The Heat Loss Analysis and Commissioning of a Commercial Helium Dewar

Marcus Bellamy

University of New Mexico

U.S. Department of Energy

Stanford Linear Accelerator Center

Menlo Park, California

Science Undergraduate Laboratory Internship (SULI) Program

August 15, 2005

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Science Undergraduate Laboratory Internship under the direction of Helen Quinn at Stanford Linear Accelerator Center.

Participant: _____
Signature

Research Advisor: _____
Signature

Table of Contents

Abstract	iii.
Introduction	1
Materials and Methods	2
Results	5
Discussion and Conclusion	8
Acknowledgements	9
References	9
Tables	10
Figures	11

Abstract

A low temperature cryostat suitable for many different experiments will be commissioned at the cryogenic test facility at SLAC. The scope of the project is to make commission a commercial Helium dewar. The building of the top flange will be followed from its design phase through to its finished assembly. In addition, diagnostic tools such as thermometry, level detector, pressure gauge, transfer lines for He and N₂, vent lines with relief valves for He and N₂ will be incorporated. Instrumentation to read and plot this data will also be included. Once the cryostat is assembled, we will cool down the cryostat to measure its performance. A typical consumption rate of Helium will be measured and from this, the overall heat leak to the dewar will be calculated.

A processing instrumentation diagram (PID) of the dewar system was created with SolidEdge and was later approved and published as an official SLAC document. The plots comparing the liquid level changes of the 36 inch probe with the time and the heat loss as a function of time proved to be a valid indication that the data was interpreted and recorded correctly and that the dewar was put together successfully.

Introduction

A cryostat is a mechanism used to operate something under a controlled low temperature. A dewar is a form of a cryostat that is used to hold a liquid cryogen. In this case, the dewar will hold both liquid nitrogen and liquid helium. Between the two liquids are insulation and two vacuums. Insulation is needed to help remove existing paths of infrared radiation, while the vacuums are needed to minimize convection and conduction by removing air. Intermediate thermal temperature shields, which are made of materials with low emissivity, are also put into place to ward off radiation. A good portion of the dewar material is stainless steel, due to its low conductivity, good impact strength and a high tensile modulus.

While in the designing process of a dewar, it is important to understand and consider the many thermodynamic, chemical, physical, mechanical, and safety properties, in order to optimize the performance of the dewar and to maintain its reliability. While in the process of fine-tuning the design, one method of examining the performance could be to determine the typical consumption rate of Helium and compare it with a heat loss calculation.

The two primary fluids used in the cryostat design are liquid nitrogen and liquid helium. Nitrogen, as a gas, makes up 80% of the atmosphere. Liquid nitrogen is an essential intermediate chemical (precoolant) used for helium liquefaction. Some safety issues directly related with the managing of liquid nitrogen include asphyxiation, overpressure and frostbite. Overpressure could occur if the liquid nitrogen is enclosed in a container where there is no outlet or vent line (such as a relief valve) in place. If not given some path to allow the evaporation to leave, the pressure may soon build up to the

point where the container will explode. Frostbite can occur if proper handling of the liquid nitrogen is not undertaken. At the normal boiling point of nitrogen, its temperature is 77.347 K and its pressure is 1 atm. While the temperature outside of the dewar will be ambient, the inner nitrogen jacket will be cooled down by the liquid nitrogen to a consistent temperature very close to 77 K. The low temperature of liquid nitrogen will be used to maintain the very low temperature of liquid helium.

Helium is the second most common element in the universe. However, it is uncommonly found on earth because it does not combine with other elements and it is very light and very fast, allowing much of it to escape. Helium's boiling point at 1 atm is 4.224 K. Liquid helium has a high compressibility and a low viscosity. Helium also has the ability to become a superfluid, in which the thermal conductivity approaches infinity and the viscosity approaches zero. It is considered to be a superfluid if cooled below a temperature of 2.177 K (considered to be at its lower Lambda point). Normal helium is regarded as He I, while superfluid helium is regarded as He II.

Given the precautions and necessities of safely maintaining these two elements in their liquid state and maintaining consistent temperatures at designated areas, reasonable assumptions can be made on the ramifications of the dewar's performance.

Materials and Methods

Before the manufacturing process, the cryostat assembly was designed using the advanced CAD software known as Solid Edge. The CAD design included the dewar, top flange, thermometry, level detector, pressure gauge, transfer lines for He and N₂, and the vent lines with relief valves for He and N₂. This design was called a processing

instrumentation diagram (PID). Designing the top assembly on computer-based software before manufacturing is a safe, logical, and cost-effective way to understand the feasibility behind the design.

The manufacturing process initiated by welding the utility ports and installing the baffles to the top flange. The first baffles made were simply test baffles used only while examining the cryostat's viability. These test baffles were made of fiber glass and were encased with aluminum sheets, in order to improve reflectivity. There were a total of 8 baffles in a layered sequence, connected to the top flange by steel rods and bolts. An assembly stand was constructed to elevate the top flange while adding/modifying its surrounding components and to safely store the flange with baffles when removed from the inside of the dewar. Since the dewar height (without the adapter and top flange) is 60 inches, the assembly stand was set to be 59 inches. The inside of the depth of the dewar is 48 inches, so the inner components of the top flange were kept well below this dimension to provide sufficient space for the liquid helium.

The top flange is comprised of stainless steel with a cylindrical base and several ports, which are suitable for housing of relief valves, a pressure gage, liquid-level indicators, and a He transfer line. The ports were welded on the flange and the regions along connecting edges were fused to assure minimal leakage. The adapter flange (riser), also made of stainless steel, was also fabricated and is connected to the bottom surface of the top flange. The riser is a wide-body, hollow cylinder with 6 input/output ports, in place for additional feedthroughs to carry out the experiment. Each of the flange and riser parts underwent cold tests, to ensure that their material composition could handle the low

temperatures involved in the experiment. When each of the flange and riser ports are not being used, they are blanked off with a metal plate and an o-ring.

Next, the riser was fastened onto the dewar and the top flange was fastened onto the riser, in order to first ensure that the dewar was vacuum tight by pumping out any accumulated air. The pumping process was done by connecting a Tops turbo pump to the dewar vacuum. The Tops base pressure was 5×10^{-5} Torr, while the dewar base pressure was 2.8×10^{-4} Torr. The vacuum pump was then disconnected and the vacuum port was blanked off. A Lexan (polycarbonate) cover was made for the top of the dewar when missing the flange and riser.

Once the vacuum check was complete, the part for liquid helium level probe was machined and assembled. The probe needed to be surrounded by a metal covering in order to manage the extremely low temperature. The baffles were initially greater in diameter than necessary, and their diameter length was abated and tailored to fit scarcely smaller than that of the riser's inner diameter.

Following this, the main vacuum valve, along with blank flanges, were installed onto the flange for leak testing. The UL 100 leak checker was connected to the dewar's inside via transfer line through valves and the dewar was then pumped down. The vacuum pump was used to draw out any moisture and atmospheric build-up in the dewar. The leak detector was then used to find any leaking joints which were then fixed until the dewar was vacuum (leak) tight.

After the vacuum leaks were adequately minimized, tubing from the helium feed on the dewar was connected to the helium suction line to provide helium backfill. The manufactured liquid level probe was also installed onto the cryostat as well as a liquid

level probe used in previous cryogenic experiments. The newer probe has six pins, and only four were needed. Therefore, to avoid heat leak from the two unused pores, the remaining pins were filled with epoxy. The helium vessel was pumped via a vacuum pump and backfilled with helium three times to reach a desired pressure below 2×10^{-1} Torr. Alongside the dewar nitrogen fill line was gradually filled with liquid nitrogen, to get down to a temperature of 77 K. The excess liquid nitrogen was sent through copper tubing, which led to the outside. A T-valve was attached to the copper tubing, in order to have the ability to open the valve and know when to stop cooling when the temperature reached 77 K. The first pump down reading was 2.6×10^{-1} Torr, the second at 2.2×10^{-1} Torr, and third at 1.9×10^{-1} Torr.

After the cooling process brought the inside of the dewar near 77 K, the liquid helium was transported to the dewar helium fill port using a transfer line secured by two flanges at each end. Beside the liquid helium tank was a helium gas tank, which fed to the liquid helium tank to maintain a high enough pressure to transfer the helium to the dewar.

After reaching a temperature close to 4.2 K, the helium liquid levels were monitored and recorded using the two intact liquid level probes. Each of the two liquid level probes were pin-connected to an electrical output, which relayed the level of the liquid helium.

Results

Two liquid level probes were installed onto the dewar, one 30 inches long and the other 36 inches long. When the reading of the 30 inch probe was 100% (99.9%), the reading of the 36 inch probe was at about 83% (82.7%), which was a good signification that the probes were displaying accurate level indications. The 36 inch probe was filled to

90.4%, and the corresponding time, pressure inside the dewar system, and liquid levels were recorded. After this point, the time, pressure and liquid levels were recorded every half an hour at first, and then every hour after the rate of helium loss decreased. The pressure stayed between 814-824 Torr. Periodically, the liquid nitrogen jacket was re-filled to maintain the low temperature. It took about four days and 8 hours (104 hours) for the liquid helium to completely run out.

Since the desired units were metric, the pressure was converted from Torr to pascals. The lower and upper pressures were converted as follows:

$$814\text{Torr} \times \frac{1\text{atm}}{760\text{Torr}} \times \frac{1.013 \times 10^5 \text{ Pa}}{1\text{atm}} = 1.085 \times 10^5 \text{ Pa}$$

$$824\text{Torr} \times \frac{1\text{atm}}{760\text{Torr}} \times \frac{1.013 \times 10^5 \text{ Pa}}{1\text{atm}} = 1.098 \times 10^5 \text{ Pa}$$

The *Handbook of Cryogenic Engineering* provided a table of different densities and latent heat (heat of vaporization) values in correspondence to various temperatures and pressures. An average pressure value of $1.089 \times 10^5 \text{ Pa}$ was a good estimate for reference to the tabulated values. For a liquid helium pressure of $1.089 \times 10^5 \text{ Pa}$ (which is equal to a temperature of about 4.3 K), the liquid density is $123.4 \frac{\text{kg}}{\text{m}^3}$, the saturated density is 18.17

$\frac{\text{kg}}{\text{m}^3}$, the liquid heat of vaporization is $0.1045 \times 10^5 \frac{\text{J}}{\text{kg}}$, and the saturated heat of

vaporization is $0.3071 \times 10^5 \frac{\text{J}}{\text{kg}}$. Latent heat (heat of vaporization) is the amount of heat

required to convert the unit mass of a liquid into the vapor without a change in

temperature. It requires converting something in a more organized state (as a liquid) to something with more spontaneity.

The volumetric flow rate was also calculated, which involved using the probe height of 30 inches, the dewar's inner jacket diameter, and the time. The 36 inch probe was primarily used to test against the 30 inch probe, so only the liquid levels of the 30 inch probe were used for further analysis. Steps to obtaining the volumetric flow rate and sample volume flow rate calculations are below:

Volume when 30 inch level probe at 100%:

$$V = \pi r^2 h = \pi \times \left[14 \text{ in} \times \frac{.0254 \text{ m}}{1 \text{ in}} \right]^2 \times 30 \text{ in} \times \frac{.0254 \text{ m}}{1 \text{ in}} = 0.303 \text{ m}^3$$

Volume when 36 inch level probe at 100%

$$V = \pi r^2 h = \pi \times \left[14 \text{ in} \times \frac{.0254 \text{ m}}{1 \text{ in}} \right]^2 \times 36 \text{ in} \times \frac{.0254 \text{ m}}{1 \text{ in}} = 0.363 \text{ m}^3$$

The volumetric flow rate from 11:20-12:20pm:

$$q = \frac{\Delta V}{\Delta t} = \frac{(0.1850 - 0.1825) \text{ m}^3}{3600 \text{ s}} = 6.73 \times 10^{-7} \frac{\text{m}^3}{\text{s}}$$

After calculating the volumetric flow rate, and looking up the corresponding densities and latent heat values, the heat loss, Q , was found using the following equation:

$$Q = q \rho H_{\text{vapor}} = q \rho (H_{\text{SAT}} - H_{\text{LIQ}})$$

The units for heat loss are joules, and a sample calculation of the heat loss for the same time increment above (11:20-12:20pm) is shown below:

$$Q = 6.73 \times 10^{-7} \frac{\text{m}^3}{\text{s}} \times 123.4 \frac{\text{kg}}{\text{m}^3} \times (0.3071 - 0.1045) \frac{\text{J}}{\text{kg}} = 1.682 \times 10^{-5} \text{ W}$$

A graph of Q vs. t (time) was created to find out if the plot characteristics were typical or desired for dewar experimentation.

Discussion and Conclusion

After several drafts, a processing instrumentation diagram (PID) was successfully created with SolidEdge. It was later approved and published as an official SLAC document. This drawing will serve as a good reference for any future experiments on the blue dewar.

Because of recurring leaks in the beginning, the dewar components were disassembled and reassembled several times, which was the longest process of the project. However, it is common for leak checking to be a lengthy process to ensure the viability of the dewar, and therefore obtaining accurate results in experiments and it is worth the extra time reserved to this process.

There was a minor set-back of having to disassemble the baffles, which involves taking them apart individually, simply because they were not covered with aluminum sheeting. Having covered them prior to connecting them to the flange rods would have saved time. Another minor set-back was the waiting process for the liquid helium to arrive.

A plot was created comparing the liquid level changes of the 36 inch probe with the time, in order to ensure that the points fashioned a gradually sloping curve. Since the graph did indeed reveal a steadily sloping curve, it was a good indication that the data was interpreted and recorded correctly.

As viewed from the plot of the heat loss as a function of time, there were no major fluctuations in heat loss. Theoretically, the heat loss should decrease as the path from the top flange extends down to the helium jacket, since the top of the flange is close to room temperature (298 K), while the bottom is close to 4.2 K. Moreover, the heat loss also

lowers after passing the baffles. The plot validated this idea because the heat loss did decrease considerably with time, meaning that as time passed, the heat loss was closer to the bottom of the helium jacket. Although some of the points were noticeably out of the realm the fit curve, the heat loss scale is in 0.2 increments, meaning that the points that were away from the expected flow of the curve were only off by a small fraction of a watt.

Acknowledgements

I offer my thanks to the U.S. Department of Energy and the SULI program for granting me the opportunity to undergo research here at the Stanford Linear Accelerator Center. A special thanks to my mentors, EunJoo Thompson and John Weisend, for providing me with their knowledge, support, and a meaningful experience through this research project. I appreciate the efforts that Michael Racine and Ron Rogers put in helping me with the project and their continuous patience and comedy. I would like to thank James Lindesay and Helen Quinn for optimizing my overall interning experience. Finally, I would like to thank each individual of the SULI program and each member of the French House for making this a memorable and fun summer.

References

- [1] Flynn, M. Thomas, "Cryogenic Engineering," Marcel Dekker, Inc., 1997
- [2] Weisend II, G. John, "Cryogenic Properties of Materials," 2003 CA Short Course Symposium, September 16, 2003.
- [3] Weisend II, G. John, "Handbook for Cryogenic Engineering," Taylor and Francis, 1998.

Tables

Time (hr)	<u>36in LL</u> (%/100)	<u>30in LL</u> (%/100)	<u>Pressure</u> (kPa)	<u>36in Volume</u> <u>Flow Rate</u> (m³/s)	<u>30in Volume</u> <u>Flow Rate</u> (m³/s)	<u>36in Heat</u> <u>Loss (W)</u>	<u>30in Heat</u> <u>Loss (W)</u>
0.00	0.904	0.996	109.30	0.000000000	0.000000000	0.000	0.000
1.00	0.899	0.996	109.03	0.000000420	0.000000000	1.051	0.000
2.00	0.892	0.996	109.70	0.000000294	0.000000000	0.736	0.000
3.00	0.884	0.996	109.83	0.000000224	0.000000000	0.561	0.000
4.00	0.873	0.996	109.16	0.000000231	0.000000000	0.578	0.000
5.00	0.860	0.995	109.03	0.000000219	0.000000020	0.547	0.050
6.00	0.851	0.993	108.76	0.000000126	0.000000034	0.315	0.084
15.50	0.824	0.881	110.23	0.000000146	0.000000729	0.366	1.823
16.50	0.777	0.874	109.56	0.000000240	0.000000043	0.599	0.107
17.25	0.737	0.872	109.43	0.000000195	0.000000012	0.487	0.029
18.75	0.734	0.867	109.70	0.000000013	0.000000027	0.034	0.067
19.75	0.730	0.863	109.30	0.000000017	0.000000020	0.043	0.051
20.75	0.727	0.856	109.56	0.000000012	0.000000034	0.030	0.085
30.95	0.721	0.843	109.43	0.000000016	0.000000042	0.041	0.106
31.15	0.718	0.841	108.50	0.000000008	0.000000006	0.020	0.016
32.15	0.712	0.835	108.90	0.000000016	0.000000019	0.039	0.047
33.35	0.705	0.826	108.63	0.000000018	0.000000027	0.044	0.068
46.10	0.687	0.810	109.83	0.000000033	0.000000035	0.082	0.088
49.60	0.666	0.801	109.30	0.000000036	0.000000018	0.089	0.046
50.80	0.623	0.747	108.76	0.000000071	0.000000107	0.178	0.268
60.80	0.603	0.714	109.83	0.000000028	0.000000055	0.069	0.137
61.80	0.597	0.707	109.43	0.000000008	0.000000011	0.020	0.029
65.00	0.589	0.699	109.30	0.000000010	0.000000012	0.026	0.031
68.75	0.582	0.687	109.43	0.000000009	0.000000018	0.021	0.044

Table 1. Time, liquid level, pressure, volume flow rate, and heat loss analysis of the blue dewar system.

Figures

Figure 1. Plot of the liquid level changes of the 36 inch probe with respect to time.

Figure 2. Plot of the heat loss along the 36 inch depth with respect to time.