

# SpinQuest (E1039) Polarized Target Cryosafety Report

July 10, 2019

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# 1 Introduction

The scope of this document is to provide the needed information to assess the cryogenic safety of the polarized target system for the SpinQuest (E1039) experiment in Fermilab NM4. The E1039 Experiment is a successor experiment to Experiment E906 and re-uses the same spectrometer but the target system is a substantially different designs and there are many additional subsystems used in the new experiment.

The E1039 target system will be located in the SpinQuest Hall inside building NM4. The target system consists of a 5 T polarizing magnet and a high-powered evaporation refrigerator system which both connect to a helium liquifier system provided by the Quantum Technologies Inc. The polarizing target magnet is a superconducting split pair constructed for nuclear and high energy physics experiments. The evaporation refrigerator is a rebuilt assembly designed and constructed by the University of Virginia. The target system is the responsibility of the University of Virginia and this document only focuses on those critical components of the full cryogenic system.

The full target system is shown in Fig. 1. A close up diagram of the top magnet and fridge flanges is shown in Fig. 2. The target cave piping and instrumentation diagram is shown in Fig. 3. A cross-section of inside the refrigerator and magnet can be seen in Fig. 6 without the target insert. The same diagram is then shown with the target insert in position in Fig. 7. The target system has four separate vessels indicated by the four following figures. These vessels include the liquid *nitrogen shield Dewar* (Fig. 8), the *magnet dewar* (Fig. 10), and the *refrigerator cryostat* (Fig. 11, 15). The refrigerator sits in the *shell*. The lower part of the shell connects to the lower volume with an indium seal making the liquid helium evaporation reservoir. This lower volume is referred to as the *nose*. The refrigerator has its own upper internal reservoir that separates the vapor from the incoming liquid. This unit is the fourth vessel known as the *separator* (Fig. 6). There is also a *U-tube* transfer-line (Fig. 17) that connects the magnet tank to the separator to supply the fridge with liquid helium. Other than the separator these vessels are all surrounded by a single insulating vacuum (IV) which should be maintained at high vacuum at all times. The separator along with the rest of the refrigerator sits in the refrigerator cryostat and so has an extra layer of controlled insulation from atmosphere.

The exact liquid helium volume of the *magnet dewar* is 135 liters. This space normally operates at atmospheric pressure and vents directly out of the cave and out of the building. During a quench the energy is exponentially dumped into the liquid helium over a period of about 100 seconds by the magnet quench protector. Quenching is a normal superconducting magnet response to part of the coil going resistive. All Oxford magnets systems are design to quench and tolerate the pressures pertaining to quenching. Oxford and UVA have both performed multiple quench tests without incident on the SpinQuest magnet. Quenching the magnet results in a large part of the target volume being vaporized. This vapor vents out of the top of the *magnet dewar* tank through the

risers and exhausts out through the quench ports. This system, when energized to full field has a considerable stray field, extending over 3 meters. The fully energized magnet can not store over 0.25 MJ by design.

## 2 Operating Principles

This target system uses cryogenically frozen solid state target materials polarized using dynamic nuclear polarization (DNP). DNP results from transferring spin polarization from electrons to nuclei, aligning the nuclear spins to near that of the extent that electron spins. The polarization of the electron spins at a given magnetic field and temperature is described by the Boltzmann distribution under thermal equilibrium. The DNP process relies on the electron's fast relaxation rate to transfer spin polarization to the nucleons using a continuous microwave source. The target cryostat operates at 1 K with the use of a high cooling power evaporation refrigerator and a 5 T magnetic field produced by a pool cooling superconducting magnet submerged in liquid helium at 4 K. In the following all cryogenic parts are analyzed for functional safety. The optimization of polarization and its measurement is a big part of the target spin asymmetry measurements and uncertainties [1].

### 2.1 General Overview

The magnet dewar holds up to 135 L of liquid helium which is surrounded by an insulating vacuum layer and a liquid nitrogen layer, which itself is surrounded by the external vacuum layer. The insulating vacuum is pumped down below  $10^{-6}$  Torr using a TMU 1001 P turbomolecular drag pump. The jumper-transfer line connects the 135 L magnet dewar to the high-cooling power evaporation refrigerator. This jumper is a vacuum insulated line that is used to continuously transfer liquid helium into the evaporation refrigerator phase separator. The function of the phase separator is to separate the vapor from the liquid creating a helium reservoir supply to feed the evaporator where the target material is positioned into the beamline and cooled to 1 K. The separator also works as a thermal barrier to help thermally isolate the cooler part of the evaporation area. The high cooling power evaporation refrigerator consists of a set of upper heat exchangers (baffles) that are cooled when vapor from the separator is pumped through, using a KNF helium compressor pump (or separator pump). Liquid enters the separator via the jumper-transfer line from the liquid helium in the magnet. The incoming helium liquid from the jumper transfer line is a mixture of helium vapor and liquid depending on how much enthalpy leaks to liquid during the transfer. The phase separator contains a sintered disk that divides the separator to upper and lower halves. In the upper half the vapor is pumped out at a rate that lowers the temperature of the remaining liquid to about 2.5 K. The cooled liquid in the lower part of the separator flows down the 1 K evaporator path through a series of gas-liquid heat exchangers and through the run valve that controls the flow, to the 1 K path. Below the lower heat

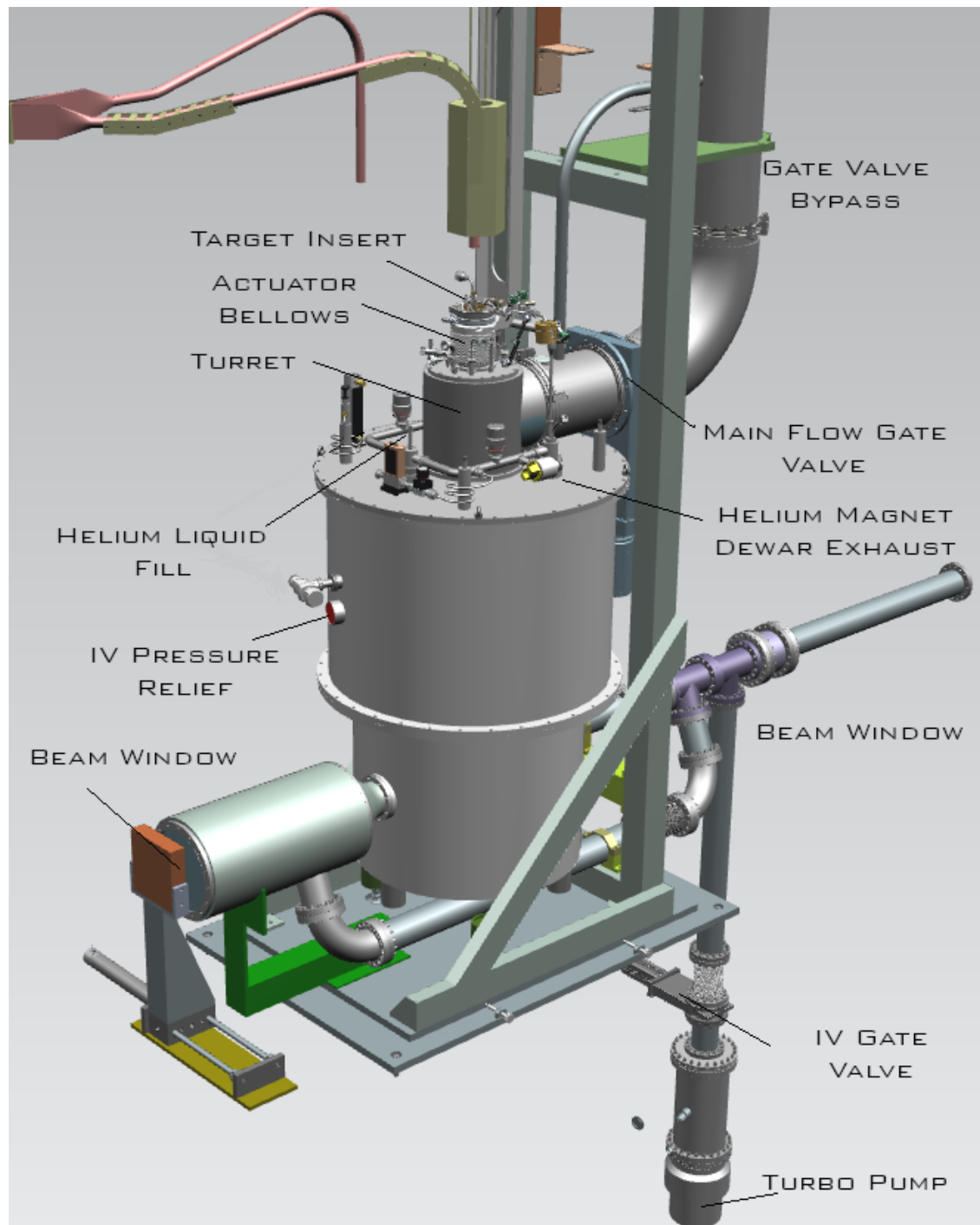


Figure 1: The full target system with beam-line connection to the insulating vacuum.

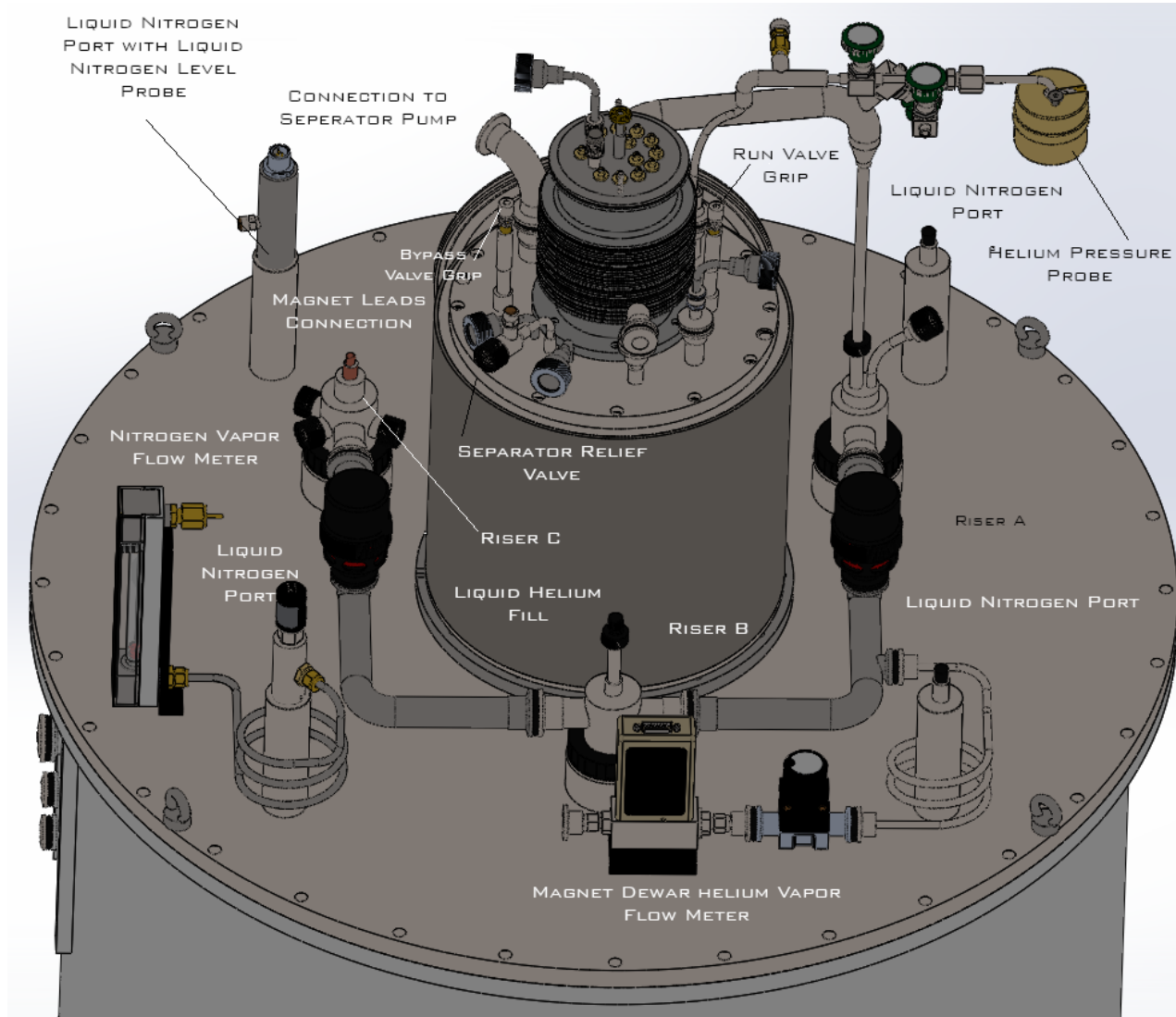


Figure 2: Close up of the top flange of the target system.

exchangers is the cold helium reservoir in the nose which is simply a helium space made of the nose and shell and connects to the large roots pumps through the turret. This volume defines the refrigerator and achieves high power from the roots pump stack to pump on the liquid helium volume creating a high degree of evaporation. Passing the cold helium vapor over the lower heat exchanger and then upper baffles optimizes cooling and functionality of the refrigerator. Over 1.6 W of cooling power is achievable with the 14,000 m<sup>3</sup>/hour pumps. This high cooling power is useful during the dynamic nuclear polarization of the target where nearly 1 W of microwave power is required to polarize the target and the additional heat load of about 0.5 W from the proton beam.

A 5 T magnetic field is produced by the set of precision superconducting iron-free quasi-Helmholtz coils. The fringe fields produced are capable of pulling any magnetic object towards them, with enough force to puncture the windows on the vacuum. In addition, medical implants that may contain ferromagnetic materials are at serious risk of being affected by the fringe fields. The operation of mechanical equipment may be impacted, and electronic devices in the vicinity stand the risk of being damaged by the powerful magnetic fields.

## 3 The Main Subsystems

### 3.1 Superconducting Magnet

The *magnet dewar* (Fig. 18) is a standard Oxford Instruments superconducting magnet dewar that has passed all EU safety requirements before being transported to the United States (Fig. 6). There are three risers that vent the liquid helium boil off and exhausts straight to the vent out of the building. These three openings provide the path for quick pressure release when the magnet quenches. Each of these are KF-25 and connect to the top venting ports of the magnet dewar tank. The piping on top is also 25 mm ID. The exhaust port is 10 mm ID. and operates at atmospheric pressure. The magnet dewar holds liquid helium cooled to 4 K simply for the sake of running the superconducting magnet. This type of vessel is standard and meets all the safety specifications to pass Oxford Instruments functionality and safety criteria.

The magnet dewar consists of two parts (Fig. 10). The lower section houses the magnet coils inside a cylindrical dewar. The quench protection diodes and resistors sit in the top of the magnet tank. The top magnet tank (Fig. 9) is a cylindrical helium reservoir. These sections are connected by two 6.0 cm ID tubes with an indium seal on both. A vertical center bore through both the upper and lower sections allows for insertion of the <sup>4</sup>He evaporation refrigerator and the target insert. There is also a rectangular open bore through the coils where the beam passes.

The magnet dewar has a large annular geometry that wraps around the refrigerator area separated by the insulating vacuum (Fig. 19). This is the main holding tank for the cold helium before being pumped over to the refrigerator through the U-tube transfer-line. This liquid helium reservoir is not a pressur-

ized vessel under normal operating conditions. It contains 4 K liquid helium at near atmospheric pressure and keeps the superconducting magnet submerged. There are three risers that give sealed access to the tank and coils. One is fitted with a liquid helium level probe, a second is fitted with the magnet leads connections, and the third is fitted with the fill port. The fill port is the 3/8" female connector designed to seal to a transfer-line bayonets. The bayonet fits into a cup inside the tank connecting to an internal tube that channels the helium down to the coil region for efficient transfer.

The magnet is made of a heavy steel former that holds the coils in place. The cylindrical dewar walls wrap around and are welded to the former making helium dewar. This beam bore goes through the magnet former and has a very rigid structure. It is along this line that the beam windows are located on the nose and up and down stream beam lines.

### 3.2 Nitrogen Shield

The liquid nitrogen shield dewar is also part of the Oxford Instruments magnet (Fig. 8). This dewar has a volume of 115 L. The nitrogen dewar surrounds the magnet dewar tank on top of the magnet and creates a thermal barrier with vacuum on either side. The nitrogen dewar operates at atmospheric pressure so this can operate as an open vessel. As nitrogen boils off it vents out of the cave and then out of the building.

The liquid nitrogen tank connects to a aluminum radiation shield that surrounds the magnet dewar. The liquid nitrogen tank should remain at least half full of liquid nitrogen in order to protect the liquid helium components from heat radiation from the outside. It is not a pressurized unit and serves only to sit at 77 K and provide thermal insulation between the outer most vacuum region and the liquid helium reservoirs. This reservoir level should be monitored at all times and refilled regularly for efficient usage of the liquid helium. This tank has four venting ports on the top of the tank to be connected to the outside exhaust system in the cave. One of the venting ports is used for measuring the boil-off rate and another is used for a level probe measurement. The only notable dangers involved with this part of the system is if the nitrogen ports are not properly connected to the exhaust channels and atmospheric ice builds up and blocks all ports.

### 3.3 Evaporation Refrigerator

The refrigerator cryostat holds the University of Virginia evaporation refrigerator. The fridge is fitted into a stainless steel shell and attaches to an aluminum nose piece on bottom. The nose piece has a thin beam window around the cylinder of 13 mils. This helium space only requires 1.45 L of liquid helium to completely cover the target material. On the top of this cryostat connected to the main flow there is one main pressure release valve set to less than 1 psig.

The top stainless steel shell (Fig. 11) fits into the Oxford Instruments magnet vacuum layer. The vacuum seal is a standard ethylene propylene rubber O-ring



around the vacuum layer on top where the metal is close to room temperature and a 0.030 indium seal is used on the aluminum nose piece where the cryostat is colder. The maximum volume of just the nose piece is 3.57 L. The volume of the shell and nose piece together is 22 L. There is never any need for this much helium in the fridge. Filling the fridge this much can freeze the top shell seal and cause a vacuum leak. The turret (Fig. 14) fits on top of the shell assembly. The refrigerator fits into the top of the turret and the roots blowers connect to the side pumpout of the turret. The top flange to access the refrigerator is a standard 4.5" Ladish flange and clamp.

The  $^4\text{He}$  refrigerator (Fig. 7) is designed to run at temperatures close to 1 K, and contain exceptionally high cooling power. The refrigerator can only run when liquid  $^4\text{He}$  is fed into the separator from the reservoir of the magnet dewar. This transfer come through the vacuum insulated U-tube. Then, the liquid and vapor are separated, and the vapor is filtered out of the separator vessel through the exhaust tube through the upper baffles while being pumped into the recycling system with the *separator pump* (KNF). The liquid in the separator will pass through by opening either the run valve, bypass valve, or both to bleed helium into the nose where the target sample space is. If it flows through the run valve, the liquid will pass through a low temperature heat exchanger and be cooled on the way down. The bypass valve bypasses this lower heat exchanger to fill the nose faster when necessary. The Fridge Bellows (Fig. 12) allows the target insert to move up and down so that the target cell can be positioned correctly in the beam.

### 3.4 Separator

The separator is a holding reservoir for cold liquid helium before it is transferred to the nose, where the target material is held. As the liquid helium is transferred from the separator to the nose, it will pass through several heat exchangers which are cooled by the evaporating helium being pumped out of the fridge (See Subsection: Evaporation Refrigerator). To maintain low temperatures, despite as much as 1 W microwave and beam power being dumped onto the target. The large roots pumps help to maintain the required low pressure. These pumps pull evaporated helium up, past the heat exchangers and baffles, and out of the fridge. The separator is a seal helium vessel with a pressure relief port connected to the top of it running out of the refrigerator. This valve opens at 3 psi and serves to vent the separator and prevent serious pressure build in this vessel.

### 3.5 Insulating Vacuum

The vacuum space works as a thermal insulator. It is critical to separate the helium layers from the atmosphere temperature to conserve the Helium and to move the helium with the least losses. This includes the U-tube jumper line which should have the vacuum insulation pumped down to a leak rate around  $10^{-10}$  mbar $\times$ L/s. The amount of liquid helium in the U-tube at any time is

estimated to be no more than 5 g. Instantaneous vacuum loss in the U-tube only results in not transferring liquid efficiently or not at all.

The insulating vacuum for the magnet and refrigerator is common. This is an annular space that surrounds both and provides a interface with the outside world. The outside can is solid stainless steel with fused welds. The weakest points of the vacuum space are the nose beam windows and the two beam-line beam windows. There is a safety pressure release on the vacuum space which is a simple pop-off valve. This safety pop-off valve on the side of the vacuum insulator is shown in Fig. 13. This valve has a very light spring holding only 0.1 psig when not under vacuum. This valve is designed to allows release under pressure build in the vacuum space from a punctured magnet dewar or refrigerator nose.

The Piping and Instrumentation Diagram for this system is shown below, and the instrumentation list is included in Fig. 16.

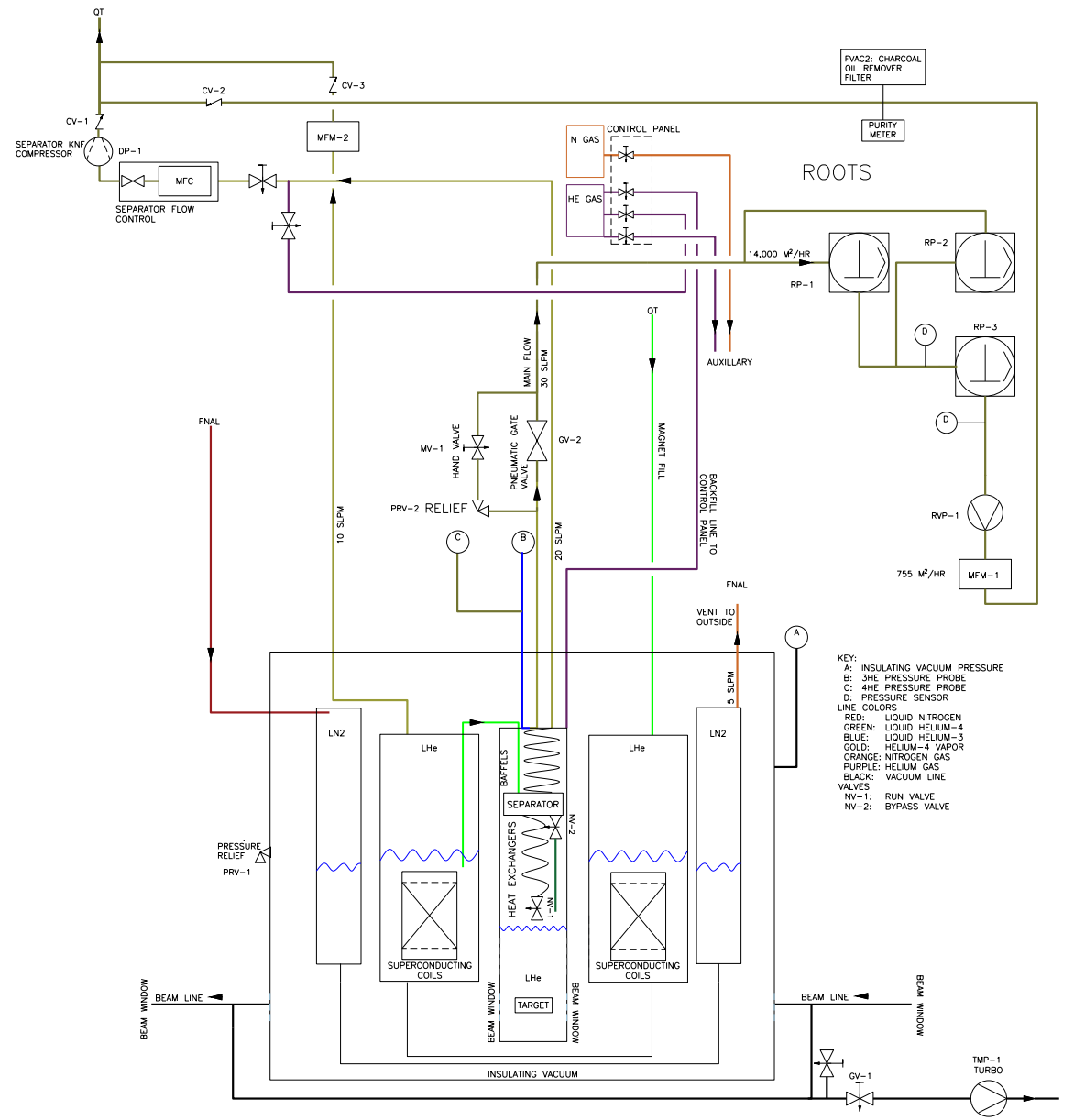


Figure 3: Piping and instrumentation diagram inside the Cave.

### 3.6 Target Insert

The target insert is a long carbon fiber shaft that holds the microwave horn for the DNP process, the NMR coils for polarization measurement and the target cells that hold the frozen solid state target material. These inserts also provide the proper impedance for the evaporation refrigerator to run optimally as well as provide a thermal barrier near the separator.

The fridge can run with or without the target insert installed and so we do not include it here as part of the cryo-safety review document. These details will be covered in different documentation.

## 4 Design Calculations

The E1039 Target System is new to Fermilab and uses a series of vessels. Here we specify the design calculations and materials for the target system and evaluated pressure build and relief.

The separator itself is fuse welded, using a DFW weld prep done in the University of Virginia's machine shop.

### 4.1 Separator Relief Tube

The separator is made from SST 304 plate and tube.

Elastic modulus:	$E = 2.86 \cdot 10^6$ ksi
Yield Strength:	$S_y = 30$ ksi
Ultimate Strength:	$S_U = 75$ ksi
Offset Strain:	$E_Y = 0.002$
Allowable Stress:	$S_a = 20$ ksi

The dimensions of the SpinQuest separator are as follows:

Outer Diameter:	$OD_{sep} = 6.5$ inches
Wall Thickness:	$t = 0.065$ inches
Length:	$L = 2.345$ inches
Main Support Tube OD:	$OD_{sup} = 3.63$ inches
Inner Thickness:	$T_I = 0.030$ inches

First, calculations for the volume and surface area of the separator will be computed. Using Equation 1.1 seen below

$$V_{sep} = \frac{\pi}{4} \cdot (OD_{sep}^2 - OD_{sup}^2) \cdot L_{sep}$$

we find the volume of the separator to be 53.5456 inches cubed, which is equivalent to 0.87745 liters.

Next, we will use the following equation to find the area of the separator.

$$A_{\text{sep}} = \pi \cdot (\text{OD}_{\text{sep}} + \text{OD}_{\text{sup}}) \cdot L_{\text{sep}} + 2 \cdot \frac{\pi}{4} \cdot (\text{OD}_{\text{sep}}^2 - \text{OD}_{\text{sup}}^2)$$

It is computed to be 120.296 inches squared, or 0.07761 meters squared.

The velocity of sound at 100K and 300K have already been computed as 593 m/s and 1020 m/s respectively. These two number will be sued to determine whether or not the escaping vapor through each portion of the relief tube is supersonic or subsonic.

The separator includes a separate relief tube. The tube is split into two main parts, a large diameter section and a small diameter section. Connecting the two is a cone-like fastener. The dimensions for this section are given below:

Length:	$L = 27$ inches
Large Diameter:	$D_L = 0.25$ inches
Small Diameter:	$D_S = 0.185$ inches
Connector Length:	$L_C = 1.1$ inches
Wall Thickness 1:	$T_1 = 0.016$ inches
Wall Thickness 2:	$T_2 = 0.02$ inches

The lengths of each portion of the relief tube were measured using the original 3D model in SolidWorks. They are listed below:

Length (Large Diameter):	$L_1 = 5.45$ inches
Length (Small Diameter):	$L_2 = 21.55$ inches

Loss of IV:

In order to lose insulation around the separator the refrigerator would have to be open to atmosphere or is a situation with very warm gas around it. This is common during the backfill process but because of location of the separator the pressure and temperature around it is very well controlled and quick transitions to room temperature are rare. In the next part of these calculations a worst case scenario is assumed where there is instantaneous insulating vacuum loss around the separator while containing liquid helium in its liquid reservoir. In this situation the heat flux, heat load, latent heat, and mass evolution rate are calculated below.

Max heat flux:	$q = 8 \frac{kW}{m^2}$
Total Heat load:	$Q = q \cdot A_{\text{sep}} = 620.881$ W
Latent Heat:	$\lambda = 21 \frac{J}{g}$
Mass Evolution Rate:	$dm = \frac{Q}{\lambda} = 29.5658 \frac{g}{s}$

The easiest way to calculate our unknowns would be to assume that the gas

reaches room temperature immediately. Unfortunately, this would create a very sizable amount of error, as the relief line is still fairly short, and the refrigerator space outside of the separator is filled with He from the boil off from the nose piece. To help mitigate this error, we will assume that the He in the first stage of the relief line is at 100K, and for the second stage of the relief pipe will be 300K.

Density of He at 300K, 30 psia:	$\rho_{300} = 0.332 \cdot 10^{-3} \cdot \text{g/cm}^3$
Density of He at 100K, 80 psia:	$\rho_{100} = 2.63 \cdot 10^{-3} \cdot \text{g/cm}^3$
Volumetric Flow rate at 100K:	$W_{100} = \frac{dm}{\rho_{100}}$
Volumetric flow rate at 300K:	$W_{300} = \frac{dm}{\rho_{300}}$
Viscosity of He at 100K:	$v_{100} = 9.87 \cdot 10^{-6} \cdot \text{Pa} \cdot \text{s}$
Viscosity of He at 300K:	$v_{300} = 19.93 \cdot 10^{-6} \cdot \text{Pa} \cdot \text{s}$
Velocity of sound at 100K:	$V_{s100} = 593 \frac{m}{s}$
Velocity of sound at 300K:	$V_{s300} = 1020 \frac{m}{s}$

Next, the exact dimensions of each part of the relief tube will be computed. Note that each calculation will be done twice, once for the smaller diameter segment, and a second for the larger diameter segment.

Inner Diameter (Small)	$ID_{\text{small}} = 0.153 \text{ inches}$
Area (Small)	$A_{\text{small}} = 0.01839 \text{ in}^2 = 1.2 \cdot 10^{-5} \text{ m}^2$
Inner Diameter (Large)	$ID_{\text{large}} = 0.21 \text{ inches}$
Area (Large)	$A_{\text{large}} = 0.03464 \text{ in}^2 = 2.2 \cdot 10^{-5} \text{ m}^2$

Now, the connector between the two segments of the relief tube will be analyzed. The length of the connector has been measured as 1.1 inches long.

$$\theta = \text{atan}\left(\frac{OD_2 - OD_1}{1 \text{ in}}\right) = 0.06491 \text{ radians} = 3.71899 \text{ degrees}$$

$$\beta = \frac{OD_1}{OD_2} = 0.74$$

The resistance coefficient for this component is:

$$K_{\text{cone}} = 2.6 \cdot (1 - \beta^2) \cdot \sin\left(\frac{\theta}{2}\right) = 0.03817$$

First Stage Flow:

$$V_1 = \frac{W_{100}}{A_{\text{small}}} = 503.081 \frac{m}{s}$$

The flow is subsonic.

$$\text{Reynolds Number: } R = ID_{\text{small}} \cdot \frac{V_1 \cdot \rho_{100}}{v_{100}} = 257994.94$$

$$\text{Friction Factor: } F_1 = (1.14 + 2 \log\left(\frac{ID_{\text{small}}}{e_1}\right))^{-2} = 0.016$$

$$\text{Pressure Drop: } \Delta P_1 = F_1 \cdot \rho \cdot L_{\text{Small}} \cdot \frac{V_1^2}{ID_{\text{small}}} = 57.628 \text{ psi}$$

Second Stage Flow:

$$V_2 = \frac{W_{300}}{A_{\text{Big}}} = 3985.247 \frac{m}{s}$$

The flow is supersonic.

$$\text{Reynolds Number:} \quad R_2 = ID_{\text{big}} \cdot \frac{V_2 \cdot \rho_{300}}{v_{300}} = 354110.70$$

$$\text{Friction Factor:} \quad F_2 = (1.14 + 2 \log(\frac{ID_{\text{big}}}{e_2}))^{-2} = 0.039$$

$$\text{Pressure Drop:} \quad \Delta P_2 = F_2 \cdot \rho \cdot L_{\text{Big}} \cdot \frac{V_2^2}{ID_{\text{Big}}} = 323.678 \text{ psi}$$

For the conical reducer section:

$$\Delta P_{\text{Cone}} = K_{\text{Cone}} \cdot \frac{\rho_{300} \cdot V_2^2}{2} = 14.59 \text{ psi}$$

This next section will go over the elbow at the end of the relief line. It is a KF 25 90 degree elbow.

$$\text{Inner Diameter:} \quad ID = 1.03 \text{ inches}$$

$$\text{Area:} \quad A = 0.83 \text{ in}^2 = 0.00054 \text{ m}^2$$

$$\text{K Factor:} \quad K = 1.18$$

In this version of the system, the relief pipe is not welded, and as such, only the welding information for the separator will be used.

## 4.2 IV Loss Calculations

During a loss of IV the walls of the magnet will also provide a heat load. The load from loss of IV will be higher for non-insulated surfaces than for the insulated ones. Considerable effort was made to insulate all exterior surfaces of the magnet. We therefore use a conservative 7 kW/m<sup>2</sup> heat flux for loss of vacuum on insulated surfaces and 38 kW/m<sup>2</sup> on uninsulated ones. In a case such as this, the pop off valve (Fig 13) will be launched from the system, and could erupt with cold pressurized helium vapor.

### Geometry of the Coils:

$$\begin{array}{ll} \text{Inner Coil:} & \\ \text{Inside Radius} & r_{1\text{in}} = 117.5 \text{ mm} \end{array}$$

$$\begin{aligned}
\text{Outer Radius} & \quad r_{\text{out}} = 151.3 \text{ mm} \\
\text{Width} & \quad w1 = 30.5 \text{ mm} \\
\text{Surface Area:} & \quad A_{\text{in}} = \\
& \quad 2 \cdot \pi \cdot (r_{\text{out}}^2 - r_{\text{in}}^2) + 2 \cdot \pi \cdot r_{\text{out}} \cdot w1 = 0.086 \text{ m}^2
\end{aligned}$$

$$\begin{aligned}
\text{Outer Coil:} \\
\text{Inside Radius} & \quad r2_{\text{in}} = 167.6 \text{ mm} \\
\text{Outer Radius} & \quad r2_{\text{out}} = 219.9 \text{ mm} \\
\text{Width} & \quad w2 = 46.8 \text{ mm} \\
\text{Surface Area:}
\end{aligned}$$

$$A_{\text{in}} = 2 \cdot \pi \cdot (r2_{\text{out}}^2 - r2_{\text{in}}^2) + 2 \cdot \pi \cdot r2_{\text{out}} \cdot w2 = 0.192 \text{ m}^2$$

Total surface area of one coil set (there is one on top and one on the bottom)

$$A_{\text{coils}} = A_{\text{in}} + A_{\text{out}} = 0.287 \text{ m}^2$$

**External magnet surface have been measured from the CAD drawing, and are listed here.**

Insulated Area of Magnet (Top):

$$A_{\text{top}} = 0.593 \text{ m}^2$$

Insulated Area of Magnet (Bottom)

$$A_{\text{bottom}} = 0.654 \text{ m}^2$$

Insulated Area of Dewar:

$$A_{\text{dewar}} = 1.66 \text{ m}^2$$

Uninsulated Area of Dewar:

$$A_{\text{uns}} = 0.2 \text{ m}^2$$

Heat Flux From Loss of Vacuum on an Insulated Surface:

$$\Phi_{\text{vac}} = 7 \frac{\text{kW}}{\text{m}^2}$$

Heat Flux From Loss of Vacuum on an Uninsulated Surface:

$$\Phi_{\text{uns}} = 38 \frac{\text{kW}}{\text{m}^2}$$

Latent Heat of He:

$$\lambda_{\text{He}} = 21 \frac{\text{J}}{\text{g}}$$

Mass Flow From Magnet:

$$\begin{aligned}
dm_{\text{bottom}} &= \Phi_{\text{vac}} \cdot \left( \frac{A_{\text{bottom}}}{\lambda_{\text{He}}} \right) + \Phi_{\text{quench}} \cdot \frac{A_{\text{coils}}}{\lambda_{\text{He}}} = 0.35 \frac{\text{kg}}{\text{s}} \\
dm_{\text{top}} &= \Phi_{\text{vac}} \cdot \left( \frac{A_{\text{top}}}{\lambda_{\text{He}}} \right) + \Phi_{\text{quench}} \cdot \frac{A_{\text{coils}}}{\lambda_{\text{He}}} = 0.33 \frac{\text{kg}}{\text{s}}
\end{aligned}$$

Mass Flow From Dewar:

$$dm_{\text{dewar}} = \Phi_{\text{vac}} \cdot \left( \frac{A_{\text{dewar}}}{\lambda_{\text{He}}} \right) + \Phi_{\text{quench}} \cdot \frac{A_{\text{uns}}}{\lambda_{\text{He}}} = 0.915 \frac{\text{kg}}{\text{s}}$$

The resulting total mass flow must be relieved from the magnet and dewar through the current external relief path. The mass flow from the magnet must



pass through plumbing to enter the dewar first. We assume that the mass flow from the magnet to the dewar is very cold, at 6 K. From the dewar to the relief valves and average temperature of 10 K is assumed. The relief path for the magnet is complicated by the separation of the two halves of the magnet.

Gas constant for He:

$$R_{\text{He}} = 2207 \frac{J}{kg \cdot K}$$

Assumed Temperature of He:

$$T_{\text{mag}} = 6 \text{ K}$$

ID of tubes:

$$ID_{\text{top}} = 0.37 \text{ in}$$

Mass Flow in One Tube:

$$\dot{m}_{\text{tube}} = \frac{\dot{m}_{\text{top}}}{4}$$

Friction Factor For Tube is Chosen to be the Simple

but Conservative Weymouth Factor:

$$f_{\text{top}} = \frac{0.032 \cdot \text{in}^{1/3}}{ID_{\text{top}}^{1/3}} = 0.045$$

We assume a conservative absolute pressure of 45 psia for the magnet.

$$P_{\text{top}} = 45 \text{ psi}$$

Density of He:

$$\rho_{\text{top}} = 58 \frac{kg}{m^3}$$

Length of tubes:

$$l_{\text{top}} = 6 \text{ in}$$

Velocity of the flow in one tube:

$$v_{\text{top}} = \frac{\dot{m}_{\text{tube}}}{\rho \cdot \pi \frac{ID_{\text{top}}^2}{4}} = 20.511 \frac{m}{s}$$

Pressure drop from top to bottom of magnet

$$\Delta P = f_{\text{top}} \cdot \left( \frac{\rho \cdot v_{\text{top}}^2}{2} \right) \cdot \frac{l_{\text{top}}}{ID_{\text{top}}} = 1.279 \text{ psi}$$

The magnet volume relieves through the two connecting tubes. The opening is 1.4" (Inner Diameter) and is connected to a 1.87" (Inner Diameter) tube with bends and fittings to the dewar. This line also contains the magnet wires. These are assumed to be  $\frac{1}{4}$ " (Outer Diameter) each. The reduced hydraulic diameter for the relief path will be used in the calculations. The path contains about 35" of tubing and 3 elbows at 90 degrees.

Hydraulic Diameter of Opening:

$$OD_{\text{wire}} = 0.25 \text{ in}$$

$$ID_{\text{open}} = 1.4 \text{ in}$$

$$ID_1 = \frac{2 \cdot \frac{OD_{\text{wire}}^2}{4} + \frac{ID_{\text{open}}^2}{4}}{2 \cdot OD_{\text{wire}} + ID_{\text{open}}} \cdot 4 = 1.097 \text{ in}$$

Hydraulic Diameter of Relief Path Tubing:

$$ID_{\text{path}}$$

$$ID_2 = \frac{2 \cdot \frac{OD_{\text{wire}}^2}{4} + \frac{ID_{\text{path}}^2}{4}}{2 \cdot OD_{\text{wire}} + ID_{\text{path}}} \cdot 4 = 1.528 \text{ in}$$

The flow velocity and friction factor for the larger section are:

$$f_{\text{bottom}} = \frac{0.032 \text{ in}^{1/3}}{ID_2^{1/3}} = 0.028$$

The density at the of the GasPak is:

$$\rho_{\text{bottom}} = 58 \frac{\text{kg}}{\text{m}^3}$$

Assumed pressure at bottom of magnet absolute:

$$P_{\text{bottom}} = 45 \text{ psi}$$

$$v_{\text{bottom}} = \frac{(dm_{\text{top}} + dm_{\text{bottom}})}{\rho \cdot \pi \cdot \frac{ID_2^2}{4}} = 9.914 \frac{\text{m}}{\text{s}}$$

We use the resistance coefficient method for determining the pressure drop from the magnet to the dewar. There are three (3) 90 degree elbows, two enlargements, and the flex hose, which will be treated as 3 straight pipes. This gives an equivalent tube length of 35" in and four (4) K factors for the bellows (2) and enlargement. There is a further enlargement at the entrance of the dewar. Note that one of the elbows is a 90 degree miter.

$$K_{\text{encl}} = (1 - \frac{ID_1^2}{ID_2^2})^2 = 0.235$$

$$K_{\text{tube}} = \frac{(35 \text{ in})}{ID_2} \cdot f_{\text{bottom}} = 0.636$$

$$K_{\text{elbow}} = 30 \cdot f_{\text{bottom}} = 0.833$$

$$K_{\text{miter}} = 60 \cdot f_{\text{bottom}} = 1.667$$

$$K_{\text{dewar}} = 1$$

$\Delta P = (K_{\text{encl}} + K_{\text{tube}} + 2 \cdot K_{\text{elbow}} + K_{\text{miter}} + K_{\text{dewar}}) \cdot \rho_{\text{bottom}} \cdot \frac{v_{\text{bottom}}^2}{2} = 2.152 \text{ psi}$   
The relief path from the dewar to the relief valves has three (3) 0.93" (Inner Diameter) tubes. The magnet current leads in one tube are hollow thin walled brass tubes and have been ignored for this calculation. We assume that only two of these tubes carry the total mass flow. The average temperature is assumed to be 10 K in the relief tubes and 10 K at the relief valves. The magnet line and the level probe are in separate relief tubes.

Pressure at the relief tube:

$$P_{\text{tube}} = 48 \text{ psi}$$

Temperature at relief tube:

$$T_{\text{tube}} = 10 \text{ K}$$

Density of He at the relief tube:

$$\rho_{\text{tube}} = \frac{P_{\text{tube}}}{R_{\text{He}} \cdot T_{\text{tube}}}$$

Nose Calculations:

The nose of the magnet is made with 6061 T6 Aluminum, which has a maximum strength of 30 ksi.

Properties of the nose are given below:

Name	Value	Unit
Radius	1.885	in
Diameter	3.77	in
Thickness	0.013	in
Tensile Strength	45	ksi

The equation to find the maximum allowable pressure is:

$$P = \frac{\sigma_h \cdot t}{d}$$

Plugging in the values listed above, we find the maximum pressure to be 310 psi.

#### Magnet Dewar Calculations:

The Helium Magnet Dewar is made from 316L Stainless Steel, which has a maximum strength of 70 ksi.

Properties of the Helium Magnet Dewar are given below:

Name	Value	Unit
Radius	8.7495	in
Diameter	17.499	in
Thickness	0.060	in
Tensile Strength	70	ksi

The equation to find the maximum allowable pressure is:

$$P = \frac{\sigma_h \cdot t}{d}$$

Plugging in the values in the table gives us an allowable pressure of .48 ksi, or 480 psi.

The magnet dewar is made from 316L Stainless Steel. The following are listed material properties for the dewar.

Elastic Modulus	$E_y = 27992.3$ ksi
Yield Strength	$S_y = 24.6564$ ksi
Ultimate Strength	$S_u = 70.3433$ ksi
Offset Strength	$\epsilon_y = 0.002$
Allowable stress	$S_a = 0.48$

#### **Magnet Dewar**

The dewar is a large enclosed volume inside the system. This systems relief path will be the three risers.

Dimension of the dewar:

Outer Diameter	$OD_{\text{dewar}} = 17.515$ in
Wall Thickness	$t_{\text{dewar}} = 0.06$ in
Length	$L_{\text{dewar}} = 19.32$

Volume of dewar:

$$V_{\text{dewar}} = \frac{\pi}{4} \cdot (\text{OD}_{\text{dewar}})^2 \cdot L_{\text{dewar}} = 76.2814 \text{ L}$$

Surface area of dewar:

$$A_{\text{dewar}} = \pi \cdot (\text{OD}_{\text{dewar}}) \cdot L_{\text{dewar}} + 2 \cdot \frac{\pi}{4} \cdot (\text{OD}_{\text{dewar}})^2 = 0.997 \text{ m}^2$$

### Loss of IV

Max Heat Flux

$$q = 8 \frac{\text{kW}}{\text{m}^2}$$

The total heat load on the He fluid is

$$Q = q \cdot A_{\text{dewar}} = 7976 \text{ W}$$

The latent heat of He is

$$\Lambda = 21 \frac{\text{J}}{\text{g}}$$

The total mass evolution rate is then

$$\dot{m} = \frac{Q}{\Lambda} = 379.80952 \frac{\text{g}}{\text{s}}$$

It is a conservative estimate to assume that the He gas reaches room temperature immediately.

the density of He at 300 K, 30 psia is

$$\rho_{300} = 0.332 \cdot 10^{-3} \frac{\text{g}}{\text{cm}^3}$$

The density of He at 100 K, 80 psia is

$$\rho_{100} = 2.63 \cdot 10^{-3} \frac{\text{g}}{\text{cm}^3}$$

Volumetric flow rate at 100 K

$$W_{100} = \frac{\dot{m}}{\rho_{100}} = 0.1444 \frac{\text{m}^3}{\text{s}}$$

Volumetric flow rate at 300 K

$$W_{300} = \frac{\dot{m}}{\rho_{300}} = 1.1795 \frac{\text{m}^3}{\text{s}}$$

Viscosity of He at 100 K

$$\nu_{100} = 9.87 \cdot 10^{-6} \text{ Pa}\cdot\text{s}$$

Viscosity of He at 300 K

$$\nu_{300} = 19.93 \cdot 10^{-6} \text{ Pa}\cdot\text{s}$$

Velocity of sound at 100 K

$$V_{s100} = 593 \frac{\text{m}}{\text{s}}$$

Velocity of sound at 300 K

$$V_{s300} = 1020 \frac{\text{m}}{\text{s}}$$

### Relief of Dewar

The dewar relieves through a set of three risers, the dimensions of which are listed below:

	Riser A	Riser B	Riser C
Length	$L_1 = 14.016 \text{ in}$	$L_2 = 17.22 \text{ in}$	$L_3 = 17.22 \text{ in}$
Outer Diameter	—	$\text{OD}_2 = 1.06 \text{ in}$	$\text{OD}_3 = 0.96 \text{ in}$
Wall Thickness	—	—	—
Inner Diameter	$\text{ID}_1 = 0.96 \text{ in}$	$\text{ID}_2 = 0.98 \text{ in}$	$\text{ID}_3 = 0.5 \text{ in}$
Area	$A_1 = 0.72382 \text{ in}^2$	$A_2 = 0.754 \text{ in}^2$	$A_3 = 0.19635 \text{ in}^2$
Surface Roughness	$e_1 = 0.00006 \text{ in}$	$e_2 = 0.0006 \text{ in}$	$e_3 = 0.0006 \text{ in}$

Next, the velocities of the flow for each riser will be calculated.

$$v = \frac{W_{100}}{A}$$

$$\text{so, } v_1 = 309.238 \frac{\text{m}}{\text{s}}, v_2 = 296.7823 \frac{\text{m}}{\text{s}}, \text{ and } v_3 = 1139.81 \frac{\text{m}}{\text{s}}.$$

Next, the Reynolds Number for each riser will be computed.

$$R_e = \text{ID} \cdot \frac{v \cdot \rho_{100}}{\nu_{100}}$$

$$\text{so, } R_{e1} = 2009.26, R_{e2} = 1968.5044, \text{ and } R_{e3} = 3857.23.$$

The friction factor will be used to compute the final pressure drop, which is

found using the equation:  
 $f = (1.14 + 2 \cdot \log(\frac{ID}{e}))^{-2}$

This gives us that  $f_1 = 0.01097$ ,  $f_2 = 0.01092$ , and  $f_3 = 0.0124$

Finally, the pressure drop for each riser will be computed.

$$\Delta P_1 = f \cdot \rho_{100} \cdot L \cdot \frac{v^2}{ID}$$

This gives us the  $\Delta P_1 = 2255.36$  psi,  $\Delta P_2 = 2704.2268$  psi, and  $\Delta P_3 = 6012.6$  psi.

This means that the total pressure drop between the three risers is a total 10972.2 psi.

In a worst case scenario, if there was an instantaneous loss of insulating vacuum in the Magnet dewar, the pressure drop would be higher than the allowable pressure by quite a large amount. However, due to the high strength in the Nitrogen Shield, any worst-case scenario risk is mitigated greatly. The calculations for the Nitrogen Dewar are covered in the next section.

Nitrogen Dewar Calculations The Nitrogen Dewar is made from 316L Stainless Steel, which has a maximum strength of 70 ksi. Properties of the Nitrogen Dewar are given below:

Name	Value	Unit
Radius	14.2815	in
Diameter	28.563	in
Thickness	0.10	in
Tensile Strength	70	ksi

The equation to find the maximum allowable pressure is:

$$P = \frac{s \cdot t}{r + (0.6t)}$$

Plugging in these values we get the allowable pressure to be 48.81 ksi.

Due to the high allowable pressure in the Nitrogen Dewar, it is extremely unlikely that the walls would buckle in the case of instantaneous IV loss.

### 4.3 Quench Calculations

The worst case scenario pressure load will follow a magnet quench and sudden loss of insulating vacuum, or IV. During a magnet quench the superconducting

wire will provide a heat load. There are two pairs of coil packs. The heat load to the magnet has been experimentally determined by Oxford to be 1 W/cm<sup>2</sup>.

Heat Flux In Coil From Quench:

$$\Phi_{\text{quench}} = 1 \frac{W}{cm^2}$$

Magnet Stored Energy:

Magnet Inductance:

$$L = 71 \text{ Henry}$$

Magnet Max Current:

$$I = 78.3 \text{ Amps}$$

Magnet initial stored energy:

$$E_0 = 0.5 \cdot L \cdot I \cdot |0.001 \frac{kJ}{Henry-A^2}|$$

Start time when the initial energy stored is at its maximum:

$$time_0 = 0 \text{ seconds}$$

Decay time constant:

$$\tau = \frac{L}{R}$$

$$\tau = 27 \text{ seconds}$$

Helium Properties:

Atmospheric Pressure:

$$P_{\text{atm}} = 100 \text{ kPa}$$

Magnet reservoir fully open relieving pressure:

$$P_{\text{magnet}} = P_{\text{atm}} + 3.5 \text{ psi} \cdot |6.895 \cdot \frac{kPa}{psi}|$$

Heat of vaporization:

$$h_{\text{fg}} = \mathbf{h}(\text{Helium}, P = P_{\text{magnet}}, x = 1) - \mathbf{h}(\text{Helium}, P = P_{\text{magnet}}, x = 0)$$

Volume at vaporization:

$$v_{\text{fg}} = \mathbf{v}(\text{Helium}, P = P_{\text{magnet}}, x = 1) - \mathbf{v}(\text{Helium}, P = P_{\text{magnet}}, x = 0)$$

$$v_g = \mathbf{v}(\text{Helium}, P = P_{\text{magnet}}, x = 1)$$

$$v_f = \mathbf{v}(\text{Helium}, P = P_{\text{magnet}}, x = 0)$$

Quantity of LHe in magnet reservoir:

Physical volume of magnet helium reservoir:

$$\text{Vol} = 135 \text{ L} \cdot |0.001 \cdot \frac{m^3}{L}|$$

Mass of liquid helium present in reservoir:

$$m_{\text{reservoir}} = \frac{\text{Vol}}{v_f}$$

Calculated helium fluid properties:

Inlet temperature assuming saturated vapor:

$$T_{\text{inlet}} = \mathbf{T}(\text{Helium}, P = P_{\text{magnet}}, x = 1)$$

Cp for ideal gas at relieving temperature:

$$C_{p\text{He,ideal}} = \mathbf{Cp}(\text{He}, T = T_{\text{inlet}})$$

Cv for ideal gas at relieving temperature:

$$C_{v\text{He,ideal}} = \mathbf{Cv}(\text{He}, T = T_{\text{inlet}})$$

Ratio of specific heats for ideal gas at relieving temperatures:

$$k_{\text{He}} = \frac{C_{p\text{He,ideal}}}{C_{v\text{He,ideal}}}$$

Molar Mass:

$$M_{\text{He}} = \mathbf{MolarMass}(\text{He})$$

Compressibility Factor:

$$Z_{\text{He}} = P_{\text{magnet}} \cdot M_{\text{He}} \cdot \frac{v_g}{8.314 \text{ kJ/mol} \cdot K \cdot T_{\text{inlet}}}$$

Critical flow equation constant:

$$C_{\text{He}} = \frac{0.03948 [kg^{0.5} - g/mol^{0.5} \cdot K^{0.5}]}{1 [mm^2 \cdot hr \cdot kPa]} \cdot \sqrt{k_{\text{He}} \left[ \frac{2}{k_{\text{He}} + 1} \right]^{k_{\text{He}} + 1 / k_{\text{He}} - 1}}$$

Critical flow nozzle pressure:

$$P_{\text{cf,He}} = P_{\text{magnet}} \cdot \left[ \left[ \frac{2}{k_{\text{He}} + 1} \right] \left( \frac{k_{\text{He}}}{k_{\text{He}} - 1} \right) \right]$$

Text statement whether the flow through relief orifice is critical or subcritical:

$$\text{Flow}_{\text{He}} = \text{if}(P_{\text{atm}}, P_{\text{cf,He}}, \text{'critical'}, \text{'critical'}, \text{'subcritical'})$$

$$N_{\text{steps}} = 150$$

$$\text{time}_{\text{step}} = 0.1$$

Determine heat transfer rate:

Time after quench:

$$\text{time}_j = \text{time}_{j-1} + \text{time}_{\text{step}} \quad (\text{for } j = 1 \text{ to } N_{\text{steps}})$$

Stored energy in magnet:

$$E_j = E_0 \cdot \exp\left[-\frac{\text{time}_j}{\tau}\right] \quad (\text{for } j = 1 \text{ to } N_{\text{steps}})$$

Heat transfer rate to helium:

$$\dot{Q} = \frac{E_{j-1} - E_j}{\text{time}_{\text{step}}} \quad (\text{for } j = 1 \text{ to } N_{\text{steps}})$$

Determine minimum relief valve size (assume saturated vapor at inlet)

Required mass flow rate:

$$\dot{m}_j = \dot{Q}_j \cdot \frac{v_{\text{gf}}}{h_{\text{fg}} \cdot v_g} \quad (\text{for } J = 1 \text{ to } N_{\text{steps}})$$

Peak mass flow rate:

$$\dot{m}_{\text{max}} = \text{Max}(\dot{m}_{1..N_{\text{steps}}})$$

Equations fpr critical flow:

Discharge coefficient \* orifice area:

$$KdA_{\text{crit}} = \frac{\dot{m}_{\text{max}}}{C_{\text{He}} \cdot P_{\text{magnet}}} \cdot \sqrt{Z_{\text{He}} \cdot \frac{T_{\text{inlet}}}{M_{\text{He}}} \cdot |3600 \cdot \frac{1}{\text{hr}}|}$$

Equations for Subcritical Flow:

Ratio of backpressure to upstream relieving pressure:

$$r_{\text{subcrit}} = \frac{P_{\text{atm}}}{P_{\text{magnet}}}$$

Coefficient for subcritical flow:

$$F_{2,\text{He}} = \sqrt{\left[ \frac{k_{\text{He}}}{k_{\text{He}} - 1} \right] \cdot r_{\text{subcrit}}^{2/k_{\text{He}}} \cdot \left[ \frac{1 - r_{\text{subcrit}}^{[k_{\text{He}} - 1 / k_{\text{He}}]}}{1 - r_{\text{subcrit}}} \right]}$$

Equation coefficient and unit conversion factor:

$$\text{Unitfactor} = \frac{17.9 [hr \cdot mm^2 - kPa]}{1 [kg^{0.5} - g/mol^{0.5} \cdot K^{0.5}]}$$

Discharge coefficient, orifice area

$$KdA = \dot{m}_{\text{max}} \cdot \frac{\text{UnitFactor}}{F_{2,\text{He}}} \cdot \sqrt{Z_{\text{He}} \cdot \frac{T_{\text{inlet}}}{M_{\text{He}} \cdot P_{\text{magnet}} \cdot (P_{\text{magnet}} - P_{\text{atm}})}} \cdot |3600 \cdot \frac{1}{\text{hr}}|$$

$$KdA = \text{If} (P_{\text{atm}}, P_{\text{cf,He}}, KdA_{\text{crit}}, KdA_{\text{crit}}, KdA_{\text{subcrit}})$$

Solutions:

$$C_{p_{\text{He,ideal}}} = 5.193 \text{ kJ/kg-K}$$

$C_{\text{He}} = 0.02867 \text{ (kg} \cdot \text{kgmol} \cdot \text{K)}^{0.5} / \text{mm}^2 \cdot \text{hr} \cdot \text{kPa}$   
 $F_{2,\text{He}} = 0.9066$   
 $I = 78.3 \text{ A}$   
 $KdA_{\text{crit}} = 295.8 \text{ mm}^2$   
 $k_{\text{He}} = 1.667$   
 $\dot{m}_{\text{max}} = 0.3471 \text{ kg/s}$   
 $m_{\text{reservoir}} = 16.22 \text{ kg}$   
 $P_{\text{atm}} = 100 \text{ kPa}$   
 $P_{\text{magnet}} = 124.1 \text{ kPa}$   
 $r_{\text{subcrit}} = 0.8056$   
 $\text{time}_{\text{step}} = 0.1 \text{ sec}$   
 $\text{UnitFactor} = 17.9 \text{ hr} \cdot \text{mm}^2 \cdot \text{kPa} / (\text{kg} \cdot \text{kgmol} \cdot \text{K})^{0.5}$   
 $v_f = 0.008321 \text{ m}^3/\text{kg}$   
 $v_{fg} = 0.04753 \text{ m}^3/\text{kg}$   
 $Cv_{\text{He,ideal}} = 3.116 \text{ kJ/kg} \cdot \text{K}$   
 $\text{Flow}_{\text{He}} = \text{subcritical}$   
 $h_{fg} = 19.12 \text{ kJ/kg}$   
 $KdA = 379.7 \text{ mm}^2$   
 $KdA_{\text{subcrit}} = 379.7 \text{ mm}^2$   
 $L = 71 \text{ Henry}$   
 $M_{\text{He}} = 4.003 \text{ kg/kmol}$   
 $N_{\text{steps}} = 150$   
 $P_{\text{cf,He}} = 60.47 \text{ kPa}$   
 $R = 2.63 \text{ } \Omega$   
 $\tau = 27 \text{ sec}$   
 $T_{\text{inlet}} = 4.446 \text{ K}$   
 $\text{Vol} = 0.135 \text{ m}^3$   
 $v_{fg} = 0.03921$   
 $Z_{\text{He}} = 0.639$

#### 4.4 Quench Calculations Summary

Based on the calculations done above, the system should be sufficient to handle a magnet quench event. Because the flow is subcritical (as shown in the calculations above), the magnet dewar should hold in the event of a magnet quench.

#### 4.5 Overview of Risers

The calculations on the risers are conducted in a way to make them more simple. A change made to the calculation is the impedance of the baffles being ignored. This allows us to calculate mass and energy flow more conservatively.

Riser A: Withdrawal tube/level probe: This riser carries two tubes, a 1.422 cm diameter tube and a 0.478 cm diameter tube. The riser is fitted with radiation baffles which are soldered to the tubes. The baffles are round and fit



closely inside the 2.438 cm ID riser tube. One baffle is located near the bottom of the riser, one near the center and one near the top.

Riser B: fill tube/bottom line: This riser has three tubes, one 1.422 cm diameter, and two 0.635 cm diameter. The riser is fitted with one full round radiation baffle located near the bottom of the riser. The baffle fits closely inside the ID of the riser.

Riser C: Magnet leads/sensor leads: This riser has a single tube 0.5 in (1.27 cm) in diameter. Wrapped around the tube are six wires or wire bundles each contained in a  $\frac{1}{8}$  in diameter plastic sheath. The wires are wrapped loosely around the central tube and make approximately 6 turns over the length of the riser. At the bottom of the riser a cylindrical plastic plug 0.5 inches high fits securely between the inner tube and the ID of the riser. This plug has four semicircular channels cut along its length to allow the wires to pass through to the helium space. The wires completely fill two of the four channels. The remaining open area at the plug is estimated to be 0.32 cm<sup>2</sup>.

## 4.6 Evaluation of Risers

Parameters used:

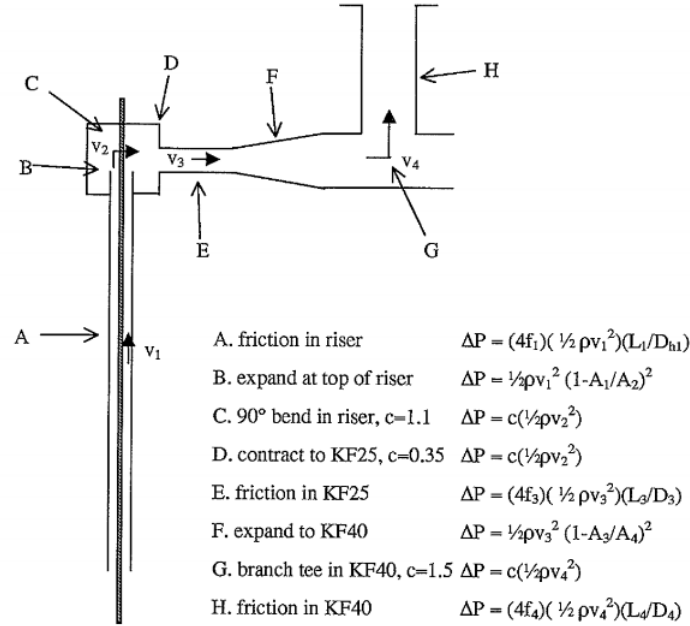
Magnet Dewar Surface Area: 402.838 cm<sup>2</sup>  
 Helium Reservoir Surface Area: 18,931.6 cm<sup>2</sup>  
**Total Dewar Surface Area: 19,334.4 cm<sup>2</sup>**

Heat Flux due to IV Loss: 0.6 W/cm<sup>2</sup>  
 Heat of Vaporization of LHe: 21 J/g (4.2 K, 1 atm)  
**Mass Flow on IV Loss:** 19,334.4 cm<sup>2</sup> · 0.6 W/cm<sup>2</sup> / 21 J/g = **552.412 g/s**  
 Mass Flow on Quench: 300 g/s

**Total Mass Flow: 852.412 g/s**  
**Exhaust Gas Temperature: 20 K**  
 ( $\rho = 0.00242$  g/cm<sup>3</sup> at 1.0 atm,  
 $\rho = 0.0732$  g/sm<sup>3</sup> at 3.0 atm,  
 $\rho = 0.00977$  g/sm<sup>3</sup> at 4.0 atm)

The use of the heat of evaporation of liquid helium to derive the mass flow and the use of 20 Kelvin as the exhaust temperature are assumptions used by Oxford in their own analysis. These assumptions give the calculations a slight safety factor. The actual enthalpy change in converting 4.2 Kelvin liquid helium to 20 Kelvin vapor is 100 J/g. The mass flow due to IV loss would only be 233 g/s if the correct enthalpy change is used.

Figure 4: Pressure drop in risers and relief manifold:



The friction in the riser and expansion at the top of the riser will be different for each one. The discharge coefficient of the parallel-plate relief valve has also been neglected. The relief valve is taken as a constant 4 psi pressure drop.

**Riser A:** 0.96" (2.438 cm) ID, 14" (35.6 cm) long contains one 0.56" (1.422 cm) tube and one 0.188" (0.478 cm) tube.

### Friction

Perimeter:

$$\pi(2.438 \text{ cm}) = 7.659 \text{ cm}$$

$$\pi(1.422 \text{ cm}) = 4.467 \text{ cm}$$

$$\pi(0.478 \text{ cm}) = 1.502 \text{ cm}$$

total perimeter 13.628 cm

Area:  $\pi(2.438 \text{ cm}/2)^2 = 4.668 \text{ cm}^2$

area blocked  $\pi(1.422 \text{ cm}/2)^2 = 1.588 \text{ cm}^2$

area blocked  $\pi(0.478 \text{ cm}/2)^2 = 0.179 \text{ cm}^2$

flow area:  $2.901 \text{ cm}^2$



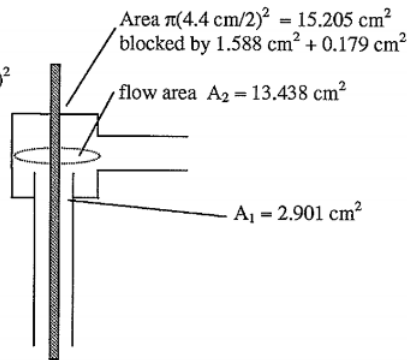
hydraulic diameter:  $D_{1h} = 4A/P = 4(2.901 \text{ cm}^2) / 13.628 \text{ cm} = 0.851 \text{ cm}$

pressure drop due to friction:

$$\Delta P = (4f_1) \left( \frac{1}{2} \rho v_1^2 \right) (L_1 / D_{1h}) = (4f_1) \left( \frac{1}{2} \rho v_1^2 \right) (35.6 \text{ cm} / 0.851 \text{ cm}) = (4f_1) \left( \frac{1}{2} \rho v_1^2 \right) (41.83)$$

### Expansion at top of riser

$$\begin{aligned} \Delta P &= \frac{1}{2} \rho v_1^2 (1 - A_1/A_2)^2 \\ &= \frac{1}{2} \rho v_1^2 (1 - 2.901 \text{ cm}^2 / 13.438 \text{ cm}^2)^2 \\ &= \frac{1}{2} \rho v_1^2 (0.615) \end{aligned}$$



**Bend and flow path at the top of the riser:**  $\Delta P = c \left( \frac{1}{2} \rho v_2^2 \right)$  with  $c = 1.1$

**Reduction to KF25:** For simplicity, we will neglect partial blockage of the area at the top of the riser and assume that we are making a transition from  $d_2 = 4.4 \text{ cm}$  to  $d_3 = 2.2 \text{ cm}$ . For  $d_3/d_2 = 0.5$  tables give  $c = 0.35$ .  $\Delta P = c \left( \frac{1}{2} \rho v_3^2 \right)$  with  $c = 0.35$

**Riser B:** 0.98" (2.489 cm) ID, 17.22" (43.79 cm) long  
contains one 0.54" (1.372 cm) Ø tube and two 0.25" (0.635 cm) Ø tubes.

Friction:  
Perimeter:

$$\begin{aligned}\pi(2.489 \text{ cm}) &= 7.82 \text{ cm} \\ \pi(1.372 \text{ cm}) &= 4.31 \text{ cm} \\ 2\pi(0.635 \text{ cm}) &= 3.99 \text{ cm}\end{aligned}$$

total perimeter: 16.12 cm

$$\text{Area: } \pi(2.489 \text{ cm}/2)^2 = 4.886 \text{ cm}^2$$

$$\text{Area blocked: } \pi(1.372 \text{ cm}/2)^2 = 1.478 \text{ cm}^2$$

$$\text{Area blocked: } \pi(0.635 \text{ cm}/2)^2 = 0.317$$

Flow area: 3.07 cm<sup>2</sup>

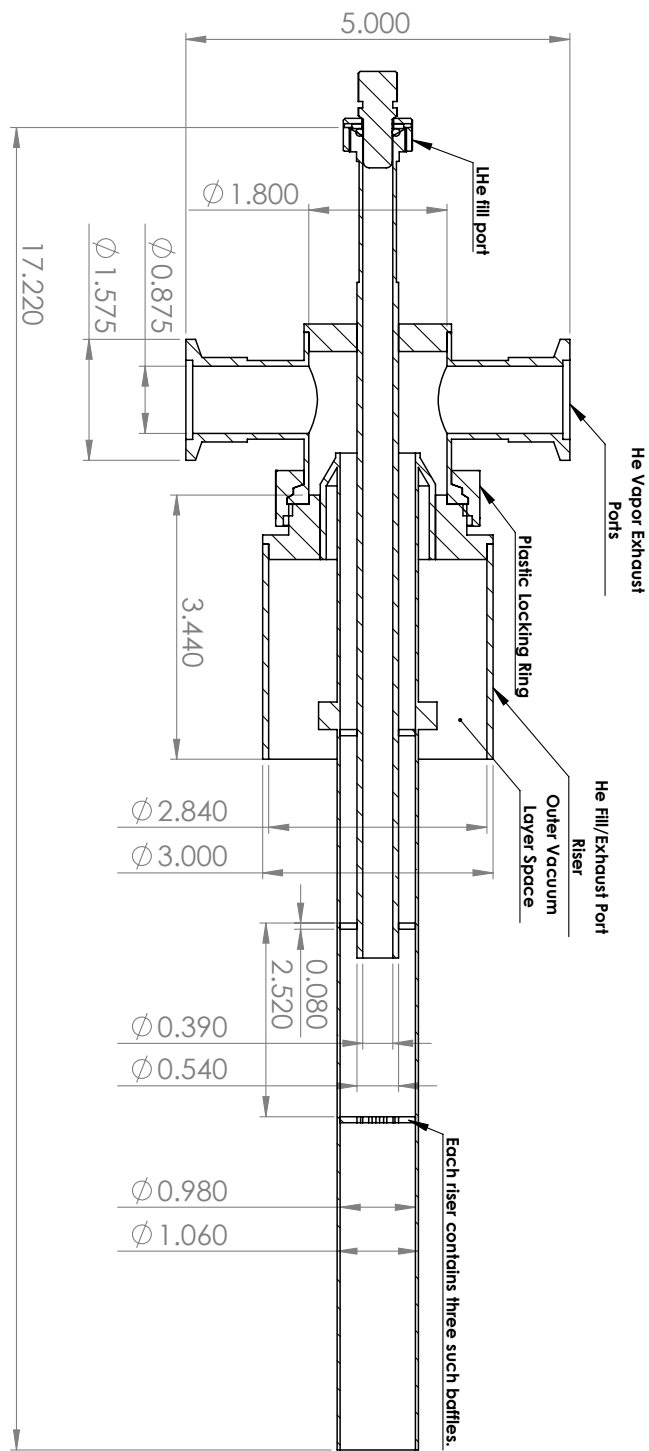
$$\begin{aligned}\text{Hydraulic Diameter: } D_h &= 4A/P = 4(3.07 \text{ cm}^2)/16.12 \text{ cm} = 0.76 \text{ cm} \\ \Delta &= (4f_1)(\frac{1}{2}\rho v_1^2)(L_1/D_h) - (4f_1)(\frac{1}{2}\rho v_1^2)(43.79 \text{ cm}/0.317 \text{ cm}) = (4f_1)(\frac{1}{2}\rho v_1^2)(138.269)\end{aligned}$$

**Expansion at top of riser**

$$\begin{aligned}\Delta P &= \frac{1}{2}\rho v_1^2(1-A_1/A_2)^2 \\ &= \frac{1}{2}\rho v_1^2(1-3.07 \text{ cm}^2/12.789 \text{ cm}^2)^2 \\ &= \frac{1}{2}\rho v_1^2(0.577)\end{aligned}$$

**Bend and flow path at the top of the riser:**  $\Delta P = c(\frac{1}{2}\rho v_2^2)$  with c = 1.1

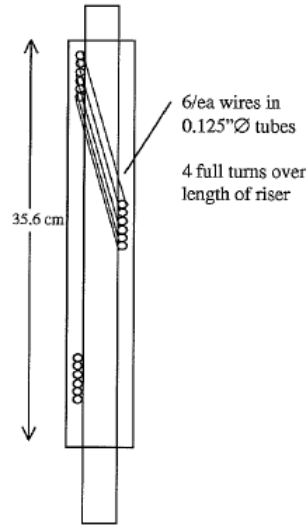
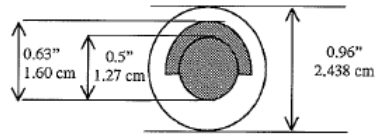
**Reduction to KF25:** For simplicity, neglect partial blockage of the area at the top of the riser and assume that we are making a transition from d<sub>2</sub> = 4.4 cm to d<sub>3</sub> = 2.2 cm. For d<sub>3</sub>/d<sub>2</sub> = 0.5 tables give c = 0.35.  $\Delta P = c(\frac{1}{2}\rho v_3^2)$  with c = 0.35



29  
Figure 5: Fill Riser

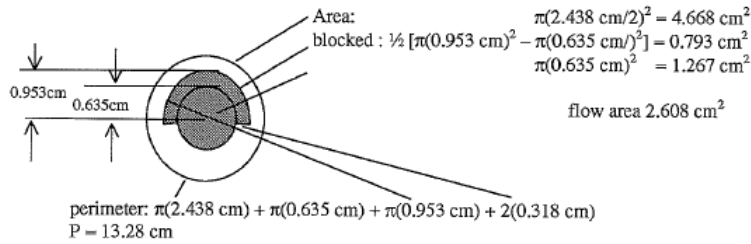
**Riser C:**

At any given point along tube, leads partially obscure the flow area over  $\sim 1/2$  of the circumference.



Estimate the flow area based on the figure above. To account for the helical shape of the flow path, calculate length assuming a helical flow path. With  $r = 0.927$  cm (half way inside the annular region between the two tubes):

$$L = [(4 \times 2\pi r)^2 + (35.6 \text{ cm})^2]^{1/2} = 42.5 \text{ cm}$$



$$\text{hydraulic diameter } D_{ih} = 4(2.608 \text{ cm}^2)/(13.28 \text{ cm}) = 0.785 \text{ cm}$$

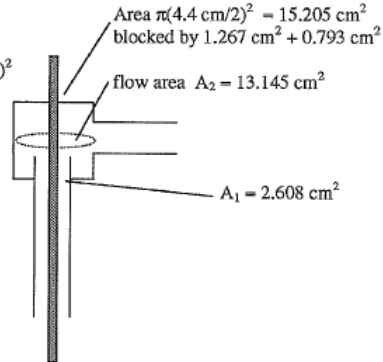
pressure drop due to friction:

$$\Delta P = (4f_1)(\frac{1}{2} \rho v_1^2)(L_1/D_{ih}) = (4f_1)(\frac{1}{2} \rho v_1^2)(42.5 \text{ cm}/0.785 \text{ cm}) = (4f_1)(\frac{1}{2} \rho v_1^2)(54.1)$$

Riser C continued:

Expansion at top of riser

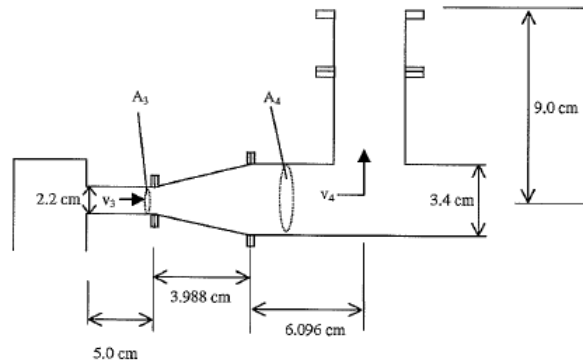
$$\begin{aligned}\Delta P &= \frac{1}{2}\rho v_1^2 (1 - A_1/A_2)^2 \\ &= \frac{1}{2}\rho v_1^2 (1 - 2.608 \text{ cm}^2 / 13.145 \text{ cm}^2)^2 \\ &= \frac{1}{2}\rho v_1^2 (0.642)\end{aligned}$$



**Bend and flow path at the top of the riser:**  $\Delta P = c(\frac{1}{2}\rho v_2^2)$  with  $c = 1.1$

**Reduction to KF25:** For simplicity, neglect partial blockage of the area at the top of the riser and assume that we are making a transition from  $d_2 = 4.4$  cm to  $d_3 = 2.2$  cm. For  $d_3/d_2 = 0.5$  tables give  $c = 0.35$ .  $\Delta P = c(\frac{1}{2}\rho v_3^2)$  with  $c = 0.35$

**Manifold:**



Each riser and its relief valve are treated independently. The fact that they are connected by the manifold is neglected in this scenario.

**Friction in the KF25 Section:**

To include the KF25/40 adapter, the length of the adapter is added to the KF25 section.

$$\Delta P = (4f_3)(\frac{1}{2}\rho v_3^2)(L_3/D_3) = (4f_3)(\frac{1}{2}\rho v_3^2)(9 \text{ cm}/2.2 \text{ cm})$$

**Expansion to KF40:** ( $A_3$  to  $A_4$ );  $\Delta P = \frac{1}{2}\rho v_3^2(1 - A_3/A_4)^2$

$$A_3 = \pi(2.2 \text{ cm}/2)^2 = 3.801 \text{ cm}^2$$

$$A_4 = \pi(3.4 \text{ cm}/2)^2 = 9.079 \text{ cm}^2$$

$$\Delta P = \frac{1}{2}\rho v_3^2(1 - 3.801 \text{ cm}^2/9.079 \text{ cm}^2)^2 = \frac{1}{2}\rho v_3^2(0.338)$$

**Branch Tee in KF40:**  $\Delta P = c(\frac{1}{2}\rho v_4^2)$  with  $c = 1.5$

**Friction in KF40:** We take the total length through the tee and assume that the relief valve will add an additional 3 cm.  $\Delta P = (4f_4)(\frac{1}{2}\rho v_4^2)(15 \text{ cm}/4.4 \text{ cm})$ .

	Riser A	Riser B	Riser C
friction in riser	$(4f_1)(\frac{1}{2}\rho v_1^2)(L_1/D_{b1})$	$(4f_1)(\frac{1}{2}\rho v_1^2)(L_1/D_{b1})$	$(4f_1)(\frac{1}{2}\rho v_1^2)(L_1/D_{b1})$
expand at top of riser	$\frac{1}{2}\rho v_1^2(1 - A_1/A_2)^2$	$\frac{1}{2}\rho v_1^2(1 - A_1/A_2)^2$	$\frac{1}{2}\rho v_1^2(1 - A_1/A_2)^2$
90° bend in riser,	$c(\frac{1}{2}\rho v_2^2)$	$c(\frac{1}{2}\rho v_2^2)$	$c(\frac{1}{2}\rho v_2^2)$
contract to KF25	$c(\frac{1}{2}\rho v_2^2)$	$c(\frac{1}{2}\rho v_2^2)$	$\Delta P = c(\frac{1}{2}\rho v_2^2)$
friction in KF25	$(4f_3)(\frac{1}{2}\rho v_3^2)(L_3/D_3)$	$(4f_3)(\frac{1}{2}\rho v_3^2)(L_3/D_3)$	$(4f_3)(\frac{1}{2}\rho v_3^2)(L_3/D_3)$
expand to KF40	$\frac{1}{2}\rho v_3^2(1 - A_3/A_4)^2$	$\frac{1}{2}\rho v_3^2(1 - A_3/A_4)^2$	$\frac{1}{2}\rho v_3^2(1 - A_3/A_4)^2$
branch tee in KF40	$c(\frac{1}{2}\rho v_4^2)$	$c(\frac{1}{2}\rho v_4^2)$	$c(\frac{1}{2}\rho v_4^2)$
friction in KF40	$(4f_4)(\frac{1}{2}\rho v_4^2)(L_4/D_4)$	$(4f_4)(\frac{1}{2}\rho v_4^2)(L_4/D_4)$	$(4f_4)(\frac{1}{2}\rho v_4^2)(L_4/D_4)$

Each riser and its relief valve are treated independently. The fact that they are connected together by the manifold is neglected.

#### Friction in KF25 Section:

To include the KF25/40 adapter, the length of the adapter is added to the KF25 section.

$$\Delta P = (4f_3)(\frac{1}{2}\rho v_3^2)(L_3/D_3) = (4f_4)(\frac{1}{2}\rho v_4^2)(9 \text{ cm}/2.2 \text{ cm})$$

**Expansion to KF40:** ( $A_3$  to  $A_4$ );  $\Delta P = \frac{1}{2}\rho v_3^2(1 - A_3/A_4)^2$

$$A_3 = \pi(2.2 \text{ cm}/2)^2 = 3.801 \text{ cm}^2$$

$$A_4 = \pi(3.4 \text{ cm}/2)^2 = 9.079 \text{ cm}^2$$

$$\Delta P = \frac{1}{2}\rho v_3^2(1 - 3.801 \text{ cm}^2/9.079 \text{ cm}^2)^2 = \frac{1}{2}\rho v_3^2(0.338)$$

**Branch Tee in KF40:**  $\Delta P = c(\frac{1}{2}\rho v_4^2)$  with  $c = 1.5$

**Friction in KF40:** We take the total length through the tee and assume that the relief valve will add an additional 3 cm.  $\Delta P = (4f_4)(\frac{1}{2}\rho v_4^2)(15 \text{ cm}/$



4.4 cm).

### Summary of Geometry Terms and Loss Coefficients

Table 1: Pressure drop  $\Delta P$  Terms

	Riser A	Riser B	Riser C
friction in riser	$(4f_1)(\frac{1}{2}\rho v_1^2)(41.83)$	$(4f_1)(\frac{1}{2}\rho v_1^2)(58.65)$	$(4f_1)(\frac{1}{2}\rho v_1^2)(54.1)$
expand at top of riser	$\frac{1}{2}\rho v_1^2 (0.615)$	$\frac{1}{2}\rho v_1^2 (0.658)$	$\frac{1}{2}\rho v_1^2 (0.642)$
90° bend in riser,	$1.1(\frac{1}{2}\rho v_2^2)$	$1.1(\frac{1}{2}\rho v_2^2)$	$1.1(\frac{1}{2}\rho v_2^2)$
contract to KF25	$0.35(\frac{1}{2}\rho v_2^2)$	$0.35(\frac{1}{2}\rho v_2^2)$	$0.35(\frac{1}{2}\rho v_2^2)$
friction in KF25	$(4f_3)(\frac{1}{2}\rho v_3^2)(4.091)$	$(4f_3)(\frac{1}{2}\rho v_3^2)(4.901)$	$(4f_3)(\frac{1}{2}\rho v_3^2)(4.901)$
expand to KF40	$\frac{1}{2}\rho v_3^2 (0.338)$	$\frac{1}{2}\rho v_3^2 (0.338)$	$\frac{1}{2}\rho v_3^2 (0.338)$
branch tee in KF40	$1.5(\frac{1}{2}\rho v_4^2)$	$1.5(\frac{1}{2}\rho v_4^2)$	$1.5(\frac{1}{2}\rho v_4^2)$
friction in KF40	$(4f_4)(\frac{1}{2}\rho v_4^2)(3.409)$	$(4f_4)(\frac{1}{2}\rho v_4^2)(3.409)$	$(4f_4)(\frac{1}{2}\rho v_4^2)(3.409)$

Table 2: Flow Areas

	Riser A	Riser B	Riser C
riser tube; $A_1$	2.901 cm <sup>2</sup>	2.447 cm <sup>2</sup>	2.608 cm <sup>2</sup>
top riser; $A_2$	13.438 cm <sup>2</sup>	12.984 cm <sup>2</sup>	13.145 cm <sup>2</sup>
KF25 section $A_3$	3.801 cm <sup>2</sup>	3.801 cm <sup>2</sup>	3.801 cm <sup>2</sup>
KF40 Section $A_4$	9.079 cm <sup>2</sup>	9.079 cm <sup>2</sup>	9.079 cm <sup>2</sup>

The friction factors  $(4f_1)$ – $(4f_4)$  depend on the Reynolds number of the flow. These factors have become nearly constant at high Reynolds numbers. We will be evaluating these expressions for the mass flows of around 300 g/s or higher. The smallest value of the Reynolds number will occur in the KF40 piping sections:

$$N_{RE} = \rho v d / \nu \quad \text{where } \rho = \text{density, } d = \text{diameter, and } \nu = \text{viscosity}$$

We can also use

$$N_{RE} = \frac{4\dot{m}}{\pi \nu d} \quad \text{where } \dot{m} \text{ is the mass flow.}$$

$$N_{RE} = 4(0.3 \text{ kg/s}) / \pi (3.8 \cdot 10^{-6} \text{ Ns/m}^2)(0.034 \text{ m}) = 3 \cdot 10^6$$

Taking a surface roughness  $e$  0.001 cm for most of our piping system. The

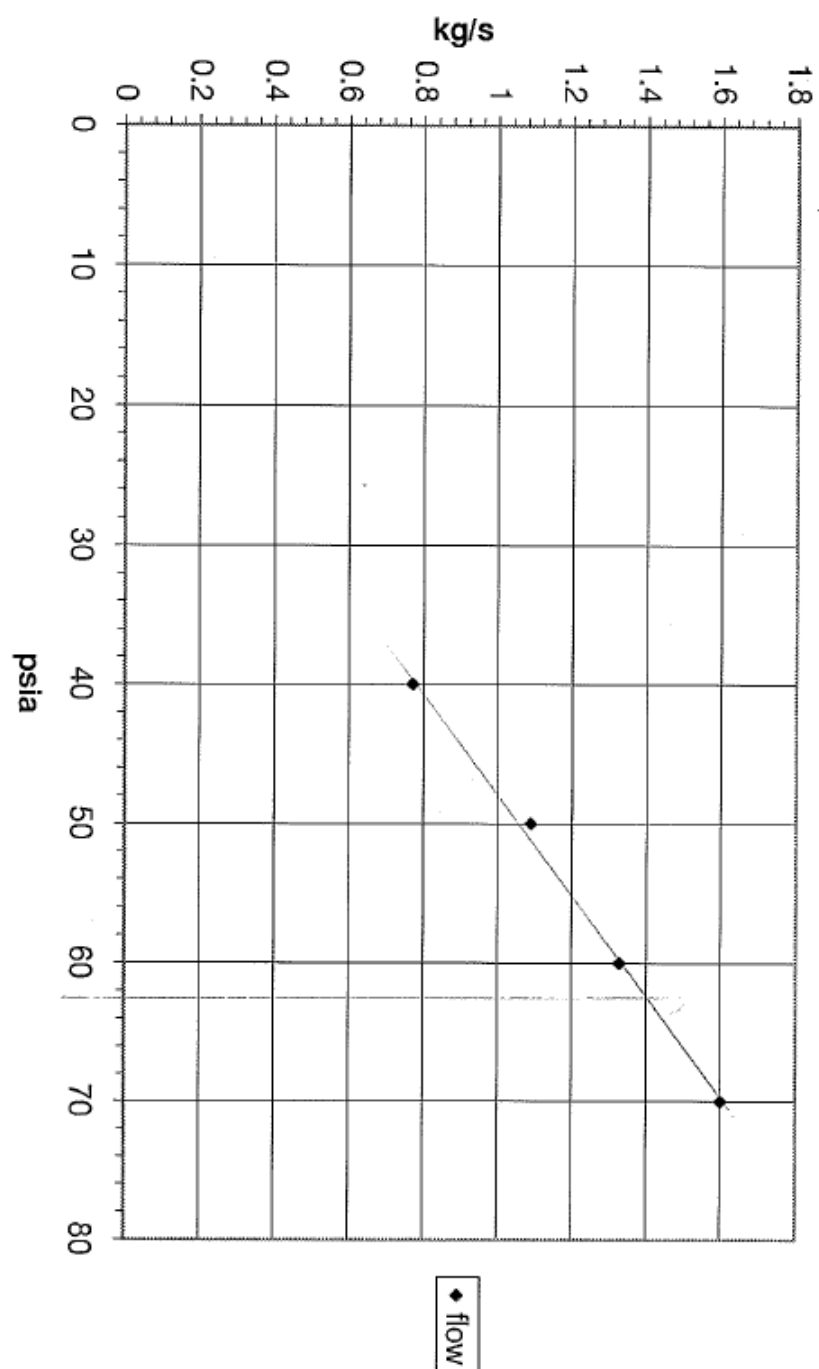
ratio  $e/d$  is approximately  $0.001 \text{ cm}/3 \text{ cm} = 0.0003$ . For pipes having  $e/d$  in this vicinity, the friction factor assumes an approximately constant value of  $(4f) = 0.015$  for Reynolds numbers of  $3 \cdot 10^6$  or higher. We will take all friction factors to be  $(4f_i) = 0.015$ .

In order to combine the factors in Table 1 to obtain an overall pressure drop for each riser, the pressure drops in each section will be rewritten in terms of the mass flow using the areas in Table 2.

$$\dot{m} = \rho v_i A_i$$

HELIUM (89)						
PRESSURE	TEMP	DENSITY	CV	VISC	CP	ENTHALPY
[atmos]	[K]	[Kg/m <sup>3</sup> ]	[J/g-K]	[uPa-s]	[J/g-K]	[J/g]
1.000	20.00	2.440	3.121	3.654	5.251	102.8
1.100	20.00	2.684	3.121	3.660	5.257	102.8
1.200	20.00	2.928	3.122	3.665	5.262	102.7
1.300	20.00	3.172	3.122	3.671	5.268	102.7
1.400	20.00	3.417	3.123	3.676	5.274	102.6
1.500	20.00	3.661	3.123	3.681	5.280	102.6
1.600	20.00	3.905	3.124	3.687	5.285	102.5
1.700	20.00	4.149	3.124	3.692	5.291	102.5
1.800	20.00	4.393	3.125	3.697	5.297	102.4
1.900	20.00	4.637	3.125	3.702	5.302	102.4
2.000	20.00	4.882	3.126	3.706	5.308	102.3
2.100	20.00	5.126	3.126	3.711	5.314	102.2
2.200	20.00	5.370	3.127	3.716	5.319	102.2
2.300	20.00	5.614	3.127	3.720	5.325	102.1
2.400	20.00	5.858	3.128	3.725	5.331	102.1
2.500	20.00	6.103	3.128	3.730	5.336	102.0
2.600	20.00	6.347	3.128	3.734	5.342	102.0
2.700	20.00	6.591	3.129	3.738	5.348	101.9
2.800	20.00	6.835	3.129	3.743	5.353	101.9
2.900	20.00	7.080	3.130	3.747	5.359	101.8
3.000	20.00	7.324	3.130	3.751	5.365	101.8
3.100	20.00	7.568	3.131	3.756	5.370	101.7
3.200	20.00	7.812	3.131	3.760	5.376	101.7
3.300	20.00	8.056	3.131	3.764	5.382	101.6
3.400	20.00	8.301	3.132	3.768	5.387	101.6
3.500	20.00	8.545	3.132	3.772	5.393	101.5
3.600	20.00	8.789	3.133	3.776	5.398	101.5
3.700	20.00	9.033	3.133	3.780	5.404	101.4
3.800	20.00	9.277	3.134	3.784	5.409	101.4
3.900	20.00	9.521	3.134	3.788	5.415	101.3
4.000	20.00	9.765	3.134	3.792	5.421	101.3

mass flow vs dewar pressure



## 5 UVA Functional Measurements and Tests

In the following section the results from UVA cooldowns and safety tests are reported. UVA has performed 10 separate cooldowns on this magnet and refrigerator system without safety incident. Several intentional forced quenching scenarios are investigated as part of the regular performance and characterization studies of the full system. Both Oxford (2015) and UVA (2015-2019) have performed several independent quench studies on this magnet to find the system responding within design parameters.

### 5.1 UVA Quenching Safety Tests

A quench is a quick termination of magnet operation that occurs when part of the superconducting coil enters the normal (resistive) state. This can occur because the field inside the magnet is too large, the rate of change of field is too large (causing eddy currents and resultant heating in the copper support matrix), or if a portion of the coils are heated above critical temperature. Scattered particles that go into the superconducting magnet can cause a quench. When this happens, that particular spot is subject to rapid Joule heating from the enormous current, which raises the temperature of the surrounding regions. This pushes those regions into the normal state as well, which leads to more heating in a chain reaction. The entire magnet rapidly becomes normal (this can take around 100 seconds, depending on the size and field of the superconducting coil). This is accompanied by a clunking sound as the energy in the magnetic field is converted to heat, and rapid boil-off of the cryogenic fluid. If a large magnet undergoes a quench, the inert vapor formed by the evaporating liquid helium fluid can present a significant asphyxiation hazard to operators by displacing breathable air.

Protection resistors and diodes are provided for all magnet sections, restricting the development of potentially high voltages in the event of a magnet quench. The resistors also dissipate most of the energy stored in the magnet during a quench thereby reducing the energy dissipation within the magnet windings. The resistors are mounted on baffles attached to the magnet support structure or on plates above the magnet itself and hard wired or coupled to the magnet via an electrical connector. The connector will also incorporate the wiring for the superconducting switch heater, making it impossible to run the magnet without the protection circuit attached. If barrier diodes are used in the protection circuit then, under limited voltage conditions, e.g. energization or de-energization of field and when the field is static, all the current passes through the magnet and ensures proportionality between energization current and magnetic field. As no current is flowing through the protection circuit the heat load from the protection resistors and hence system boil off are reduced. Under quench conditions, the barrier voltage is exceeded and the protection circuit shunts a proportion of the current away from the magnet windings.

As mentioned previously during a quench the 500 kJ is dumped into the liquid helium in the magnet dewar. The time it take for the energy to be dumped

is dependent on  $\tau = L/R$  the magnet decay constant where  $L$  is the inductance of the magnet and  $R$  is the total resistance. The total resistance is the sum of the resistance of the coil when in the normal state (non-superconducting). The quench protector circuit connect several segments of the superconducting magnet to the same number of resistor and diode pairs. The resistor in each segment is  $1/2 \Omega$ . The current needed to energize to 5 T is 74.5 A. This leads to a decay constant of  $\tau = 27$  s. This implies that the time to de-energize the magnet during a quench is about  $4\tau=108$  seconds. This safety is built into the quench protector circuit and prevents dangerous pressure from building into the magnet dewar giving the helium vapor adequate time to escape the vessel through the quench valves. This is a fail safe circuit as the resistors and diodes used in the system have been proven to be radiation hard and have worked for many many past experiments over a number of years by the University of Virginia and other groups at Cern, SLAC and Jefferson Lab [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. In some cases a magnet of the same era as the magnet for SpinQuest was used over 25 years in high intensity scattering experiments without issue.

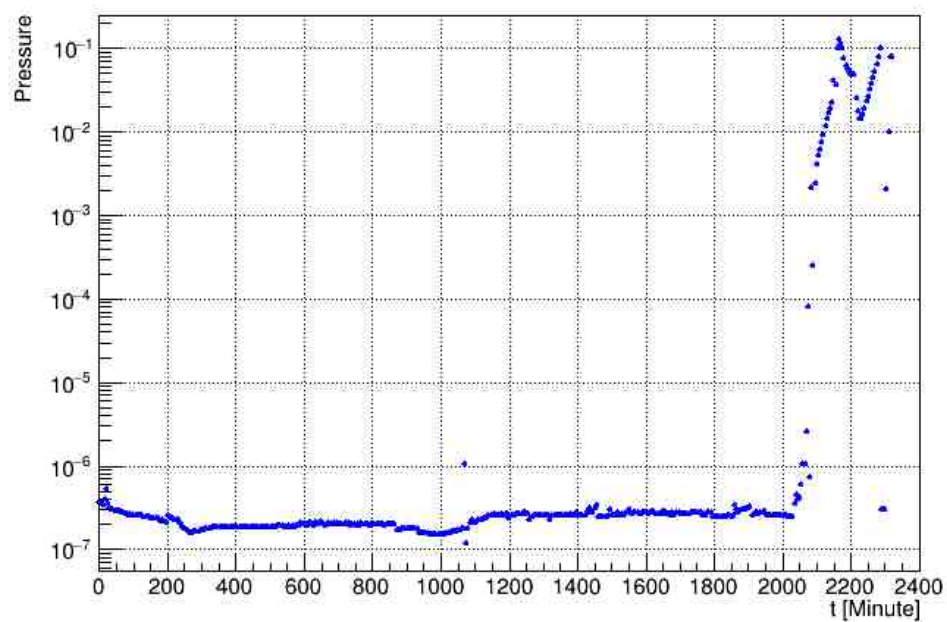
Vacuum loss studies have also been performed at UVA. The standard way to perform these studies involves cooling down the upper refrigerator seal so there is insulating vacuum loss. This cannot be compared to instantaneous vacuum loss from a ruptured beam window. The slow leakage from a frozen seal results in a vacuum loss over several minutes in most cases. An example of vacuum loss is shown in Fig. 5.1. This is induced by overfilling the liquid helium refrigerator so that the top seal get frozen and begins to let atmosphere in the vacuum space. When the superconducting magnet is ramped up and this type of vacuum loss takes place, the magnet will quench soon after as the liquid helium in the magnet dewar boils away quickly. Because it takes several minutes for the vacuum to rise the magnet boil off can be gradual in this case not building up notable excess pressure.

During a quench the helium vapor escapes through the quench valves so the pressure does not exceed much over 3 psi during the whole process. This pressure is measured on the relief line where the quench valves are connected. The pressure results as a function of time are shown in Fig. 5.1. These measurements are performed with two quench valves and one main open port for helium vapor exhaust. Several quench studies have been performed on the SpinQuest magnet. The initial Quench study was performed at Oxford with UVA present demonstrating standard quench and safety protocol. All other SpinQuest magnet characterization studies have been performed at UVA. The values reported in the plots are not precision measurements. We estimate a 10% uncertainty in these measurements.

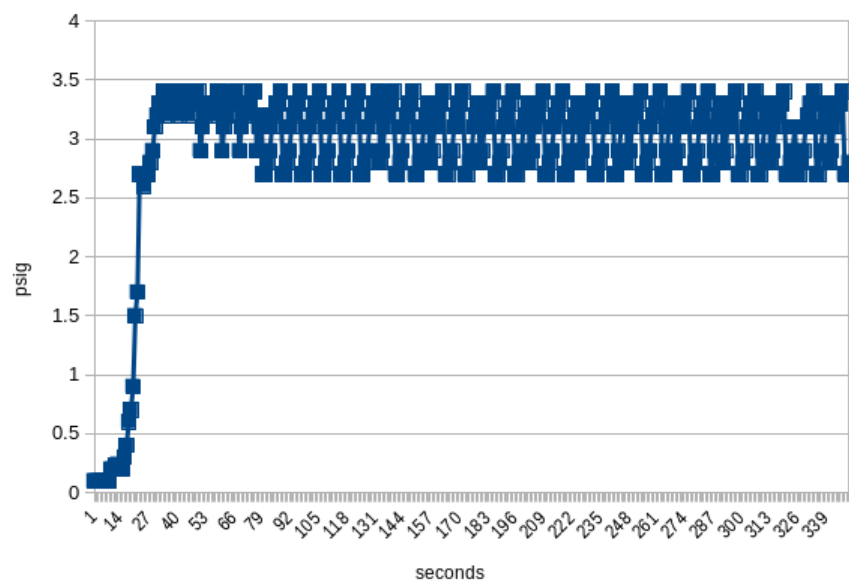
## 5.2 UVA Flow Measurements

UVA has also performed some standard operational flow measurements. These measurements are taken using MKS mass flow monitoring units during UVA cooldowns. These measurements have been studied during multiple cryogenic conditions and tested for repeat-ability. The numbers reported here are averaged

Pressure (Torr). vs. Time (minute)



Magnet Dewar Pressure



at similar operational conditions. All vessels have variable flows depending on how full the vessel is and what degree of vacuum insulation the system is running at. These numbers are for a vacuum of approximately  $1 \times 10^{-6}$  torr. Reported is the operation flow (OF) which is the normal flow recorded under standard operations, the maximum flow (Max) note that these flow meters are limited to 100 SLPm, the nominal range (NR) in percent of OF, and the estimated uncertainty derived from several measurements.

Vessel	OF	Max	NR	Error
Magnet (LHe)	10	20	50%	2%
Main (LHe)	20	100	50%	2%
Separator	20	100	50%	2%
Nitrogen Dewar (LN2)	5	10	10%	5%

## 6 Failure Mode and Effect Analysis

We need information from FNAL to produce these sheets.

### 6.1 Maximum Allowable Working Pressures

In the following table we list the MAWP for all parts that may have pressure limit pertaining to a safety issue. The normal operating pressure (NOP) is also specified. The source of the information is also provided. The Index provided is the part number or order number provided for confirmation.

For the bellows on the fridge the squirm pressure internally is 16.09 psi (30.79 psia). Here we list the bursting pressure is 104.3 psig as the MAWP. All units in the table are psia. Other theoretical limits in the table are based on the ANSI B31.3 design pressure formula.

Part	MAWP	NOP	Source	Index
Fridge Bellows	119	13.8	KeyHigh	PO187560
U-tube	3648	13.8	Cryofab	PO2116317
Separator	100	13.8	UVA	-
Nose Window	312.4	$10^{-4}$	UVA	-
Nitrogen Dewar	48809	14.7	Oxford	R260096
Helium Magnet Dewar	480	10972.19	Oxford	R260096
Insulating Vacuum	16	$10^{-8}$	Oxford	R260096

## 7 What-If Analysis

For the case of instantaneous loss of vacuum (LOV) of the large magnet dewar as much as 135 liquid liters could be vaporized instantly. In the worst case scenario all of the helium in the system is saturated liquid at 1.2 atm. When the LOV accident occurs the latent heat load is 33 kW. The volume of the liquid

is 55.8 liters. The mass of the system is constant until the relief valves open. At constant density the internal energy increases to 10.7 J/g, and the time it takes to get to 1.6 atm is only 0.2 seconds. It is assumed that only gas is vented through the relief valves. The enthalpy of the gas escaping the system is 29 J/g. The flow rate of the vent flow due to the loss of vacuum is 1132 g/s. The additional 200 g/s from the quench is added to this for a total of 1332 g/s.

If in the case that loose metal can be pulled into the magnet when the magnetic field ramped is up, it can easily become a projectile that could collide with the magnet and cause a LOV event. In addition, the thin beam window can also be punctured to result in a LOV event. However, in the case of any instantaneous LOV the resultant pressure change can not escape from out vacuum can. Because of the thick outer shell of the system, only the emergency relief will open to allow pressurized helium vapor to escape. This negates the risk in any area around the outer can (with the exception of the area around the plug).

### **Loss of Main Insulating Vacuum**

#### Initiation:

1. Turbo pump failure
2. Puncture of beam windows
3. Puncture of nose window
4. damage to vacuum space exterior

#### Automatic Response:

1. Gate Valve closes
2. Relief valve opens

#### Results of Failure:

1. Possible eruption of magnet dewar
2. cold pressurize relief at emergency valve
3. cold pressurized relief at beam windows

### **Loss of U-tube Insulating Vacuum**

#### Initiation:

1. U-tube pump-out seal failure
2. Puncture of U-tube



3. Bending damage

Automatic Response:

1. None (None Needed)
2. Seen in Refrigerator liquid level

Results of Failure:

1. No liquid helium to refrigerator
2. Only vapor transferred

### **Loss of Insulation Around Separator**

Initiation:

1. Refrigerator open to atmosphere
2. Refrigerator surrounded by warm helium gas
3. Nose window broken

Automatic Response:

1. None (None Needed)
2. Seen in other monitors

Results of Failure:

1. Venting helium vapor out separator relief
2. Venting helium out into the magnet

## **8 Summary**

In the case of the separator relief pipe, the calculations have concluded that the design is adequate for this experiment. Because the separator is split in to two tanks of Helium that would need to escape in the case of instantaneous insulating vacuum loss, even with a relief pipe of a smaller diameter, the design will still work, and will ensure that the relief pipe will not burst in a worst case scenario.

## **9 Figures**

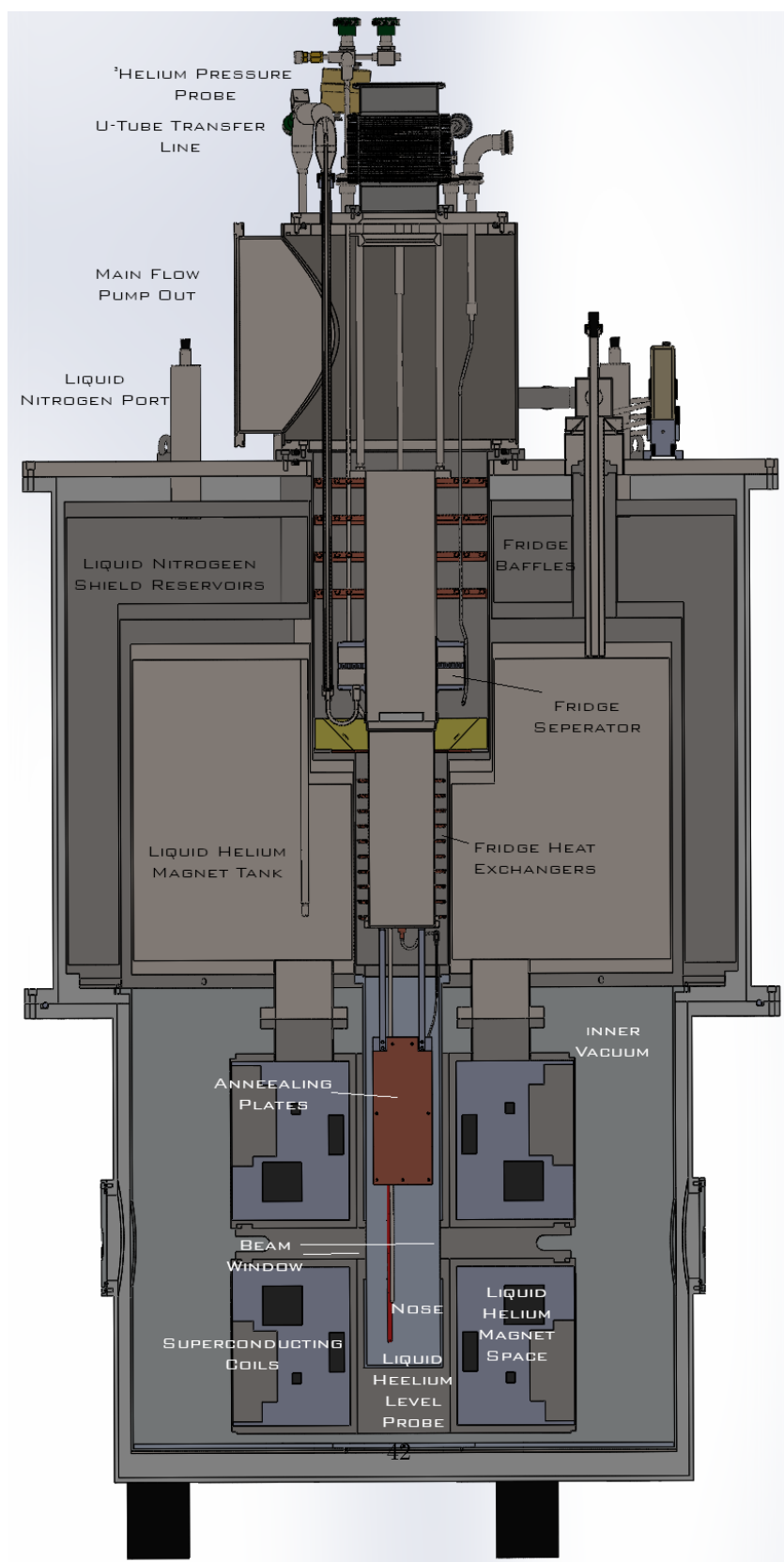


Figure 6: Magnet and refrigerator with no target insert

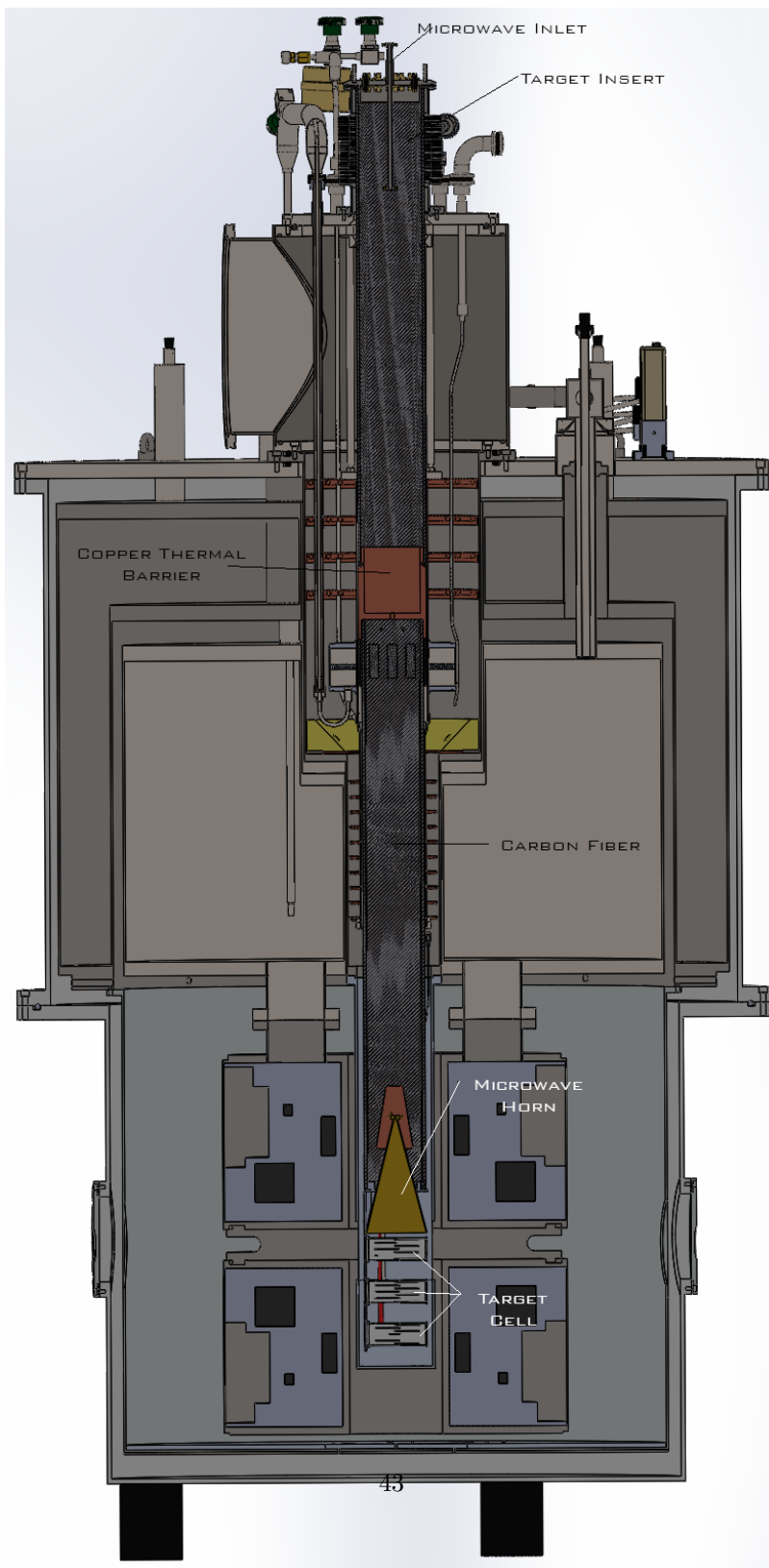


Figure 7: Magnet and refrigerator with the target insert

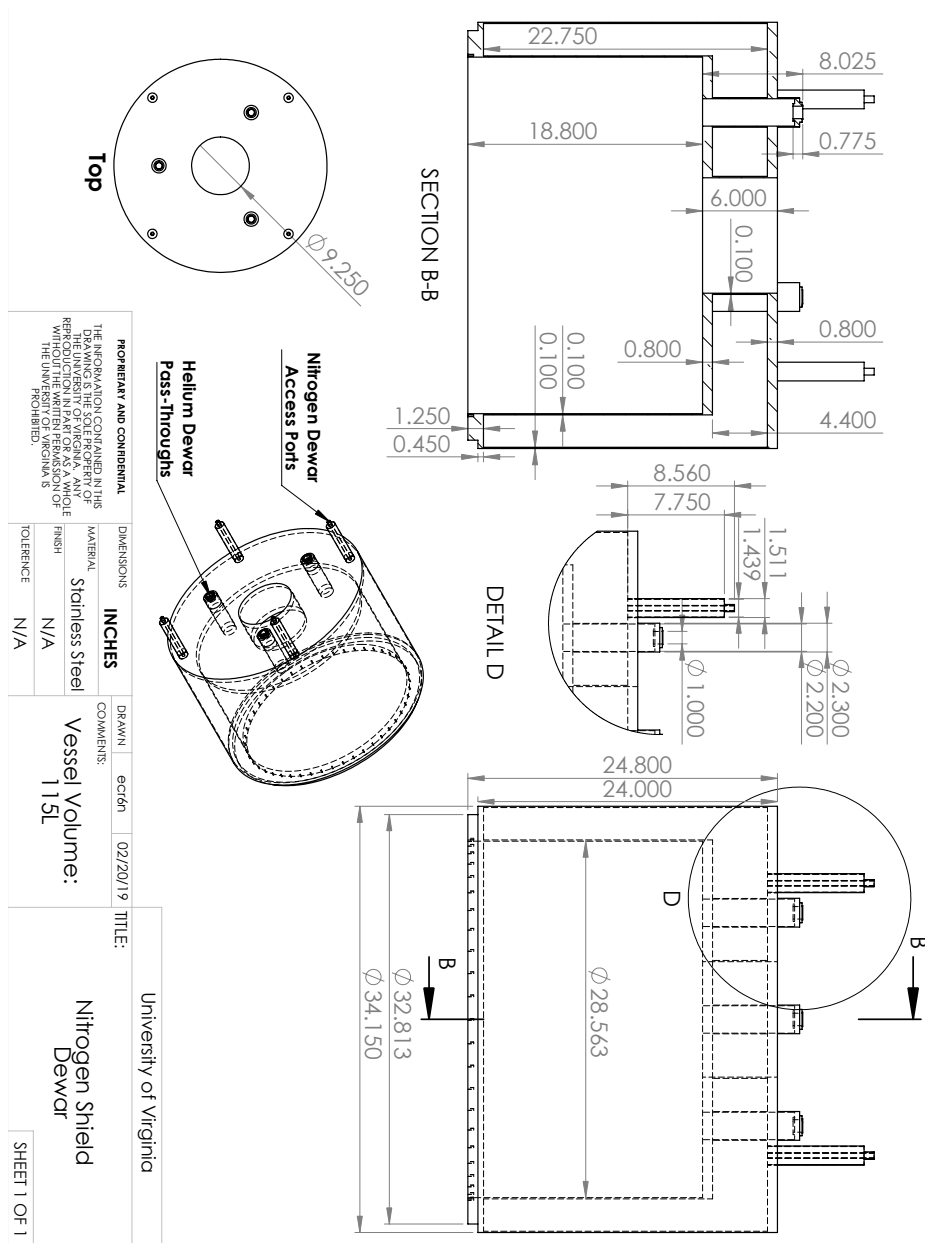


Figure 8: Nitrogen Shield Dewar is an annular volume that holds liquid nitrogen.

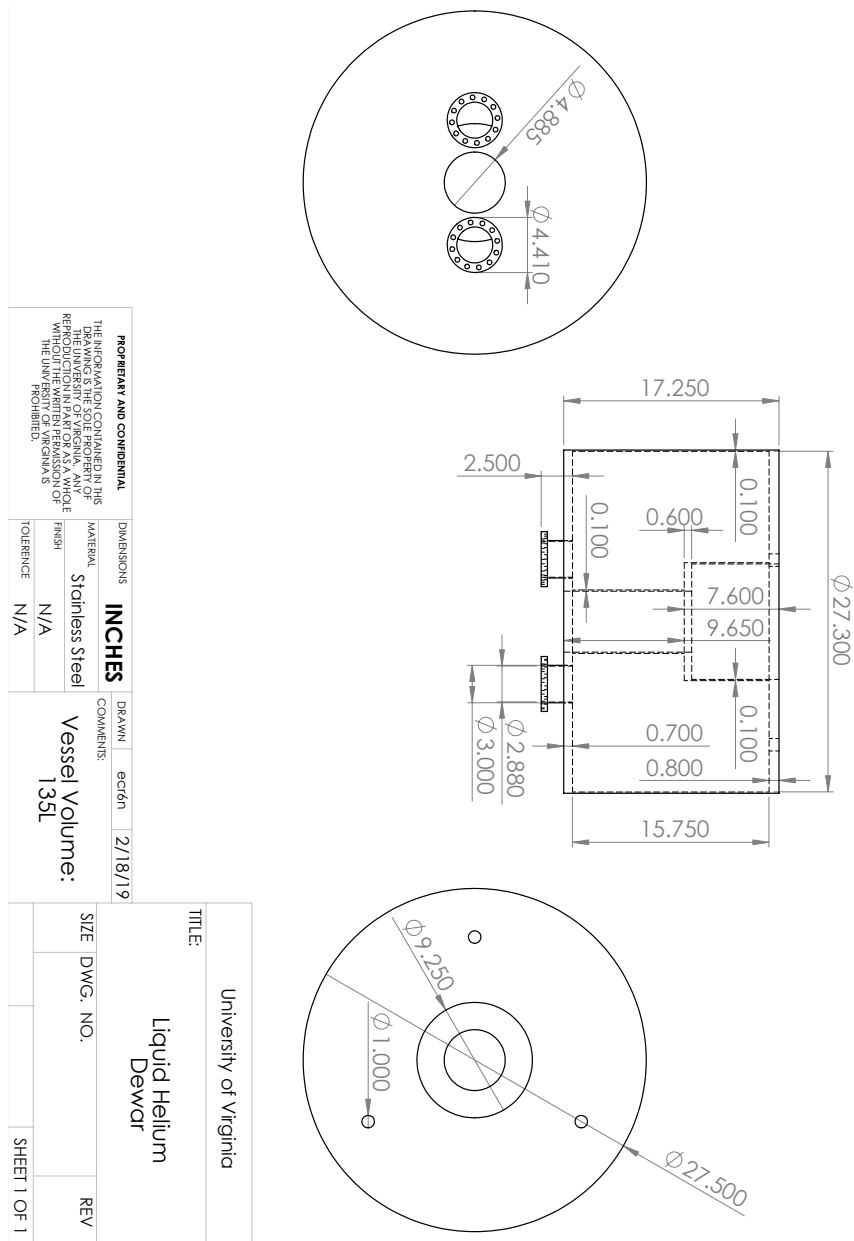


Figure 9: Liquid Helium Magnet Dewar(bottom, side, and top view). This is only the tank portion. In the bottom view the two indium connections to the coil portion can be seen. On the top view the tree ports for the risers can be seen.

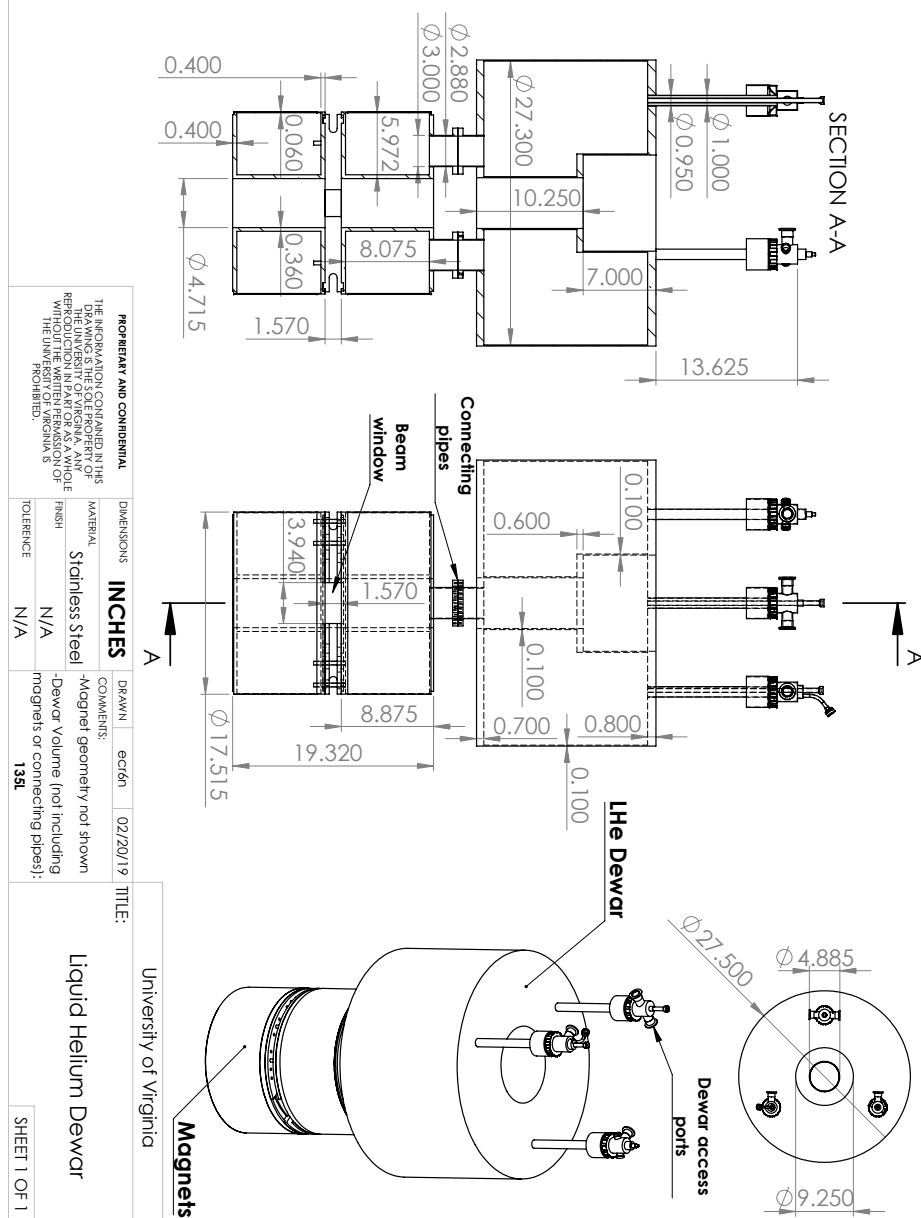


Figure 10: Liquid Helium Magnet Dewar (Side View). Here both the liquid helium tank and magnet coils can be seen. Both of these volumes contain liquid helium. Indium seals connect the volumes. This entire volume is surrounded in vacuum.

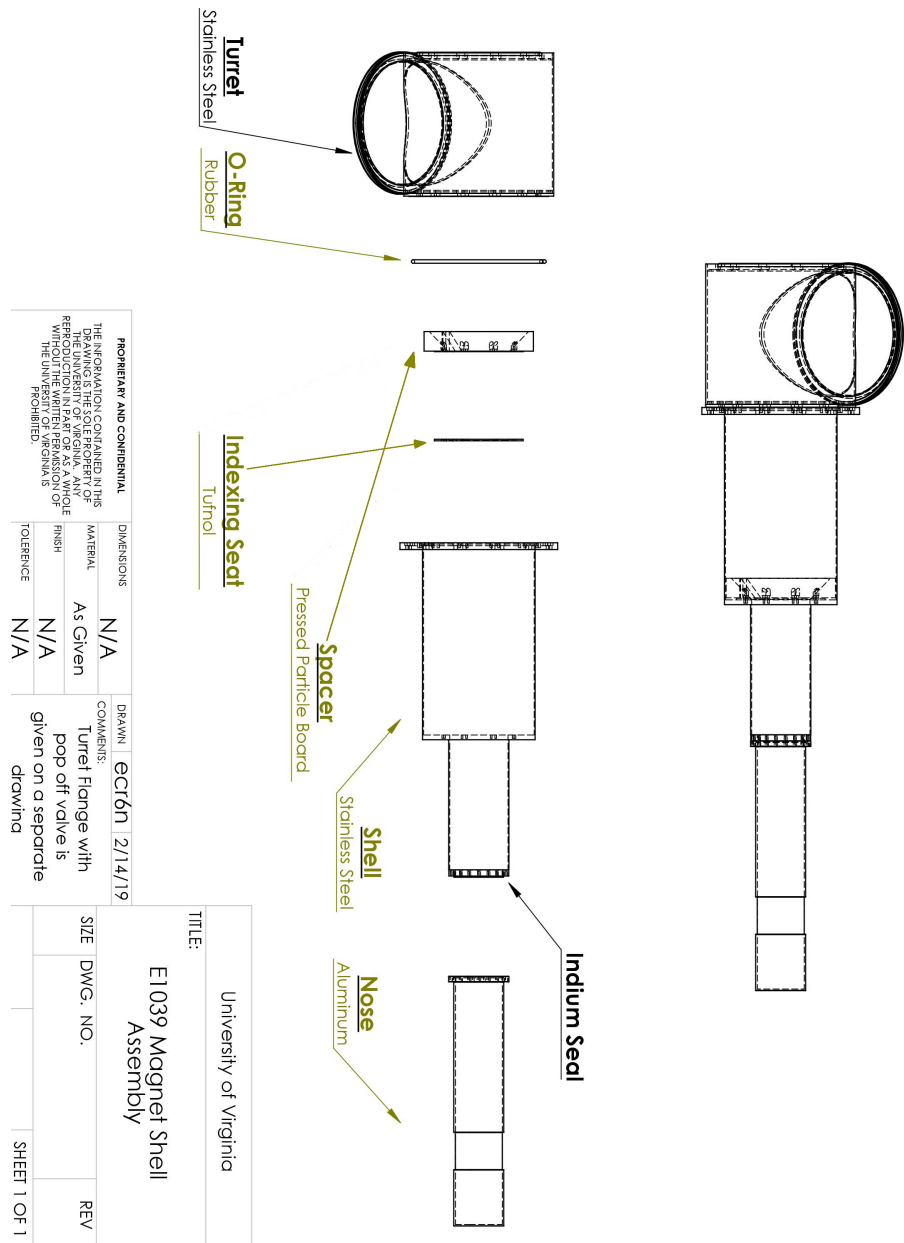
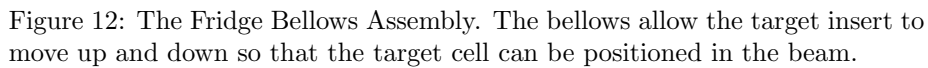


Figure 11: Refrigerator Shell Assembly showing the Turret which connects to the main pump out, the shell and nose which are connected with an indium seal, and the nose with a 12 mils window all the way around. The evaporation refrigerator sits in this volume.





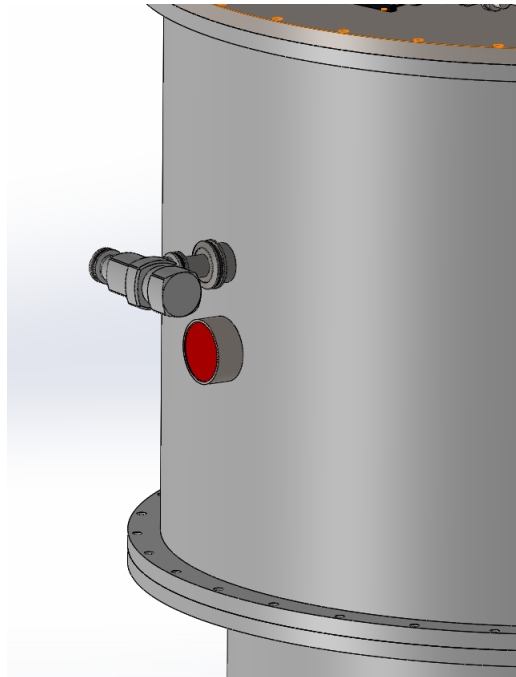


Figure 13: The pop off valve that will detach from the system in the event of IV loss. The valve can potentially erupt with cold pressurized helium vapor and should be shrouded to protect people in the area.

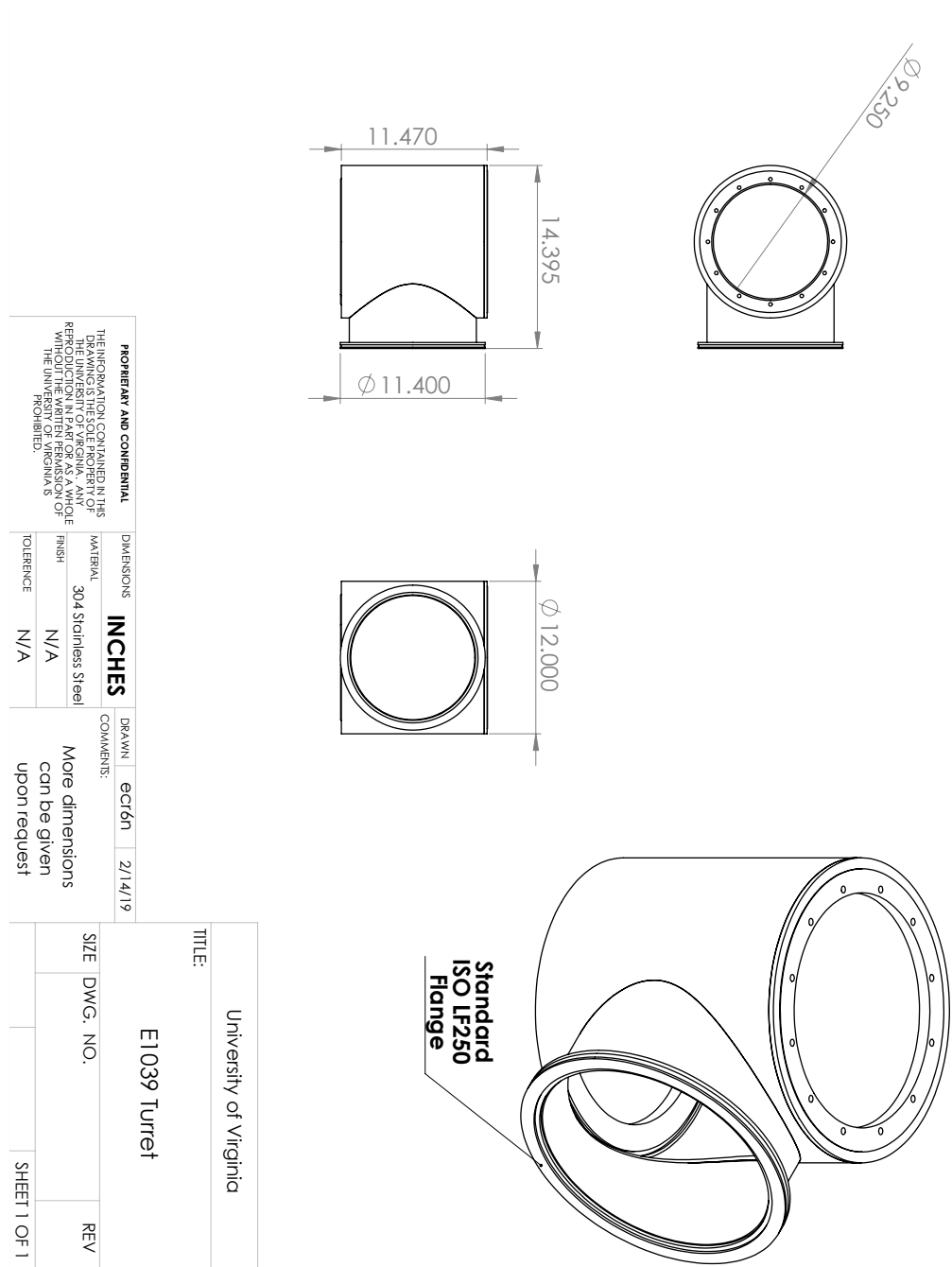


Figure 14: Drawing of the Turret. The Turret connects the evaporation refrigerator to the roots pumping system.



Full Name	ID	Type	Fluid	Design Pressure	Component Rating	Manufacturer	Model Number	Set Pressure/Range	Size	Capacity
Turbo Molecular Pump	TMP-1	Pump	A	NA	NA	Pfeiffer	TMU 1001 P	NA	Inlet: DN 200 ISO-K Outlet: DN 40 ISO-KF Venting: G 1/8"	N2: 920 l/s He: 920 l/s H2: 720 l/s
Gate Valve	GV-1	Gate Valve	A	1e-8 torr	7.5e-10 torr	VAT Valve	09140-JE08	NA	4"	NA
Pressure Relief Valve	PRV-1	Relief Valve	V	2.72	NA	Oxford	NA	1 atm	5.4 in <sup>2</sup>	NA
Mass Flow Meter	MFM-1	Mass Flow Mtr	He4	2 psig	500 psig	Teledyne Hasting	HFM-305	NA	1" NPT Male	0-1000 slm
Rotary Vane Pump	RP-1	Pump	He4	NA	NA	Oerlikon Sogevac	SV630 B	NA	Inlet: N 100 ISO-K Outlet: N 100 ISO-K	755 m <sup>3</sup> /h
Root Pump	RP-1	Pump	He4	NA	NA	Oerlikon	RUVAC WH 7000	NA	Inlet: DN 320 ISO-K Outlet: DN 160 ISO-K	8400 M <sup>3</sup> H <sup>-1</sup>
Root Pump	RP-2	Pump	He4	NA	NA	Oerlikon	RUVAC WH 7000	NA	Inlet: DN 320 ISO-K Outlet: DN 160 ISO-K	8400 M <sup>3</sup> H <sup>-1</sup>
Root Pump	RP-3	Pump	He4	NA	NA	Oerlikon	RUVAC WH 7000	NA	Inlet: DN 320 ISO-K Outlet: DN 160 ISO-K	8400 M <sup>3</sup> H <sup>-1</sup>
Pressure Relief Valve	PRV-2	Relief Valve	He4	NA	NA	Oxford	A3-202	3.48 psi	KF40	1.95 in <sup>2</sup>
Manual Valve	MV-1	NV	He4			Not Defined				
Gate Valve	GV-2	Gate Valve	He4	1e10~3 torr	1e-11 torr	MDC Vacuum	307008-01	NA	10" ID	NA
Mass Flow Meter	MFM-2	Mass Flow Mtr	He4	2 psig	500 psig	Teledyne Hasting	HFM-305	NA	1" NPT Male	0-1000 slm
Check Valve	CV-1	CV	He4	2 psig	4500 psi	Generant Co.	CV-1000SS-FS-0.15 EI8	NA	1" NPT Female	NA
Check Valve	CV-2	CV	He4	2 psig	4500 psi	Generant Co.	CV-1000SS-FS-0.15 EI8	NA	1" NPT Female	NA
Check Valve	CV-3	CV	He4	2 psig	4500 psi	Generant Co.	CV-1000SS-FS-0.15 EI8	NA	1" NPT Female	NA
Mass Flow Controller	MFC-1	Mass Flow Controller	He4	Upstream: 2.14 psi Downstream: 0 psi	500 psig	Teledyne Hasting	HFM-303	NA	1/2" STD Swagelok	0-1000 slm
Needle Valve	NV-1	NV	He4							
Needle Valve	NV-2	NV	He4							
Diaphragm Pump	DP-1	Pump	He4	1 ± 20% psig	14 psig	KNF Dual Diaphragm	KNF NO150.1.2AN.12E	NA	Thread size G 1/4"	130 ± 30% slm @ 1 atm
Insulating Vacuum Pressure	A	Sensor	V	NA	NA	Pfeiffer	MP7200AR	NA	DN 25 ISO KF	
3He Pressure Probe	B	Probe	He3	NA	NA	UVA Custom	NA	NA		
4He Pressure Probe	C	Probe	He4	NA	1000 torr	MKS Instruments	690A12 TRA	NA	1/2" STD Swagelok	
4He Pressure Probe	C	Probe	He4	NA	100 torr	MKS Instruments	690A12 TRA	NA	1/2" STD Swagelok	
Pressure Sensor	D	Sensor	He4	NA	NA	Oerlikon				

Figure 16: Instrumentation List for the P&ID

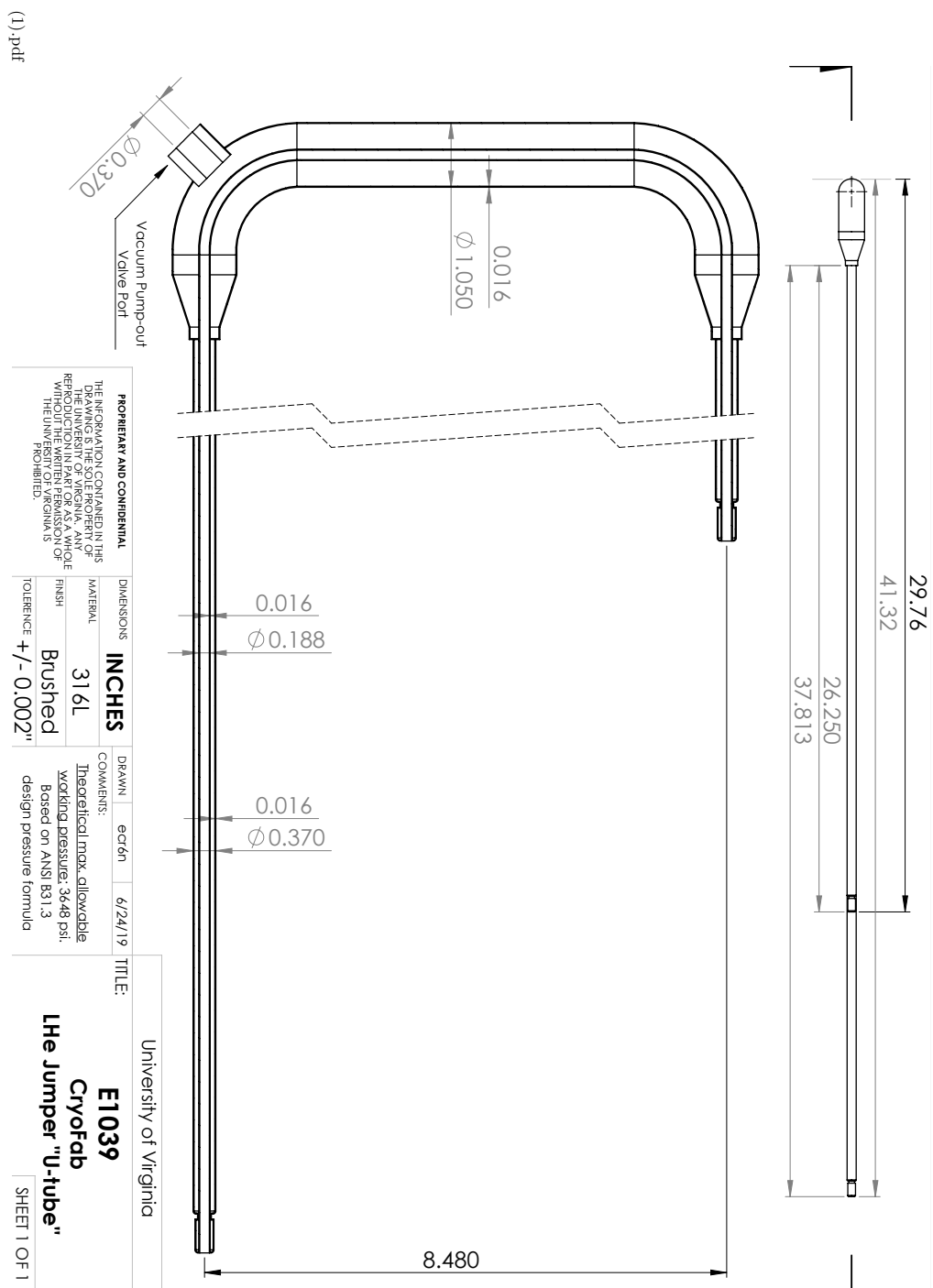
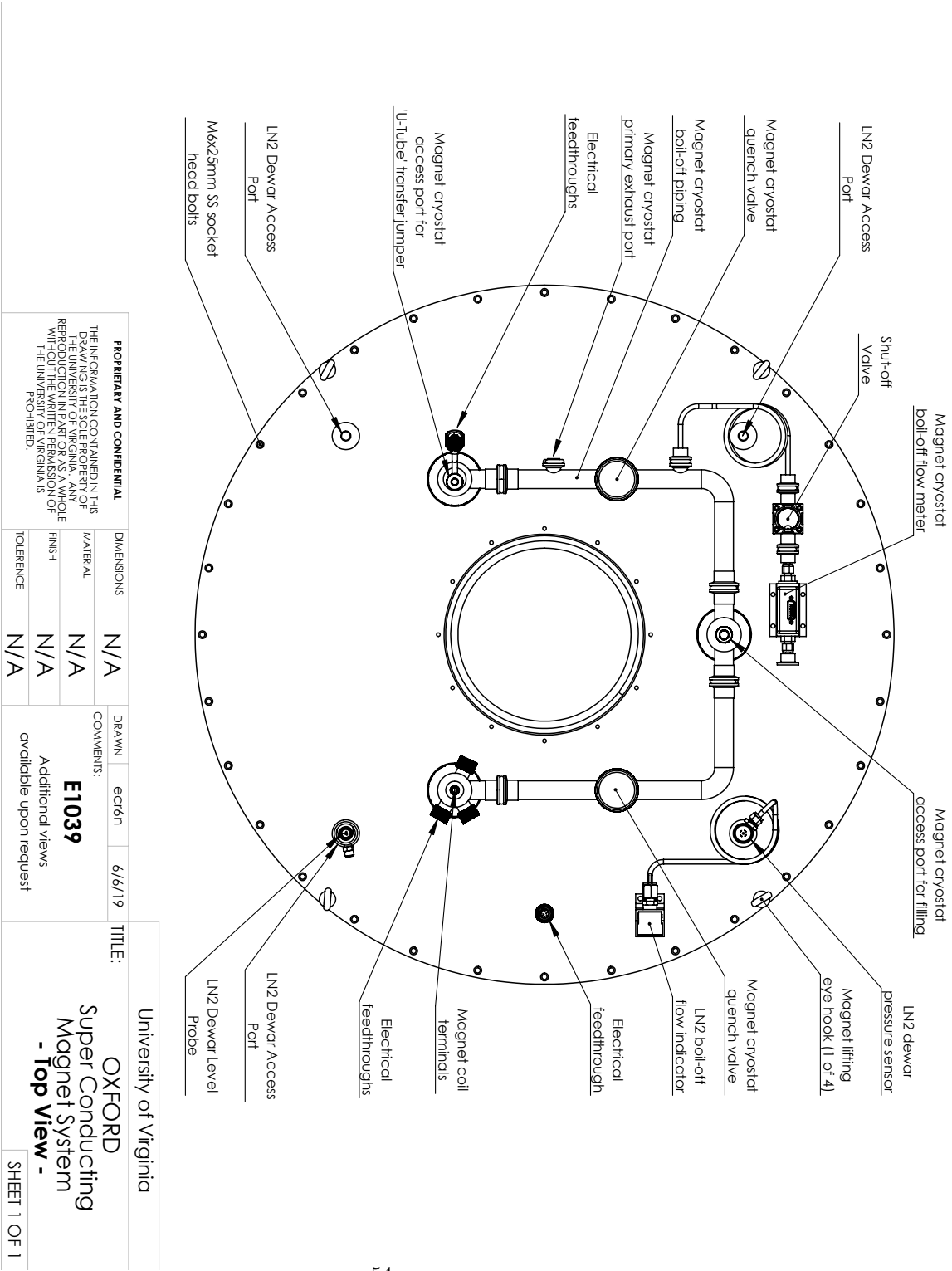


Figure 17: LHe Jumper



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Figure 18: Top view of superconducting magnet and top flange.

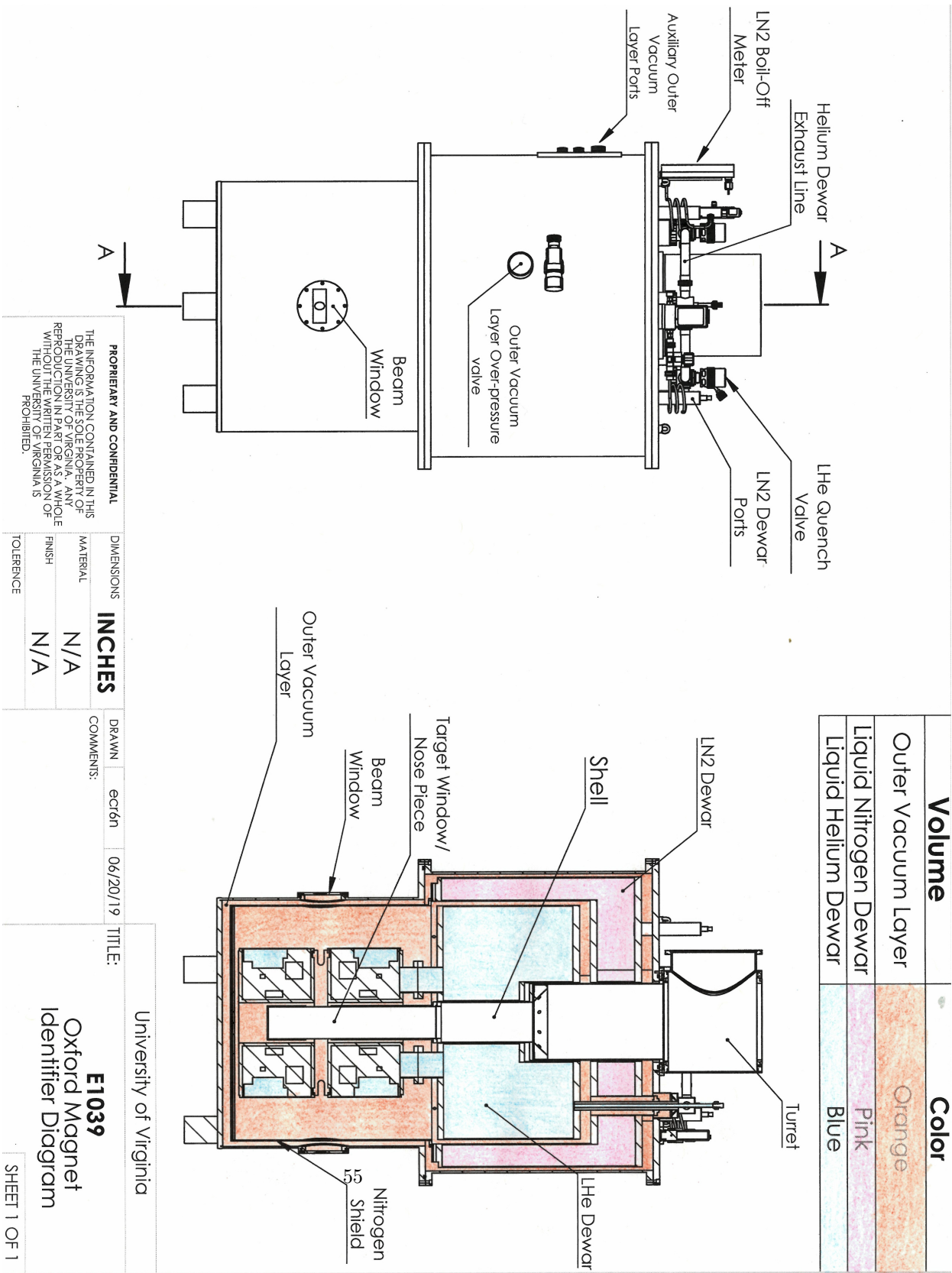


Figure 19: The Insulating Vacuum: All Orange space represents the insulating vacuum layer.

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