occurs with the 0.68in tubing is desirable, the increased cost makes it a poor choice. For this reason, tubing with 0.555in inner diameter (½in tubing size) will be used for all three arms of the array.

As was stated before, a single tube from the 1000L Dewar will feed the center of the array using a 3-port manifold. While using a single line to feed all three arms from the center requires more tubing, the simplicity of the system and the fact that it will provide equal flow to all three arms at all times makes it a more viable option.

If one large tube feeds all three arms, the maximum flow rate will be equal to the purges in six imaging stations, four astrometric huts, and the set of six gate valves (32CFH). This is because of the way that the interferometer is setup, there will be no circumstances where multiple sets of gate valves or imaging station actuators will be used at once. The pressure drop for this section must be quite small, because it will deny the whole system of nitrogen once the tank outlet reaches a pressure equal to the needed line pressure plus the pressure drop (the larger the pressure drop, the higher the pressure where it becomes unusable). The calculation for this large tubing size is done with a length of 100m.

>> Tubingsizetank
What is diameter?0.68
Flowrate [CFH]?32
Total Pressure Drop
0.4992

>> **Tubingsizetank**
What is diameter?0.555
Flowrate [CFH]?32
Total Pressure Drop
1.2766

Since the total allowable pressure drop from the Dewar to the end of each arm is 5PSI, it is safe to use 0.555in tubing to feed the center of the array. This is also advantageous in the fact that only one size of tubing will need to be ordered, and kept on site in case of emergency.

Table 3.1- Summary of supply tubing pressure drop.

Location	**Tubing ID (in)**	**ΔP (PSI)**
250m arm	0.555	1.9474
Main line feeding center of array	0.555	1.2766
Total system	0.555	**3.224**

3.6 Thermal Expansion

Any material that experiences a change in temperature will suffer from thermal expansion. The change in length due to a change in temperature is dependent on the coefficient of thermal expansion, the initial length, and the difference between the installed temperature and the maximum or minimum temperature that is seen by the material.

$\alpha = 9.3 \times 10^{-6}/°F$ for copper
$T_{max} = 120°F$
T_{min}= -20°F
$T_{install} = 70°F$

$$\Delta L_{hot} = L_o \alpha (T_{max} - T_{install})$$
$$\Delta L_{cold} = L_o \alpha (T_{install} - T_{min})$$
$$\Delta L_{hot} = 700 \times 9.3 \times 10^{-6}(120 - 70) = 0.3255\text{ft}= 3.906\text{in}$$
$$\Delta L_{cold} = 700 \times 9.3 \times 10^{-6}(70 - -20) = 0.5859\text{ft}= 7.0308\text{in}$$

Since this change in length is quite high, it brings up the risk of stress being larger than the tubing can handle. For this reason, the maximum stress will also be calculated for the tubing. The maximum allowable stress, as well as the stress induced by the change in temperature is shown below:

$\sigma_{max} = 6E^3 PSI$
Modulus of elasticity, E=$16E^6 PSI$
$\sigma = \alpha \Delta T E$

$$\sigma_1 = 9.3E^{-6}(120 - 70) \times 16E^6 = 7.44E^3 PSI$$
$$\sigma_2 = 9.3E^{-6}(120 - -20) \times 16E^6 = 13.39E^3 PSI$$

As seen in the calculations, the stress induced by thermal expansion when the temperature reaches -20ºF far exceeds the allowable stress for copper. Fortunately, the installation of an expansion loop will reduce this stress by absorbing the expansion/contraction of the tubing. The calculations for the loop dimensions are shown below:

$$L = \frac{1}{12}\left(\frac{3E}{\sigma_{max}}\right)^{1/2} (d_o \Delta L)^{1/2}$$

$$L = \frac{1}{12}\left(\frac{3 \times 16E^6}{6E^6}\right)^{1/2} (0.625 \times 7.03)^{1/2} = 16.1in$$

This length must then be converted to the appropriate diameter:

$$D_{loop} = \frac{L}{\pi} = \frac{16.1}{\pi} = 5.12in$$

As is shown in the above calculations, an expansion loop with a 5.12in diameter will have the ability to absorb the stress induced by thermal expansion. To help reduce the problems caused by the expansion/contraction of the tubing, the rubber lined loop clamps will only be tightened enough to reduced lateral motion, but not so tight that they restrict lateral motion.

Chapter 4. Prototype Fabrication

4.1 Tee Assemblies and Coil Construction

In an effort to reduce the time spent on site, and to prevent cold solder joints (improper heating of the solder in the joint that can cause leaks) the tee assemblies were soldered indoors. This process involved cutting and prepping a small section of tube to attach to the branch of the tee. This was soldered into the tee and a female tube to female NPT fitting was soldered to the end. All of the soldering was performed using a handheld Benzomatic torch with MAPP gas fuel and plumbing solder. MAPP gas burns hotter than propane (3730ºF vs. 3600ºF [12]), which makes it more suitable for soldering tubing of this size. The coil was also constructed at this time by simply soldering two 50ft rolls together using a coupling

4.2 Supply Line Installation

As was stated before, the copper tubing came in 50ft rolls with a soft annealed temper. This allowed the tubing to be easily rolled out straight by applying pressure onto the roll and rolling it along a smooth, flat concrete surface. The covers of the cable tray were removed using a flathead screwdriver and 9/16in wrench. Due to the curves in the cable tray, the ends of the tubing had to be secured while two people carefully bent the tubing to match the curvature of the tray. After the tubing was properly located the tee assemblies were soldered into place and the covers were reinstalled.

4.3 Attachment of Devices

The first object to be connected to the system was the astrometric hut. This was done by feeding a double-precision low pressure Harris regulator set at 9PSI with polyvinyl hose into the building. A 0.004in orifice was then attached to the end of the polyvinyl hose and placed near the mirror surface. Although there are two mirrors that require purging in the astrometric hut, the NPOI staff requested that only a purge on the second mirror be installed so as to not affect the astronomers' nightly viewing by adding a different purge system to the commonly used mirror.

Following the completion of the astrometric hut, the gate valves and reservoir tank were attached. Originally, the reservoir was attached using a barb tee plumbed into the polyvinyl hose that feeds the regulator. However, this was later changed to allow the tank to be installed in series to prevent the flow restriction of the tee. A Harris regulator was set to 40PSI and fed into the plenum that is used to operate the gate valves.

Finally, the imaging station distribution was attached to the supply line. Rather than using a tee, this was done by soldering a tube to NPT adapter directly to the end of the tube. ¼in polyvinyl hose then fed the barb tee that splits the flow into two separate regulators. One regulator was set to 9PSI for the mirror purges, while the other was set to 40PSI for the actuators. However, the staff at NPOI requested that the purge not be attached as to not affect the astronomers' nightly viewing. Fortunately, the flow rate for the purge is so small that it does not affect the testing phase of the project.

Chapter 5. Testing and Results

5.1 Initial Testing

To ensure construction was not continued on an ineffective system, preliminary testing was performed on each device as it was installed. The first test was performed after installing the nitrogen tank, supply tubing, and soldering the three tees into the tubing. Since the tees were installed with the female NPT fittings already in place, it was easy to install NPT plugs to seal the system. After sealing the system, the tank was opened to bring the line pressure to 60PSI. The system was then left at this pressure for several days to ensure there were no leaks in any of the solder joints or fittings.

5.2 Functional Testing

Quite possibly, the most important aspect of this prototype was ensuring that all of the devices work properly. Pressure drop and durability of the system are important, but these attributes can be modified for the final design by increasing tubing size, adding more reservoir tanks, or placing a protective liner on the supply tubing. The mirror purge operates by using a ¼in inner diameter tube with a 0.004in orifice in the end. For an orifice plate with these physical dimensions, supplying nitrogen with a gauge pressure of 9PSI will ensure 0.5CFH. After setting the low-pressure regulator for each mirror purge to 9PSI it was confirmed that they performing properly.

The most complicated and important device in the system is the gate valve station. For these gate valves to function properly, the pressure and flow rate of nitrogen are both very important. If the pressure is too low, there will not be enough force to begin movement of the piston in the actuator, and if the flow rate is too low, there will not be enough volume to close all three valves. Upon installation of the 3-gallon reservoir tank and in-line regulator, the supply line was pressurized to 50PSI and the regulator set to 40PSI, respectively. Indicator lights are installed in the gate valve station that illuminate when all three valves are fully open or closed. To the delight of the group and NPOI staff, all three gate valves opened and closed successfully on the first attempt.

At the end of the 200ft of tubing lies the imaging station supply. The actuators in the lizardhead have an operating pressure of 30-50PSI. However, if the input pressure is too high, the piston and seals in the actuator may prematurely fail. The regulator was set at precisely 40PSI and since there was minimal pressure drop in the supply line, all three actuators operated smoothly while pulling 18CFH.

The simple fact that the prototype used the same materials as the proposed final design, and was able to operate all devices from a single tank it has met all of the basic requirements of the project. However, it is also very important to ensure that the prototype and resulting final design have an efficient flow of nitrogen with minimal pressure drop.

5.3 Pressure Testing

Rather than spending a large deal of money on a digital pressure monitoring system, all pressure drop testing was done using 270º sweep mechanical pressure gauge. Although the flow rate of the gate valves (22CFH) is greater than that of the imaging station actuators (18CFH), the pressure drop is proportional to length, so the 200ft of tubing required to reach the imaging station would induce a larger pressure drop than the gate valves. To perform this test, the pressure in the supply line was set to 40PSI and the pressure was measured several times at the inlet to the imaging station. The pressure drop was found to be 0.50PSI on nearly every single test, with one test showing slightly less.

5.4 Interpretation of Test Results

The numerical prediction of the pressure drop for the prototype was performed using the MATLAB code with the following parameters:

Table 5.1- Prototype pressure drop prediction.

	Quantity
Line length [ft]	200
Coil radius [in]	6
Coil length [ft]	100
Flow rate [CFH]	18
Flow diameter [in]	0.555
Pressure drop [PSI]	**0.368**

As was previously stated, the actual pressure drop was found to be 0.50PSI, which is slightly larger than predicted. There are several different reasons that could contribute to this: the tubing was not installed perfectly straight in the cable tray, the fittings and joints are not shaped the same as an ideal one, variations in surface roughness of tubing, etc. Comparing the actual pressure drop to the predicted gives an error of 36%. Assuming that the final design will have the same underestimate in pressure drop along the total length gives the ability to better predict the pressure drop that will occur in the final design. Table 3.1 has been updated with new approximations.

Table 5.2- Revised predicted pressure drop.

Location	**Tubing ID [in]**	**ΔP [PSI]**	**Error term [PSI]**	**Revised ΔP [PSI]**
250m arm	0.555	1.95	0.70	2.65
Main line feeding center of array	0.555	1.28	0.46	1.74
Total system	0.555	3.23	1.16	**4.39**

Chapter 6. Cost Analysis

6.1 Final Design Parts Summary

As stated several times, ½in cleaned and capped copper tubing will be used from the tank to the center of the array and from the center to the end of each arm. After each tee, ¼in polyvinyl tubing will be used to provide nitrogen to each device. Shown below are tables showing the length and cost of all tubing used in the system.

Table 6.1- Summary of tubing sizes and lengths

Location	**Size (in)**	**Length (ft)**
Main supply	½	350
Three arms	½	3000
Supply to device	¼ polyvinyl	500

Table 6.2- Cost of all tubing

Description	**Size**	**Length (ft)**	**Quantity**	**Cost $**	**Total Cost $**
Copper	½in	100ft	34	202.80	6895.20
Black PVC	$^{3}/_{8}$in	100ft	5	44.00	220.00
					7115.20

Table 6.3- Description, quantity, and cost of fittings [8].

Item	**Quantity**	**Cost ($)**	**Total Cost**
½in tee	37	1.45	53.65
½in coupling	35	0.37	12.95
¼in ball valve	37	8.27	314.26

½in tube- $^1/_4$in female NPT	37	2.62	96.94
$^1/_4$in male NPT-¼in barb	37	1.20	44.40
Hose clamps	140	0.72	100.80
3-Port aluminum manifold	1	18.84	18.84
$^3/_8$in male NPT-½in tube	3	2.77	8.31
½in tube-½in male NPT	1	1.07	1.07
Total cost			**651.22**

There are several different uses and needs for a simple 5-gallon air tank. This allows for a large variety of shapes to be readily available. One tank is needed for each arm, so three 5-gallon, round, 6 port air tanks will be used. While four of the ports will be unused, it is actually cheaper to purchase a tank with 6 ports vs. 2. To attach the supply line to the tanks, a ½in tubing to ½in male NPT fitting must be used on each end. To cap off the unneeded ports, ½in NPT plugs will be used.

Table 6.4- Storage tank supplies [7] [8]

Description	**Quantity**	**Cost ($)**	**Total Cost ($)**
5-gallon tank	3	84.99	254.97
½in tube-½in male NPT	6	1.07	6.42
½in NPT plug	12	2.58	30.96
			292.35

There will be thermal expansion, vibrations, wind, rain, and snow affecting the cable tray that houses the copper tubing. For this reason, the tubing must be restrained at several locations with a vibration damping rubber isolator. These mounts will be placed on both sides of each tee, and every 10m between each station. This will require 96 of these on each of the three arms, and 32 between the tank and center. While using self-tapping screws would be cheaper and easier, everything at NPOI has been built with the finest quality and detail so it would be wise to follow suit. Jim Clark has stated that he uses stainless steel for the mounting hardware of every object on the site. Therefore, ¼-20 SS316 bolts that are 1-inch long will be used with a nylon-insert locknut. Each bracket uses two ¼in mounting holes so every bracket will require two bolts, two washers, and two locknuts.

Table 6.5- Mounting hardware [8]

Description	**Quantity**	**Package Qty.**	**Cost ($)**	**Qty. of packages**	**Total Cost ($)**
¼-20 SS316 bolt	320	25	7.22	13	93.86
¼in SS316 washer	320	100	8.25	4	33.00
¼-20 nylon-insert locknut	320	50	9.26	13	120.38
TPR Vibration-	320	25	10.56	13	137.28

damping clamp					
	1280			46	**384.52**

Table 6.6- Final Design Bill of Materials

Description	**Cost ($)**
Tubing	7115.20
Fittings	651.22
Tank supplies	292.35
Mounting hardware	384.52
Total Cost	**8443.29**

6.2 Installation Costs

The labor involved in the installation of this system is relatively simple. Installation will require bending of the copper tubing, cutting and soldering of the connections, securing the tubing in the cable tray, drilling holes in the side of the cable tray at each exit, and routing all tubing to the appropriate locations. The staff at NPOI has a workshop with a relatively large amount of tools; so few tools will need to be purchased. Considering the vast amount of knowledge and hands-on experience that both Jim Clark and Steve Winchester possess, along with the several employees contracted by Lowell to perform day-to-day maintenance, there will be no need to hire or pay a third-party to perform the work.

When cleaned and capped copper tubing is ordered in 100ft rolls, the material has a soft temper that makes it easy to bend without kinking. This bending can be done by hand or with a spring-type tubing bender. The staff at NPOI already owns several of these, so this process is of no cost to them. After the tubing is bent, it must be cut smoothly and normal to the tube so the fittings will fit properly. To perform these cuts, a plumbing metal tube cutter will be used. The holes that need to be drilled in the cable tray can be performed using a cordless drill and a bi-metal hole-saw or step bit. It is safe to assume that these items are already available to the NPOI staff.

All copper fittings that are used in the system will be soldered using an air-acetylene torch and plumbing. This method is much easier to perform than using brazing rod, and since all joints will be soldered in a horizontal configuration, the risk of introducing excess solder into the tubing is very minimal. The staff at NPOI is well versed in this type of work, and all equipment is readily available in their workshop.

6.3 Prototype Bill of Materials

The proof of concept prototype that was built used all of the same type of materials as the proposed design, but in a much smaller quantity. However, NPOI already owned the majority of the materials, with a few others being purchased at the local hardware store. Since the amount of materials that were purchased is so small relative to the final design, the bill of materials simply lists the products and their quantity.

Table 6.7- Prototype bill of materials.

Description	Quantity
½in Copper tubing	200ft
¼in Polyvinyl hose	50ft
½in Copper tees	3
½in tube-1/4in female NPT	3
1/4in male NPT-¼in barb	3
½in tube- ½in female NPT	2
½in male NPT-½in barb	2
½in vinyl hose	20ft
3-gallon tank	1
Harris in-line regulator	4
¼in brass angle valve	4
Nitrogen tank w/ regulator	1

6.4 Cost of Operation

One of the main advantages to using a central nitrogen supply system with a liquid nitrogen Dewar is the reduced cost per unit of nitrogen. 1000L of liquid nitrogen expands to a much larger volume of gaseous nitrogen. While the small gaseous nitrogen tanks are filled to a pressure of 165bar (~2400PSI), the expansion is still not as great as that of liquid nitrogen. The conversion for both liquid nitrogen and pressurized nitrogen are shown below. The liquid nitrogen conversion is found on a common nitrogen supplier's website [11].

$$V_g = V_L * 0.6965$$

Where:

$V_L = Volume\ of\ liquid, L$

$V_g = Volume\ of\ gas\ at\ 1atm, m^3$

$$V_g = 1000 * 0.6965 = 696.5m^3$$

The conversion for gaseous nitrogen is done using the ideal gas law. To create a fair comparison, both cases will be converted to the equivalent volume at 40PSI since that is the most common pressure that is seen in the system.

$$PV = nRT$$

Since the gas constant, R, temperature, T, and the number of moles, n are held constant. The predicted volume is found using the equation shown below:

$$V_{tank} = \left(\frac{P_1}{P_2}\right) V_1$$

Where:

$V_1 = volume\ of\ each\ tank = 49L = 0.049m^3$

$P_1 = 165bar = 16718625Pa$

$P_2 = 40PSI = 275789.33Pa$

V_{tank}= Equivalent volume at 40PSI

$$V_{tank} = \left(\frac{16718625}{275789.33}\right) 0.049 = 2.97m^3 = 105ft^3$$

There are currently 30 tanks on site, which equates to 3150ft^3 total volume. Each tank costs $35 to refill, bringing the cost of 3150ft^3 to $1050.00. This is then compared to that of the Dewar tank:

$$V_{dewar} = \left(\frac{101325}{275789.33}\right) 696.5 = 255.9\text{m}^3 = 9037\text{ft}^3$$

Comparing the volume of these two shows that the 1000L Dewar is equal to 86 small tanks. The Dewar will cost $1000.00 per refill, which is actually less than the 30 small tanks. Therefore, the liquid nitrogen tank will only cost 1/3 that of the current design per unit of nitrogen.

Conclusion

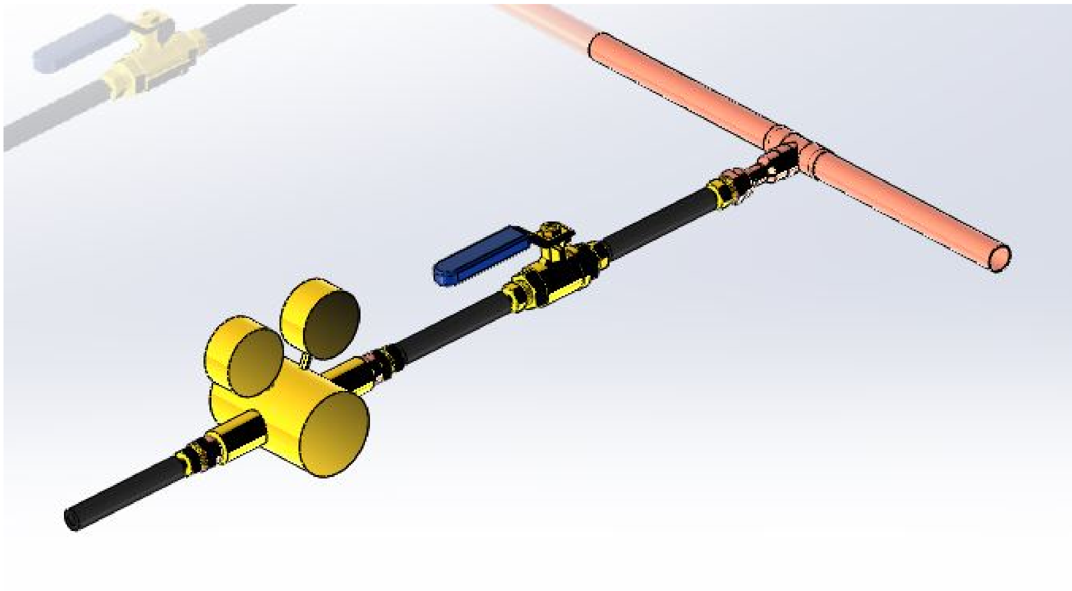
The Naval Research Laboratory uses an array telescope near Flagstaff that is called the Navy Precision Optical Interferometer. In order to operate this array telescope, several instruments located throughout the site are operated by the use of compressed nitrogen. Nitrogen is used rather than compressed air because gaseous nitrogen does not contain moisture that can affect the siderostat mirrors. The current system has 30 individual nitrogen tanks, which have proven expensive and labor intensive to maintain. As a result, the NPOI staff has approached the NAU Engineering Department with the request of a centralized nitrogen supply system. A finished design has to work at the same parameters currently used on site, which includes proper volumetric flow rates and pressures.

Due to the nature of the operating conditions, robust materials such as copper tubing and black polyvinyl hose were chosen to act as the supply system. Through fluid mechanic analysis, proper dimension sizes were chosen. Other static calculations were also made and the design of the system changed accordingly, for example, a loop to compensate for changing lengths of the copper tubing. Our analysis showed that the optimum sized copper tubing was ½" cleaned and capped refrigeration line. Pressure drops were calculated to be within operating constraints. To prove these calculations, a prototype was erected on site using one of each of the NPOI instruments. With compensation for length, the design was shown to work without any problems. In total, the cost of materials for completing this prototype came below the $500 budget. However, because all materials were located on site, no expenses were made. The cost analysis of operating the full final design showed a substantial decrease in maintenance costs. Materials for installing the final design were figured to be just over $8000.00. This does not include the cost of labor, but NPOI has several employees whose job consists of standard maintenance and construction on site. These employees will be able to perform all construction of the final design with ease. With the analysis completed before hand and the test results to prove this, we are confident that the NPOI would greatly benefit by the installation of this centralized nitrogen distribution system.

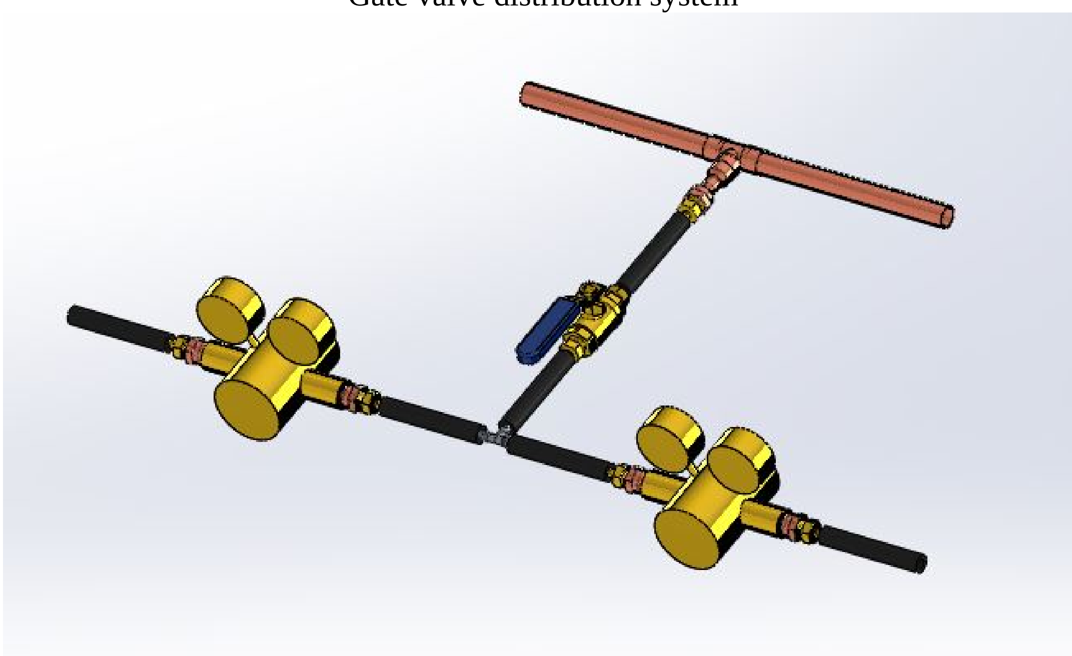
References

[1] Flow rate equation through orifice plate pg. 438: Beasley, Donald E., Figliola, Richard S. (2011). *Theory and Design for Mechanical Measurements (5th Edition)*. Danvers, Ma. Wiley & Sons, Inc.
[2] Loss coefficients for various components pg. 439: Munson, Okiishi et all. (2013). *Fundamentals of Fluid Mechanics (7th edition).* Danvers, Ma. Wiley & Sons, Inc.
[3] Flow rate equation for pneumatic cylinders. http://www.parkermotion.com/pneu/simplify/Sizing_Cylinders.pdf
[4] Pressure measurement. http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html
[5] Pneumatic cylinder. http://www.airoil.com/v6/contents/en-us/d123.html
[6] Pneumatic gate valve. http://www.vatvalve.com/products/catalog/A/481_1_V
[7] Firestone 5 gallon air tank. http://www.truckspring.com/products/Firestone-5-Gallon-Air-Tank---Long__FIR9248.aspx
[8] Fittings, valves, mounting hardware http://www.mcmaster.com
[9] Black Anodized Aluminum Manifold. http://www.polyconn.com/black-anodized-manifolds-p-2626-l-en.html
[10] Copper tube, Great Lakes Copper, Inc. http://www.glcopper.com
[11] Air Products Nitrogen. http://www.airproducts.com/products/Gases/gas-facts/conversion-formulas/weight-and-volume-equivalents/nitrogen.aspx
[12] Benzomatic. *Fuel Safety Information. http://www.bernzomatic.com/safety.html*

Appendix A: Engineering Drawings

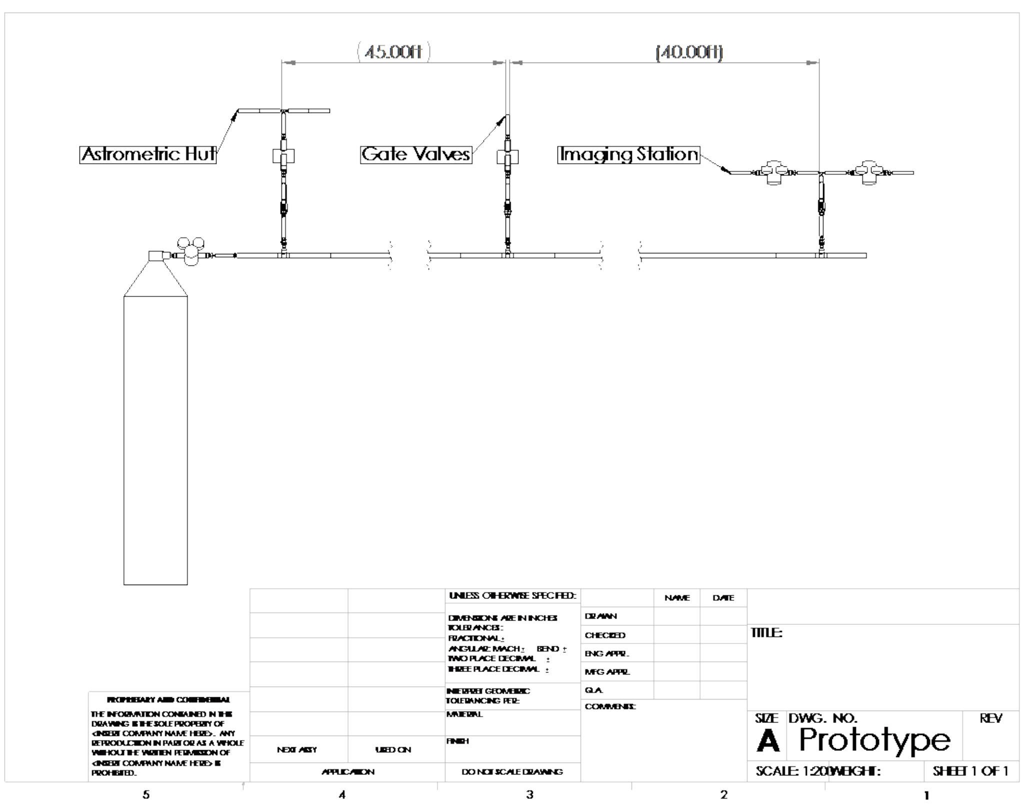


Gate valve distribution system



Lizardhead distribution system

Astrometric hut distribution system



Prototype Overview