Inductive Output Tubes (IOTs) and Power Dissipation through Coaxial Load Resistors for Project X and Superconducting RF Programs

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Participant: ______________________________________
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Research Advisors: ______________________________________
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TABLE OF CONTENTS

ABSTRACT

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Retired inductive output tube equipment will be used to amplify power that can be utilized by future accelerator beam programs. The electrical energy generated will need to be dissipated through the use of coaxial load resistors. This configuration is referred to as the Mayflower System. Both components of this system are temperature sensitive, and as a result, a coolant-based solution needed to be implemented in order to remove the excess heat that will generate during runtime. However, construction of a new Mayflower-specific coolant system was dubbed highly impractical. Utilization of already existing coolant lines was required. A new manifold was retrofitted into the already established MS6 low-conductivity water pipings. Flow rates and pressure needed to be taken into consideration during this implementation, also due to component sensitivities. For this reason, instrumentation of regulators, relief valves, and switches were put into effect to protect equipment. This cooling system will allow the Mayflower to be an active power source for future accelerators created under Project X.

INTRODUCTION

During my time at Fermilab I applied the practices of mechanical engineering in order to solve various technical issues regarding future accelerator projects. My work directly affects the next generation of particle accelerators at this prestigious laboratory.

Project X

Project X is the title given to the new proton accelerator facility projected to be constructed at Fermilab in the coming decade. The hope is to provide the most intense beams for muon, kaon, and neutrino physics experiments in the world. This extraordinary undertaking is a joint venture between many laboratories domestic and abroad. It will incorporate superconducting radio frequency (RF) to accelerate particles. This highly-efficient method utilizes niobium cavities that will be strung together like pearls. An electric field will course through the array of cavities, oscillating between negative and positive. It is in this way the accelerator will be able to literally push and pull particles to unfathomable speeds [1].

In essence, Project X is an endeavor to future proof Fermi National Accelerator Laboratory. The United States elementary particle physics community has concluded that within the next ten years Fermilab will be the solitary American site for research in accelerator based particle physics [1]. Furthermore, programs such as Japan’s J-PARC facility for neutrino research have added a dimension of competition in this field of study. As a result the current 40-year-old accelerator and aging booster ring are in need of a successor. Project X aims to be the replacement for our legacy accelerators.

Mayflower/IOT System

The Mayflower System can be viewed as Fermilab’s effort to reuse squandered technology. As of June 2009, over-the-air television signals in the United States have switched from analog to digital**.** Due to this change, perfectly functioning analog equipment was retired. This included the amplifiers television stations used to intensify broadcasts so that they are able to reach hundreds upon thousands of homes. The Mayflower System is Fermilab's attempt to breathe new life into this equipment by using it as a power source for future accelerators. We aim to utilize the amplifiers' power boost capabilities to charge the superconducting radio frequency cavities that will be used in Project X.

Project Overview

Recently the Accelerator Division of Fermilab received inductive output tubes (IOTs) that had been decommissioned from television broadcast stations. The IOTs amplify UHF signals. This functionality is an applicable power source for accelerator research at Fermilab. However, this equipment was not designed for our intended purpose, and needs to be tested before being put into real time use. This assessment is to avoid risking the health of multimillion-dollar accelerators.

A system needed to be designed to properly test and troubleshoot the IOTs. To accomplish this goal, coaxial load resistors will be used to dissipate the energy generated by the output tubes. If tests are successful the resistors will be removed and the energy will be harnessed to charge super conduction radio frequency cavities in accelerators. My project at Fermilab was to design a functional testing system for the IOTs and coaxial load resistors. We classify this project under the title, Mayflower System. This research paper is a summary of my contributions to the system.

The project will be implemented inside the Meson building at Fermilab. Accommodating for temperature and pressure sensitivities of both the IOTs and coaxial load resistors were my main challenge. Both components required some means of liquid cooling in order to remove the immense heat they generate during runtime. The installation of additional cooling lines in Meson was dubbed impractical by my superiors, so instead I had to incorporate the system into the already existing MS6 low-conductivity water system.

Figure 1: Meson building at Fermi National Accelerator Laboratory.

MATERIALS AND METHODS

Inductive Output Tubes

The inductive output tube, or IOT, was created in 1938 by Andrew V. Haeff. It was used to transmit the earliest known television images. Since then the television industry has been using them, along with similar technologies, in order to transmit their broadcasts to the masses. The underlying principles of how it functions lies within vacuum tubes. In essence, an IOT is a vacuum tube that is able to be used as a high-power radio frequency amplifier [4].

A basic vacuum tube amplifier consists of a glass tube, two diodes, a plate, filament, and appropriate wiring. In the tube the actual vacuum is created inside the glass; this is also where the filament is contained. Current is applied to the tube, and eventually reaches the filament. This energy excites the filament and causes it to release electrons inside the vacuum, thus resulting in a charge cloud of electrons. At the same time the current is also making the metal plate emit an overly positive charge. This setup produces a highly energized voltage differential between the anode, the electron cloud, and the cathode, the positively charged plate. The electrons are drawn to the plate at high speeds. They travel to the plate, and afterwards are intercepted and redirected by one of the diodes as current output. This process results in amplification [3].

Figure 2: Inductive output tube.

The inductive output tubes function in this same basic manner. However, an IOT is specifically designed for the purpose of amplifying UHF television signals. The specific model I worked with was the E2V IOTD2130. The challenges I faced when dealing with them related to properly cooling the device in order to maintain operating temperature. As mentioned before, these IOTs are retired models from television stations. They were used constantly and heavily under many harsh working conditions. This had to be taken into consideration in every decision I made.

The specific issue I faced dealt with deciding upon a proper coolant. While I intended to utilize a low-conductivity water system, a co-worker had predicted a future operation failure sprouting from this decision. It would seem that the prior owner operated the IOTs in an outside environment. As a result, they used glycol as a coolant in order to avoid possible freezing. I had to ensure that low-conductivity water would not hurt the glycol-tempered equipment.

In order to do this, I contacted the company responsible for manufacturing the equipment, E2V. Afterwards I also contacted Thomson, the company that writes service and repair manuals for the IOTs, to confirm. Both explicitly stated that substituting glycol for low-conductivity water shouldn't be an issue. However, they both indicated that the IOT would need to first be flushed of any glycol residue. I passed this information on to my superiors who promptly scheduled the IOTs to be flushed by appropriate technicians.

Coaxial Load Resistors

For our purposes, we can view the coaxial load resistor as a means to dissipate the immense energy produced by the inductive output tubes. Recall that the IOTs will eventually be used to power cavities of an accelerator, however, first they have to be properly tested. For now, we will take the power amplified by the output tubes and drive them into these coaxial loads. The coaxial load resistors work like any other resistor; they simply dissipate energy. However, these loads are specially designed to absorb enormous amounts of electricity.

For this system we will be incorporating a specific model of coaxial load resistor manufactured by Altronic Research, Inc. It will be one of two models, the 52700B or the 57125B. After reviewing the product documentation of both resistors, it would seem that for our purposes either one will function quite suitably. Both models are designed to handle loads well over 100 kW, yet we will only be inputting 60 kW; so whichever the case will be, I am rest assured there will be no issues when viewing this situation from an electrical standpoint.

The mechanical side was almost as simple. The manuals specified equations that can be used to calculate the proper flow rate of coolant needed based upon the power being dissipated. Coincidently, this equation was the same on both resistors; the only thing that differed was the value of the constants that were provided [5]. The flow rate for the 57200B resistor is shown in Calculation 1.

Figure 3: Coaxial load resistor 57125B.

Designing the Manifold Schematic

At this point in the project, it was determined that exactly two IOTs will be tested. Each will be accompanied with its own respective coaxial resistor. My supervisor and I decided that each IOT and coaxial load resistor would have its own water supply and return line for proper cooling. With this information, it can be concluded that I will need four lines tapped off the MS6 LCW supply line, one for each of the components. I will also need four lines tapped on the respective return line so that the hot water can transported to a heat exchange.

Conversely, tapping a system eight times can be very problematic and risky to the health and reliability of the piping. Therefore, it was concluded that a manifold would be created for the Mayflower System. This is a basic solution that offers an ideal amount of functionality for this issue. Simply put, a manifold is an offshoot of the original piping. Rather than tapping the supply line four times, we will tap once in order to create a lateral output line. We will then use that line to supply our components with the cool water they need. This same manifold solution will be applied to the return line.

Now that I have a solution, my next challenge is to somehow convey my ideas to the others working on this project. Though I was acting as an engineer, I had to communicate this plan to a broad audience. The technicians responsible for the manifold installation needed specific details regarding what exactly I wanted and where it would go. Also, other fellow engineers who were working on this system needed to be informed of the modifications I proposed. Furthermore, future physicists who will deal with the new accelerators may also need to view my work in order to aid in their research.

I needed something that could easily be interpreted by the diverse group of professionals working at Fermilab. To accomplish this goal, I designed a visual aid in the form of a piping schematic. The schematic would explicitly emphasize the size and location in reference to already existing fixtures and equipment.

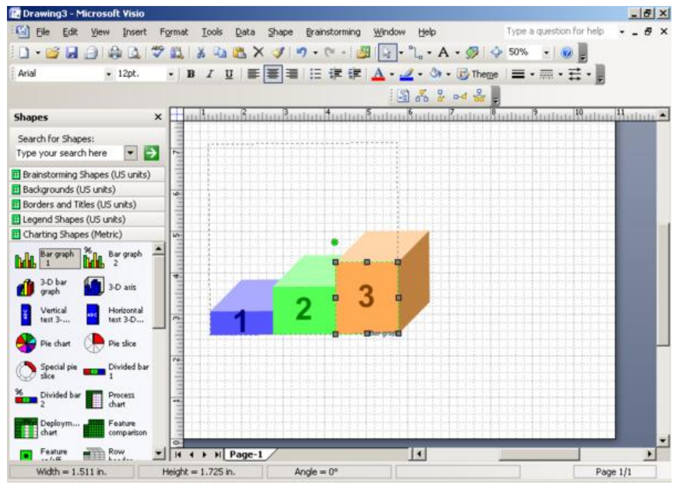

Figure 4: Screenshot from Microsoft Visio 2007.

In addition, it would also specify the different piping components that will be installed in line with the manifold. The software I used to design this schematic was Microsoft Visio.

Visio is a diagramming tool by Microsoft. It is a useful tool for generating flow charts, drawings, schematics, and other visual aids. The software is very precise and aids in making the items of a project even, symmetrical, and orderly. It helped me portray my vision to my many co-workers in a professional and undeviating manner. The schematic which I designed is shown in Figure 9.

As you can see from the schematic, the manifold minimized the number of taps needed on the MS6 LCW lines. Instead, the whole system is supported almost entirely on the manifold. This will make operation and maintenance much easier to manage. The whole system can be easily isolated from the MS6 lines by simply turning two ball valves.

In addition to the manifold, the piping components illustrated in the schematic should also be noted. The IOTs and coax load resistors have sensitivities to pressure and also require a certain amount of flow to be properly cooled. In order to compensate for these limitations, pressure regulators, pressure relief valves, flow restrictors, and flow switches were put into place to protect the Mayflower System.

Sizing the Manifold

After designing the overall cooling configuration, I needed to determine the pipe size that will be used for the manifold. This decision could not be made haphazardly. This pipe needs to be a reliable delivery system of cooling water for the entire system. In order to properly calculate a size, I needed to first establish the volumetric rate and velocity of the fluid that will pass through it.

The IOT documentation explicitly states that it will require a minimum of 12.7 gallons per minute (GPM) during runtime. For the coaxial loads, I used the equation given in the manual to calculate the flow rates needed (refer to Calculation 1). From the calculations, it would seem that they would require a minimum of about 6-8 GPM depending on the model we would use. In order to simplify the system, I decided to generalize the components from a cooling perspective. Rather than have two IOTs that require one particular flow rate, and then have two load resistors that will require another, I made everything operate under a single rate. I decided upon 15 GPM, which is safely above the minimum requirements of the two. Because there will be a total of two IOTs and two resistors, the total flow will be 60 GPM.

I now had to specify a flow velocity. Unlike the flow rate, the velocity is not mentioned in the documentation of the IOTs or coaxial loads. Technically speaking, I could stipulate any velocity I would want, but it is not wise to do so. A velocity that is too high will lead to turbulent flow, which will eventually cause erosion in the piping. On the contrary, a velocity that is to low will not hurt the piping at all. However, it is a waste of resources and materials. An overly low velocity indicates that a pipe of smaller diameter would have been sufficient. My supervisor informed me that a velocity of 4–8 ft/sec would be a good middle route.

With the flow rate and velocity, I am now able to calculate the size of the manifold. I will do so using the equation Q = VA, shown in Calculation 2.

Pressure Regulator

One of the challenges faced when dealing with the MS6 LCW system was the high pressure. The existing regulator was set to 80 Psi. Now, while the coax load resistors are rated for pressures up to 100 Psi, the IOT documentation specifies that a fluid pressure greater than 70 Psi could potentially cause damage to its internal components. Using these facts I concluded that an ideal operating pressure for the Mayflower System would be 60 Psi. That value is 14% below the max pressure rating of the IOT and 40% below the coax load resistor’s max pressure. In order to achieve this, I needed to either order a new regulator capable of the 60 Psi requirement or modify the existing one to work with our desired pressure. Before venturing upon either option, I decided to first obtain some background information on how a pressure regulator regulates pressure.

A regulator is a spring-based device. The three main components are the spring, diaphragm, and poppet. When fluid enters the regulator, it passes through an orifice opening caused by a gap between the poppet and diaphragm chamber. If the fluid passing through is below the set pressure, it will simply pass through this chamber and continue out of the regulator. However, if the pressure is too high, an abundance of fluid will want to pass through this chamber at the same time. This will cause fluid buildup. Eventually the fluid will begin to press against the diaphragm that is attached to the spring. The spring will be compressed, causing the attached poppet to close the orifice gap and restrict any fluid to enter the chamber until the chamber becomes emptier. This restriction will step down the pressure [6].

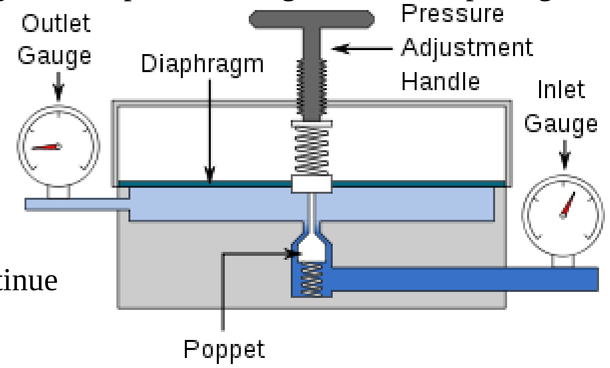

Figure 5: Regulator diagram created by Mintrick.

The science behind this elaborate contraption is quite simple. Pressure is a unit that expresses force per unit area. When fluid of high pressure enters the diaphragm chamber, force is dissipated in the act of compressing the spring. The loss in force will translate directly into loss of pressure.

Figure 6: Jordan Valve 68 series pressure regulator.

Using this knowledge, I discovered that certain regulators allow spring adjustments to allow the user to vary the pressure set point [6]. For this system I decided to modify one of our already existing pressure regulators. The specific model I dealt with was the 68 series manufactured by Jordan Valve. While it was currently set to 80 Psi, its spring was rated for applications between 55–100 Psi. This undoubtedly meets the requirements of the Mayflower System.

Pressure Relief Valve

The pressure relief valve is the fail-safe counterpart of the regulator. In the case of the regulator failing, the relief valve will offshoot the highly pressurized coolant in order to prevent potential damage to the IOTs and load resistors. It is also a spring-based device and works in a similar manner.

Fluid with pressure below the set relief point simply flows through the valve inlet to outlet. On the other hand, if pressure is overly high, the fluid will begin to compress a spring. The compression will cause the outlet orifice to close sealing off the highly pressurized fluid from the rest of the system. It will then be forced to exit through a discharge opening which is usually attached to some sort of drain [2].

I did face one dilemma when choosing the set pressure point of the relief valve, and it related directly to the regulator. I could not set the relief valve to a pressure point to similar to that of the regulator. When dealing with fluid, it should be noted that the set pressure is a sort of estimate. In reality, the pressure that passes through that regulator will be within a 1 to 2 Psi range of that set point. These small fluctuations could in fact cause the relief valve to unnecessarily begin to drain the system. In order to get around this issue, I set the relief valve a whole 10 Psi above the set point of the regulator. If the

Figure 7: Kunkle 912 series relief valve.

regulator were to fail, pressure would increase dramatically, and the relief valve would still be able to protect the system at that setting.

Using the pressure set point, type of fluid, and manifold size, I was able to order a relief valve from a manufacturer. The valve I ended up ordering was a Kunkle 912. It will be installed in line with the regulator on the MS6, and will be placed before the fluid is routed through manifold and into the equipment.

Flow Restrictor

The flow restrictor is yet another application of springs in fluid mechanics. Recall that each component will need 15 GPM of water; since there are two IOTs and two load resistors this totals to 60 GPM. If we were to spew a full 60 GPM into the manifold, the water would simply go through the component that offered the least resistance to flow. The other components would see very little fluid, and would not be properly cooled. The flow restrictor adds an equal layer of resistance to the entrance of each piece of equipment. This way the low-conductivity water will be evenly distributed between the four components. The spring inside the restrictor is what causes this resistance. Similar to the relief valve, the spring can cause the outlet orifice to shrink when faced with a volumetric flow above the set value. For the Mayflower System, four Griswold 15 GPM flow restrictors were used — one for each IOT and resistor.

Flow Switch

The flow switch is related to the restrictor very similarly to how the relief valve is related to the regulator. It acts as a safety device on the off chance that the restrictor would fail. Most switches allow the user to set a maximum and minimum flow rate. Any flow detected out of that range will trigger some sort of signal to be sent out. In most cases, this signal is used initiate some sort of shutdown in order to protect the integrity of the system.

Flow switches achieve this functionality in a variety of different ways. The particular one I choose to use is the MN series by Universal Flow Meters. It is able to measure flow using a spring system. Unlike the configuration of the regulator, relief valve, and resistor, the spring in the flow switch does little to restrict flow. Depending on the strength flow, the spring will increase the orifice opening in order to minimize any resistance. The switch is able to measure the flow rate based upon the orifice opening and the spring's compression [7].

Figure 8: Universal Flow Meters flow switch.

It should be noted that there are many other types of flow switches available. Some measure flow using acoustics and others use temperature. Flow can easily be determined by measuring the resistance the flow causes to emitted sound waves. It can also be found by measuring the temperature of the fluid at the inlet and outlet of the flow switch. From these values you can calculate the rate at which heat is lost. This is mathematically related to the flow.

Pressure Drop Calculation

Prior to ordering the relief valve and adjusting the regulator, I needed to verify that the set pressure values would be sufficient. The specified pressures would seem to be appropriate in comparison to the IOTs and load resistors rated values, however, pressure loss needed to be taken into consideration. Since we do not live in a frictionless world, it is inevitable that kinetic energy will be lost when traveling from the MS6 supply line through the manifold and to the return line. This loss of energy translates into a loss of pressure. For my purposes, I needed to verify that the water will have sufficient pressure to make this round trip.

However, in order to determine this, I needed to obtain some background knowledge of fluid mechanics. Prior to my internship at Fermilab, I had no past experience in dealing with this field of study. This assignment required a self-study of some of basic fluid mechanics. It compelled me to learn core concepts such as the Reynolds number, head loss, Bernoulli's principle, laminar flow, turbulent flow, minor losses, and major losses in order to calculate this pressure drop. Calculation 3, shown in the next section, demonstrates the pressure lost when traveling from the MS6 supply line up until right before the fluid enters the IOT and coaxial load lines.

RESULTS

Calculation 1 - Coaxial Load 57200B Flow Rate:

Goal: Calculate flow rate needed by the coaxial load resistor (Altronic Research, Inc. model number 57200B.)

Given:

- 60 kW will be going into the load.
- Input water temperature will be 90 °F (32.3 °C).
- P = 0.264(T2 - T1)Q
- Q = (Kf)(Pi)
    - Q = Flow Rate (GPM)
    - P = Power Disipated (kW)
    - T2 & T1 = Input and Output Temperatures in °C Respectivly
    - Pi = Input Power (kW)
    - Kf = Constant Value of 0.095

Model	Minimum Flow Rate (GPM)	Maximum Average (RMS) Power (kW)	Gallons per Kilowatt (Kf)
5700B	19	200	.095

Calculations:

- At 125 kW:

$$P = 0.264(T2 - T1)Q$$

$$\frac{P}{[(0.264)(Q)]} = (T2 - T1)$$

$$\frac{200}{[(0.264)(19)]} = (T2 - T1) = 39.8\ °C = 103.64\ °F$$

- At 60 kW (What we will be using):

$$Q = (Kf)(Pi)$$

$$Q = (.095)(60)$$

$$Q = 5.7\ GPM$$

$$P = 0.264(T2 - T1)Q$$

$$T2 = \frac{P}{[(0.264)(Q)]} + T1$$

$$\frac{60}{[(0.264)(6)]} + 33\ °C = T2 = 70.87\ °C = 159.56\ °F$$

Summary: In the worst case scenario, the resistor will increase the temperature of the coolant by 103.64 °F. For our application we will need to provide 5.7 GPM of water to properly cool the coaxial load. The LCW system we will be using will provide water at 90 °F. It will be heated to a temperature of 159.36 °F by the load.

Calculation 2 – Manifold Sizing:

Goal: Size the pipes of the new manifold required by the IOT/Mayflower System.

Given:

- Water will flow at a velocity of 4–8 ft/sec.
- The system will require a flow rate of 60 GPM (0.1338 ft^3/sec).
- Q = VA
    - Q = Flow Rate (ft^3/sec)
    - V = Velocity (ft/sec)
    - A = Area of Pipe Opening (ft^2)

Calculations:

- For 6 ft/sec:

$$Q = VA$$

$$0.1338 = (6)(A)$$

$$A = 0.0223 \text{ ft}^2$$

$$A = \pi r^2$$

$$\sqrt{A/\pi} = r$$

$$\sqrt{0.0223/\pi} = r$$

$$r = 0.0842\text{ft} = 1.011 \text{ in}$$

So … pipe diameter needs to be about 2 inches.

Calculation 3 - Pressure Drop:

Goal: Calculate the loss in pressure through the pipings in order to properly determine the set points of regulator and relief valve.

Equations:

$$\frac{P1}{\rho} + \frac{V1^2}{2g} + Z1 = \frac{P2}{\rho} + \frac{V2^2}{2g} + Z2 + hL$$

P1 & P2: Initial and Final Pressures (lb/ft^2)

V1 & V2: Initial and Final Flow Velocities (ft/sec)

Z1 & Z2: Initial and Final Heights (ft)

hL: Sum of Major and Minor Losses (lb/ft^2)

g: Acceleration Due to Gravity (32.2 ft/sec^2)

ρ: Water Density (62.4 lb/ft^3)

$$hL = \text{Major Losses} + \text{Minor Losses} = f\frac{L}{D}\frac{V^2}{2g} + \sum\frac{V^2}{2g}K_L$$

f: Coefficient of Friction from Moody's Chart

L: Length of Piping (ft)

D: Diameter of Pipe (ft)

V: Initial Flow Velocity (ft/sec)

K_L: Loss Coefficients

Moody's Chart Calculation: $Re = \frac{\ell VD}{\mu}$ $\quad Relative\ Roughness = \frac{\varepsilon}{D}$

ℓ: Water Density (1.94 slugs/ft^2)

V: Flow Velocity (ft/sec)

D: Diameter of Pipe (ft)

μ: Dynamic Viscosity (1.5 *10^{-5} lb*s/ft^2)

ε: Roughness (0.000005 ft)

$$Q = VA$$

Q: Volumetric Flow (ft^3/sec)

V: Flow Velocity (ft/sec)

A: Orifice Area (ft^2)

Given Values:

P1 = 65 Psi = 9360 lb/ft^2

Z1: 8.5 ft

Z2: 6.7 ft

V1, V2, and hL are calculated below.

P2: What we're trying to find in order to determine pressure loss

f: 0.01

L: 24 ft

D: 2 in = .16 ft

K_L: 1.5 for elbows (assuming worst case scenario of 5 elbows), 0.5 for pipe diameter decrease

Q1: 64 GPM = 0.14 ft^3/sec

Q2: 16 GPM = 0.0356 ft^2/sec

A1 (area of 2 in pipe): 0.0201 ft^2

A2 (area of 1in pipe): 0.00545 ft^2

D1: 2 in = 0.1667 ft

D2: 1 in = 0.0833 ft

Calculations:

Flow Velocities:

For V1: $Q = VA \rightarrow V = \frac{Q}{A} \rightarrow V = \frac{0.14 \text{ ft}^3/\text{sec}}{0.0201 \text{ ft}^2} = 6.9 \text{ ft/sec}$

For V2: $Q = VA \rightarrow V = \frac{Q}{A} \rightarrow V = \frac{0.0356 \text{ ft}^3/\text{sec}}{0.00545 \text{ ft}^2} = 6.53 \text{ ft/sec}$

Moody's Chart Values:

$$Re = \frac{\ell VD}{\mu} \rightarrow \frac{(1.94\ \text{slugs/ft2})(6.9\ \text{ft/sec})(0.16\ \text{ft})}{1.5 * 10^{-5}\ \text{lb} * \frac{\text{s}}{\text{ft 2}}} = 142{,}784$$

$$Relative\ Roughness = \frac{\varepsilon}{D} = \frac{0.000005ft}{0.16f} = 0.00003125 \approx 3 * 10^{-5}$$

Using Moody's Chart and the two above values, I determined that the friction factor (*f*) is 0.01.

Pressure Loss:

$$hL = \text{Major Losses} + \text{Minor Losses} = f\frac{L}{D}\frac{V^2}{2g} + \sum\frac{V^2}{2g}K_L$$

Major Losses = $f\frac{L}{D}\frac{V^2}{2g} = (0.01\frac{24ft}{.16ft}\frac{(6.9ft/s)^2}{2(32.2\ ft/s^2)}$ = 1.0643

Minor Losses = $\sum\frac{V^2}{2g}K_L = \frac{V^2}{2g}\sum K_L = \frac{(6.9ft/s)^2}{2(32.2\ ft/s^2)} * [(5 * 1.5) + 0.5] = 5.9142$

hL = 5.9142 + 1.0643 = 6.97

Pressure Drop:

$$\frac{P1}{\rho} + \frac{V1^2}{2g} + Z1 = \frac{P2}{\rho} + \frac{V2^2}{2g} + Z2 + hL \rightarrow P2 = \rho(\frac{p1}{\rho} + \frac{v1^2}{2g} - \frac{V2^2}{2g} + Z1 - Z2 - hL)$$

$$P2 = 62.4\ \text{lb/ft}^3\ (\frac{9360\ \text{lb/ft}^2}{62.4\text{lb/ft}^3} + \frac{(6.9ft/s)^2}{2(32ft/s^2)} - \frac{(6.53ft/s)^2}{2(32ft/s^2)} + 8.5ft - 6.7ft - 6.97)$$

$$P2 = 9037.75\ \text{lb/ft}^2$$

$$Pressure\ Drop = P1 - P2 = 9360\frac{\text{lb}}{\text{ft}^2} - 9037.75\frac{\text{lb}}{\text{ft}^2} = 322.5\frac{\text{lb}}{\text{ft}^2} = \mathbf{2.23\ PSI}$$

Summary: In the case of five elbows, the pressure drop will only be 2.23 Psi, so pressure loss will not be an issue.

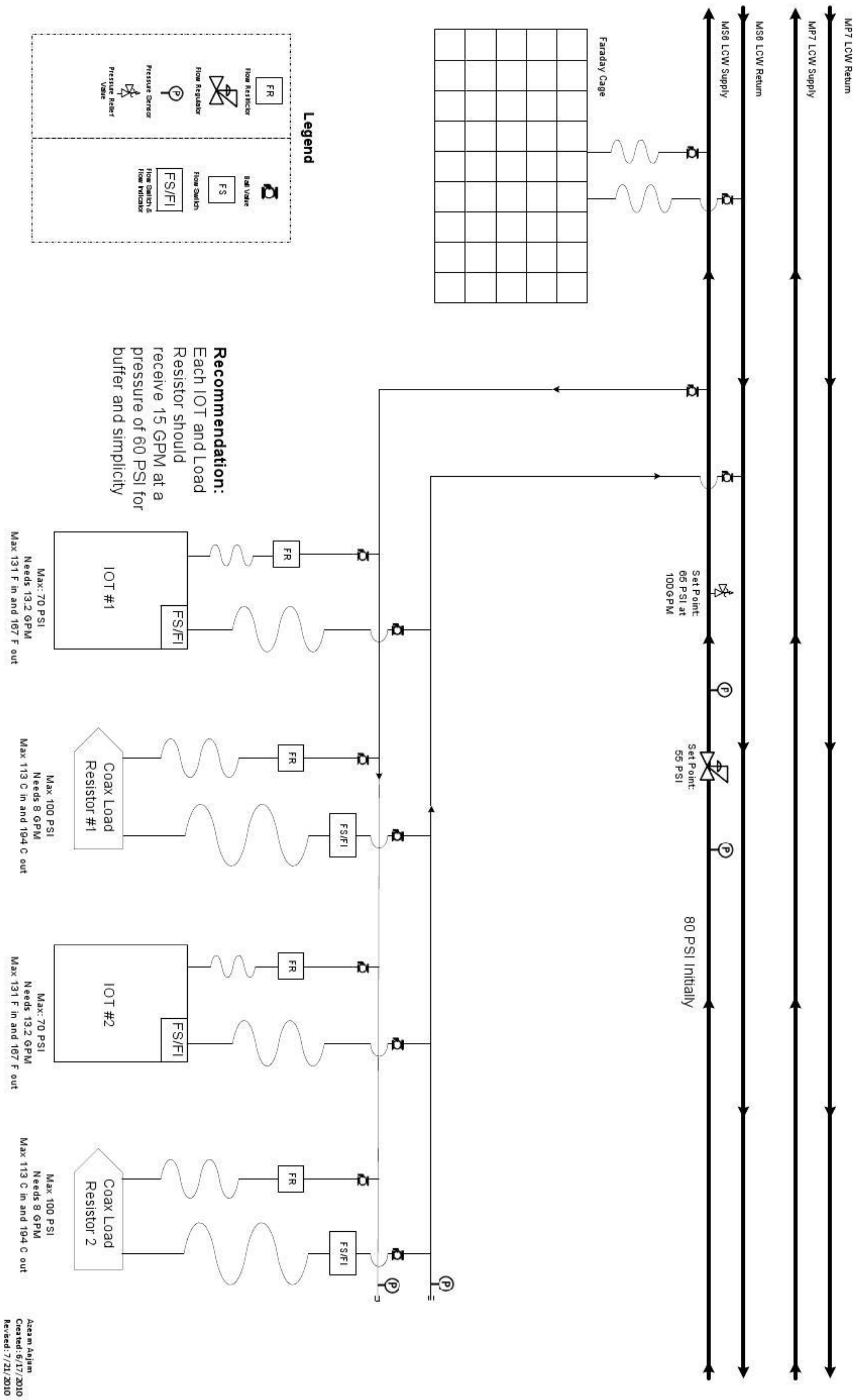

Figure 9: Mayflower schematic.

DISCUSSION/CONCLUSION

In closing, the Mayflower System will be fully operational using the designed cooling system. By incorporating the flow restrictors and the pressure regulator into the system, we are able to supply coolant water at an appropriate pressure and volumetric rate. If either one of these devices was to malfunction, fail safes such as the pressure relief valve and flow switch were put into place to protect the IOTs and coaxial load resistors from volatile flow. Also, while the entire cooling system piggybacks off the already existing MS6 low-conductivity water lines, the Mayflower System can easily be isolated using the entrance and exit ball valves shown in the schematic. This will allow straightforward access to the system for both repairs and future upgrades. The system I helped design should allow for proper testing of the IOTs at the Meson building. Let us hope to see them aid in powering a new Project X accelerator soon.

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