LABORATORY HELIUM RECOVERY SYSTEM

Designed and built by:

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Manual last updated on 9/20/2016

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HELIUM RECOVERY SYSTEM OVERVIEW

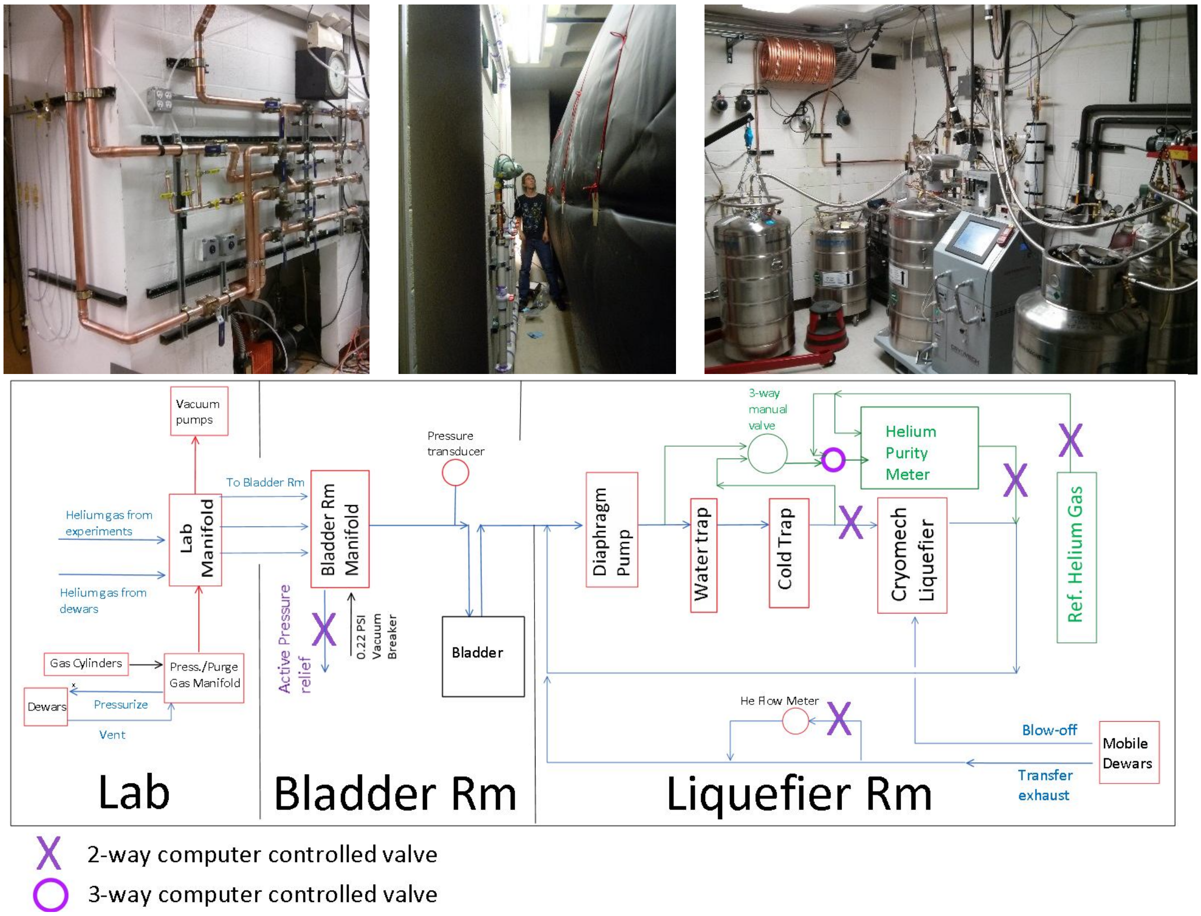


Figure 1: The top row shows the Laboratory Manifold, Bladder Room, and Liiquefier Room. The bottom schematic shows the major components in the system.

A full laboratory helium recovery system has been implemented to mitigate the burgeoning cost of liquid helium. Laboratory applications require cooling samples and superconducting magnets down to temperatures below 2K, which requires liquid helium.

Figure 1 shows a simplified schematic of the main components of the system. The gas flow of the helium gas is indicated by the arrows. The laboratory applications vaporize liquid helium which is routed through a central laboratory manifold (Figure 1a). The manifold routes recovered helium gasses to the bladder room and allows flexibility of pumping and purging fore- and back lines. The bladder room manifold merges the three exhaust lines into one large line that interfaces with a 3600 cu. ft. helium recovery bladder (Figure 1b). The bladder acts as a ballast for the upstream helium flow.

A small diaphragm pump in the liquefier room draws the helium from the bladder and creates a 5 PSI pressure differential between the atmospheric helium in the bladder and the diaphragm pump output. The slightly pressurized gas is then purified by passing through a room temperature water trap and a liquid nitrogen cold trap. The purity of the gas is measured at automated intervals. A 99.99% purity level is required before the gas enters the Cryomech liquid helium plant 22 (LHeP22) liquefier. The gas is liquefied into a 150L dewar. The accumulated liquid helium is transferred out of the 150L dewar into mobile dewars. Some of the liquid is vaporized during the transfer and the exhaust is recaptured.

The mobile dewars are brought into the laboratory where the liquid is transferred to other cryostats used in experiments, and the helium is recaptured, and the process begins of helium recovery begins anew.

The above schematic omits details of the system like manual valves, safety relief and check valves, access ports, heaters, switches, computer acquisition and control, etc.. However, the schematic sets the stage to begin discussing the major components. The manual is organized into three mains sections: the Liquefier Room, the Bladder Room, and the Laboratory. The purpose and function of the subcomponents are discussed in each of these sections. The final section discusses the Liquefier Acqusition and Control Computer.

LIQUEFIER ROOM

CRYOMECH LIQUID HELIUM PLANT 22 (LHEP22)

The heart of the system is the helium liquefier plant, the Cryomech LHeP22. Some essential information is summarized in this section, but the Cryomech manual should be read by operators of the helium recovery system.

Figure 2: Cryomech Liquid Helium Plant 22 (shown with a helium purity meter attached).

The cold head of the Cryomech utilizes pressure oscillations in a pulse tube that induces changes in entropy. A compressor is used, just like in a usual refrigeration system, raising the pressure of the refrigerant which eventually returns to the compressor at a much lower pressure. The pressurized gas travels through a rotary valve that produces an audible 2 Hz "chirping" generating gas pressure pulses. The rotary valve and pulse-tube cold-head sit atop a 150L liquid helium dewar. Pure helium gas injected into the dewar condenses on the cold surface of the cold-head and drips to the bottom of the dewar. Liquid helium accumulates in the dewar.

Very high purity helium gas is used as the refrigerant in the closed-looped system. Compressing the gas generates heat (about 10 kW) removed by chilled water. The oil in the compressor becomes too thick (just like in a normal refrigeration system) if the chilled water is too cold, which causes excessive friction and wear in the compressor. If the temperature is too high, the compressor can be damaged. A smart compressor controller measures the temperature of the compressor oil. If the oil temperature rises above 126F, the controller automatically turns off the compressor.

The liquid helium plant is also equipped with a liquid helium level gauge, dewar pressure gauge, and thermometers that measures the temperature of the cold-head, helium gas used as a refrigerant, and the input and output chilled water. A heater cartridge hangs off of the cold head and rests on the bottom of the dewar. An onboard computer reads and logs all sensor data while controlling the compressor, cold head, and heater.

The control software offers two automatic modes. The first is the "auto on/off" mode. In this mode, the dewar pressure is maintained between 0.5 and 8 PSIG. The natural boil-off of liquid helium raises the pressure in the dewar. When the pressure reaches 8 PSIG, the compressor turns on and the cold-head begins condensing helium gas reducing the dewar pressure. When the pressure reaches 0.5 PSIG, the compressor is turned off. The "auto-continuous" mode maintains the dewar pressure at 0.75 PSI by continuously running the compressor and regulating the power to the dewar heater.

A dewar vent port with an inline 10 PSI relief valve exhausts into the recovery bladder. Two catastrophic relief valves that vent to the room are set at 15 PSIG. If the dewar pressure falls below 0.25 PSIG, power is supplied to the dewar heater maintaining a pressure above atmosphere. Note that the heater controller must be manually disabled when no liquid is present in the dewar. Otherwise, the dewar insulation may be damaged.

The user supplies purified helium gas at the input of the LHeP22. A pressure regulator prevents the flow of gas into the dewar unless the pressure is greater than around 3 PSIG. The gas must be greater than 99.99% pure to prevent icing of the cold head. Ice forms an insulating layer which diminishes heat transfer to the helium gas degrading liquefaction rates.

If icing occurs, the entire 150L dewar must be warmed up to regenerate the cold head. The process takes about 10 days to warm to room temperature. To regenerate, evacuate the dewar and backfill with pure helium. Once the system is restarted, accumulation of liquid helium in the dewar requires 40 hours. The maximum measured liquefaction rate for our unit is 26.3 LLHe/day.

Modifications to the LHeP22 include relocating the chilled water ports to the back-side of the unit, connecting a dewar exhaust port and 10 PSIG relief valve to the recovery system, and reorienting the helium gas input to the back of the unit.

Special note: To gain access to a hidden settings menu, press the “O” and “H” in the Cryomech logo on the screen of the onboard computer.

THE HELIUM PURITY METER

Figure 3: Modifications of the helium purity includes automated purity readings with three computer controlled solenoid valves mounted to the back of the unit.

The helium purity meter is made by Quantum Technology. The meter utilizes a pair of hot wire anemometers. The idea is that various types of gasses have different thermal conductivities. Compared to the main constituents of air, helium has a much higher thermal conductivity. The level of air impurity changes the heat loading of the hot wire. Since the resistance of the wire is temperature dependent, a signal is generated based on impurity level. To gain sensitivity, the hot-wires in two identical chambers are measured in a bridge configuration. A trim-pot on the front panel is used to balance the bridge. Adjusting the trim-pot with the same pure reference gas flowing across both anemometers zeroes the meter. Once zeroed, a sample gas is then routed through one of the anemometer chambers and compared with the reference gas chamber.

In order to accurately measure purity level to 99.99%, the hot wires need a short time to thermally stabilize and the helium lines must be sufficiently purged. Also, flow rates should be the same through the two chambers adjusted by the valves at the bottom of the front panel rotometers (see Appendix 3 for calibration charts). The gas purifiers produce pure helium gas over many days, but the purity level degrades quickly over several hours as the adsorbent bed in the cold-trap reaches “break-through”, the point at which the final layer of the adsorbent bed begins to saturate.

The meter analog output voltage is measured by computer. Calibration of voltage output to impurity level was performed (see Appendix 2). The computer controls the gas flow through the anemometers via two 2-way and one 3-way solenoid valves that are mounted to an aluminum plate on the back of the meter.

Special Notes: A much better meter became available after purchase. I would recommend the acoustic purity meter made by Stanford Research instead. They have an application note on the operation of the meter in helium recovery system at my request during the construction of the IREAP helium recovery system.

DIAPHRAGM PUMP ASSEMBLY

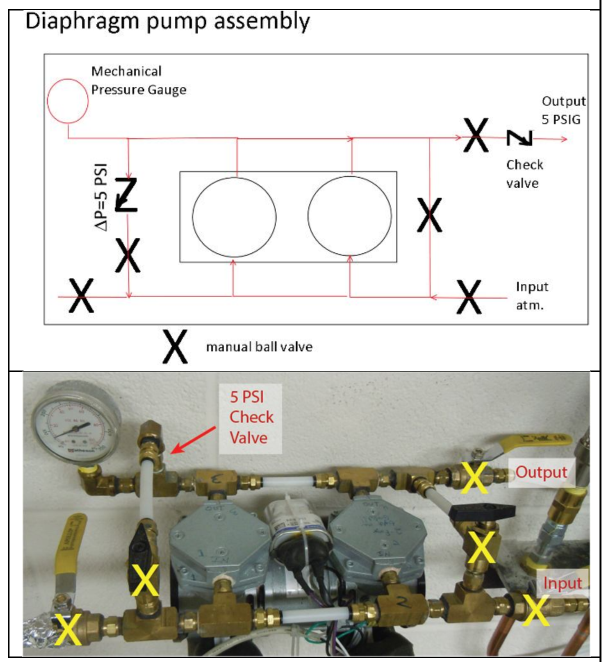


Figure 4: The diaphragm pump assembly.

A Gast MAA-P102-MB diaphragm pump is used to draw the helium from the bladder (very near 0 PSIG) and pressurize upstream components. The diaphragm pump produces much larger flow rates and pressures than necessary. Upstream 10 and 15 PSI pressure relief valves prevent over pressurization of upstream components.

One motor actuates two diaphragms that pump in parallel. An in-line check valve locks the pressure differential between the output and input to 5 PSI. The diaphragms permanently deform if left under vacuum or pressure for long durations, and leads to premature failure (and leaking). When the pump is off, the bypass valve is opened to equalize the pressure to atmosphere on both sides of the diaphragm.

A low-pressure check valve at the output of the diaphragm pump ensures that the cold trap and water trap stay under pressure when the pump is turned off.

The diaphragms are rated for 6 months of continuous use. I replace them every 3 months in order to minimize the possibility of cracked/leaking diaphragms pumping large amounts of helium into the room. Instructions and torque specifications for replacing the diaphragms are provided by Gast. Do not squeeze the diaphragms too tightly to the aluminum housing.

The diaphragms should be periodically leaked checked. Two tests should be performed, a static and dynamic leak test. Statically pressurize the input and output ports to about 10 PSI and close the input and output valves. Watch for a reduction of pressure. A Dynamic leak test involves running the pump with the output valve closed while applying a few PSIG to the input of the pump (the output is 5 PSI higher). The input valve of the pump is then closed and the pressure monitored.

A few different types of NPT sealants were used during assembly. XPando is the black, concrete-like substance that is a permanent connection. Yellow (high density and high purity) teflon tape is used on some connection. Locktite pipe dope is used. A special surface adhesion layer made by Loctite was pre-applied to the aluminum pump housing.

PURIFICATION OF HELIUM

WATER TRAP

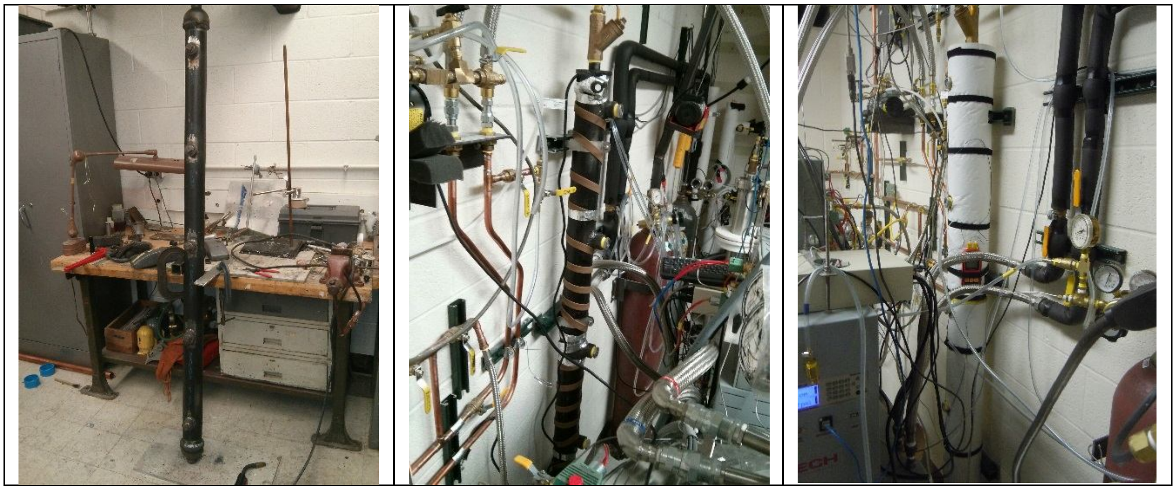


Figure 5: The water trap is filled with activated alumina.

The helium from the bladder and diaphragm pump is routed through a custom-made water trap. The trap is filled with beads of activated alumina. Indicating activated alumina is packed into windows along the length of the trap. The trap is conveniently regenerated *in situ* by heating and flowing air across the bed.

Without the water trap, excessive amounts of water are adsorbed in the cold trap. This is a problem for two reasons. Dangerous ice plugs form that block the flow of helium. Also, the zeolites in the adsorbing bed strongly trap dipolar water at the expense of trapping other impurity gasses. A bake temperature of 300C is necessary to drive off the water, so the zeolites must be removed from the cold-trap vessel. A much lower regeneration temperature is required to release trapped oxygen and nitrogen and can therefore be performed *in situ*.

End plates and NPT nubs for mounting windows was TIG welded to a 6ft long 3” diameter black steel pipe. Two 1” NPT Wye 150 mesh filters on either end retain the beads. The water trap is filled with about 15 lbs of F-200 activated alumina with an estimated net capacity of 1.3L of water at a relative humidity of 20% (see Appendix 1). Five window housings located along the length of the trap are packed with blue indicating activated alumina, where blue indicates dry and white indicates water saturation, permitting visual monitoring of the adsorbing bed.

It is estimated with an air impurity level of 1% and a volumetric flow rate corresponding to the maximum liquefaction rate (~25LLHe/day), the water trap will saturate in 1.5-2 weeks. Experimentally, I have run the trap for 1.5 weeks in high-humidity conditions (summer time) with the trap approximately 4/5 saturated at a continuous flow of 25 LLhe/day.

The activated alumina is regenerated by baking and supplying a counterflow of either air or dry N2 gas. Two 720W, 10’ long and 1” wide, silicone heater tapes with attached regulating thermostats are wrapped around the 3” diameter pipe held with Kapton tape. The silicone heaters are rated to 233C, and effective regeneration temperatures is 150C. Four K-type thermocouples measure the pipe and heater tape temperature. The pipe and heater tape are wrapped in 1” thick high-temperature glass-fiber insulation. The heaters are currently tuned so that the required temperature range is automatically maintained.

Counterflow of N2 gas is supplied by the 240L nitrogen dewar gas-vent port. The flow direction should be opposite that of the usual helium gas flow. The trap is regenerated when all the beads are blue and no liquid water is visible in the hose connected to the output located at the top of the water trap. The water trap can be regenerated in about 12 hours with a flow rate of 14 CFH of nitrogen (as measured by an argon rotometer). I usually evacuate the hot adsorbing bed immediately after turning the heaters off and backfill with industrial grade helium. The trap requires about 5 hours to cool to room temperature.

An alternative is to use a squirrel-cage blower to force room air backwards through the adsorbing bed after the beads are heated. I have used the method instead of the nitrogen, and it seems to work well.

COLD TRAP

The cold trap is made by Quantum Technology. A stainless steel vessel with an adsorbing bed of zeolites is lowered into a dewar and submerged in liquid nitrogen. Incoming dry helium flows through the cold zeolites bed removing impurities like nitrogen and oxygen. An output helium purity of 99.99% is attained.

Figure 6: The water trap is filled with activated alumina.

The input line routes gas from the top of the cold trap down through a 1” diameter pipe to near the bottom of the cold trap. A cup at the bottom of the pipe collects any water that accumulates (from ice that sticks to the walls of the pipe and, upon warmup, runs down to the bottom of the tube and into the cup). A smaller concentric tube runs from the bottom of the cup to the top of the trap. Any accumulated water is purged through this tube by pressurizing the trap. Since implementing the water trap, no water accumulates in the cold trap. I assume there are perforations in the 1” pipe near the bottom with a mesh screen. Adsorbing zeolite beads fill the 9” diameter section of the trap. Helium flows from the bottom to the top of the adsorbing bed. The 4” diameter neck section is the heat exchanger. The output port includes a 10 PSI relief valve.

The entire cold trap is lowered into a 240L cryofab nitrogen dewar with a 9.25” diameter neck. Always maintain a trap pressure above atmosphere during cooling. The adsorbing bed requires about 1.5 hours to chill.

Qantum Technology specifies that the trap capacity is about 1-1.5 kg of dry air, which translates into 9 days of continuous flow at 22 LLHe/day and a 99% purity level. The heat exchanger in the neck is a poor design, and the mass of the trap is inappropriately large causing copious amounts of LN boil-off upon cooling from room temperature as well as excessive warm-up times when regenerating the trap. No flange on the cryostat requires the trap be continuously hung from a crane.

Since I originally had no water trap, I have twice poured out the beads from the “output” port and baked the zeolites at 300C in an external oven. To replace the beads, suction on the “input” port using a shop vacuum draws a vacuum inside the vessel, which suctions the beads into the trap via the “out” port. There are explicit instructions on how to do this from Quantum Technology. The hoses and fittings for this procedure are stored in the liquefier room.

LN AutoRefill system:

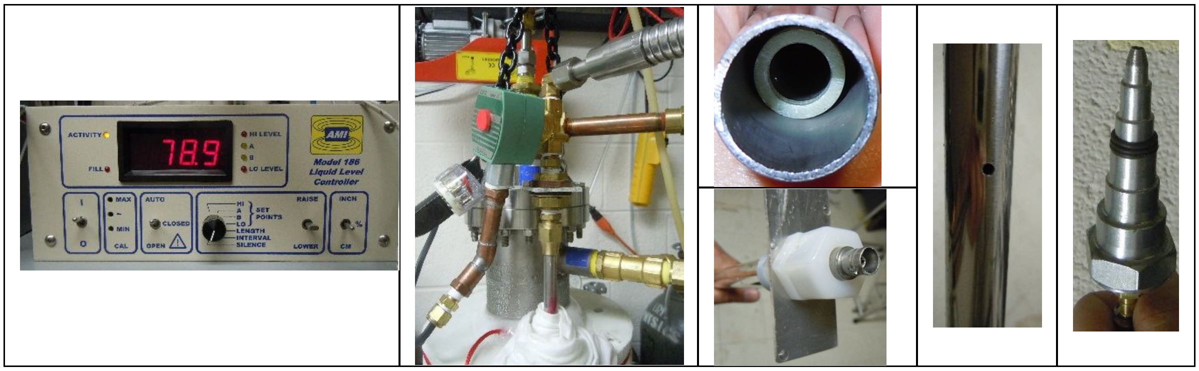


Figure 7: (a) LN level controller, (b) LN transfer solenoid valve and transfer line mounted to cold trap, (c-d) armored LN level gauge, (e) conical tube for purging level gauge.

The cold-trap was outfitted with an autorefill system. The level should be maintained very near the bottom of the 4" diameter neck. An American Magnetics LN-Level capacitiance sensor attaches to the controller. Set points A and B define the high and low LN levels. When the LN level reaches set point B, the onboard relay energizes and powers an external cryogenic solenoid allowing flow from a pressurized 240L mobile LN dewar. When the cold trap reaches set point A, the controller shuts off the flow. Set points "High" and "Low" are points that, when breached, trigger a fault mode where the controller no longer automatically acts. A maximum time interval can be set for the refill process (to go from level B to A). If the time interval is exceeded, then the flow is stopped and fault mode is triggered. This is an extra safety feature preventing accidental overfilling.

The capacitance level gauge is a pair of concentric fragile thin-walled stainless steel tubes. The cold trap is suspended at two points by a hoist. The expensive and fragile level gauge slides between the cold trap and dewar neck and can easily become bent or dented if the cold trap is bumped. Also, pressure equalization holes in the outer tube of the gauge is located outside the dewar causing water to cryopump between the tubes. The capacitance therefore changed and the level readings failed. Furthermore, removal of the capacitance gauge from LN caused icing inside and outside the level gauge. It therefore had to be thoroughly dried before re-inserting into the LN dewar. To solve these problems I placed the fragile capacitance gauge inside a thicker-walled stainless steel tube (shown in Figure 7), sealed the upper end of the gauge inside the tube, and drilled pressure equalizing holes so that they now reside inside the cold trap dewar just above the LN level. Upon removing the assembly from LN, a conical-shaped tube with o-rings is inserted into the outer armored sheeth. Dry nitrogen gas flows through the assembly and out the pressure equalization holes preventing ice and water from contaminating the capacitance gauge.

A transfer line was built onto the cold trap. It consists of a JIC fitting, a 2-way cryogenic solenoid valve, a bracket, a gas diffuser, and a thick copper-foil liquid-deflection shield that prevents asymmetrically cooling of the trap during LN transfers. The solenoid valve is actuated by the American Magnetics controller and a computer reads the LN level from the RS-232 serial port.

Electric hoist and crane:

An electric hoist and custom-built crane maneuver the cold trap into the 240L 9" wide-mouth LN dewar. The steel crane was MIG welded together. The hoist can cause terrible damage if not carefully used. Care must be taken not to damage the crane's aluminum pulley by running steel cable clamps into it. A dead-man's switch at the hoist housing to prevents catastrophic collision of the cold trap with the ceiling. Before hoisting the cold trap out of the dewar, it is imperative that the liquid nitrogen transfer line and the transfer solenoid power cable are disconnected, and the capacitance LN level gauge is removed. The gauge could be crushed between the dewar and cold trap, damaging both. While raising and lowering the trap into and out of the dewar, careful alignment of the cold trap and dewar mouth is necessary to prevent damaging the dewar opening.

New adsorbing bed:

The adsorbing bed is spherical beads of zeolite that are approximately 2.3 mm in diameter. I ordered acid-washed coconut-shell activated charcoal with a mesh size 4x8 as a possible replacement. Liquid water causes zeolites to disintegrate, and removal of water vapor requires bake temperatures of 300C. For activated carbon, the bake temperature is 150F and are not damaged from water exposure. The regeneration should therefore be quicker and easier to fully regenerate, The performance and capacity to adsorb nitrogen and oxygen is very similar at LN temperatures.

Figure 8: Styrofoam Lid for 240L wide-mouthed cold-trap LN dewar.

Styrofoam Lid:

No lid to the wide-mouth LN dewar was provided. A 4x4x2' brick of polystyrene (a $20 archer's target) was cut using a home-made bow strung with NiCr wire. The wire was heated with a variac. The Styrofoam was rough cut and then placed on a plate with a screw that pierced the Styrofoam providing a rotation axis. The piece was spun about the point as the NiCr sliced through it. Two cylinders were cut and then glued together to make a tight fitting polystyrene lid.

LIQUEFIER MANIFOLD

Figure 9 shows most of the mechanical room manifold. The yellow x's mark the location of manual ball valves. Red arrows indicate the path of the helium gas flow. The usual gas flow is sequential numbered 1 through 12. Helium arrives at the manifold (1) from the bladder, and is routed (2) to the diaphragm pump assembly (3). The pump assembly draws helium from the bladder and pressurizes the upstream components to around 5 PSIG. From the pump assembly, the helium flows through a check valve (4). The check valve maintains the upstream components above atmospheric pressure even when the pump is off. The helium then flows through a flexible corrugated hose, and to the top of the water trap.

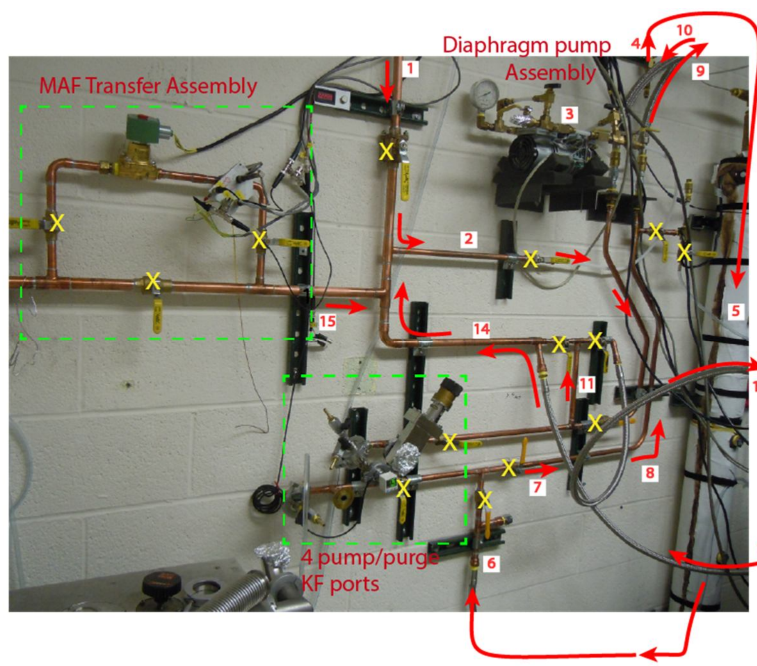


Figure 9: Most of the Liquefier Room Manifold is shown. The red arrows indicate helium gas flow, and the yellow x's demarcate manual valves.

At the top of the water trap are three manual ball valves as shown in Figure 10. Opening the left ball valve directs the flow to the helium purity meter. The right ball valve vents to the room. The flow traverses through the water trap (5), past the water trap relief valve (6), through the copper pipes (7 and 8), and sent into a corrugated stainless steel hose (9) and into the cold trap. The purified gas is returned from the cold trap (10) and routed through the copper manifold (11) and into another corrugated stainless steel hose that attaches to the input of the liquefier (12).

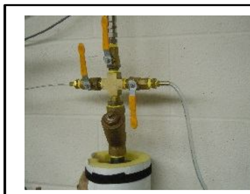


Figure 10: Top of water trap

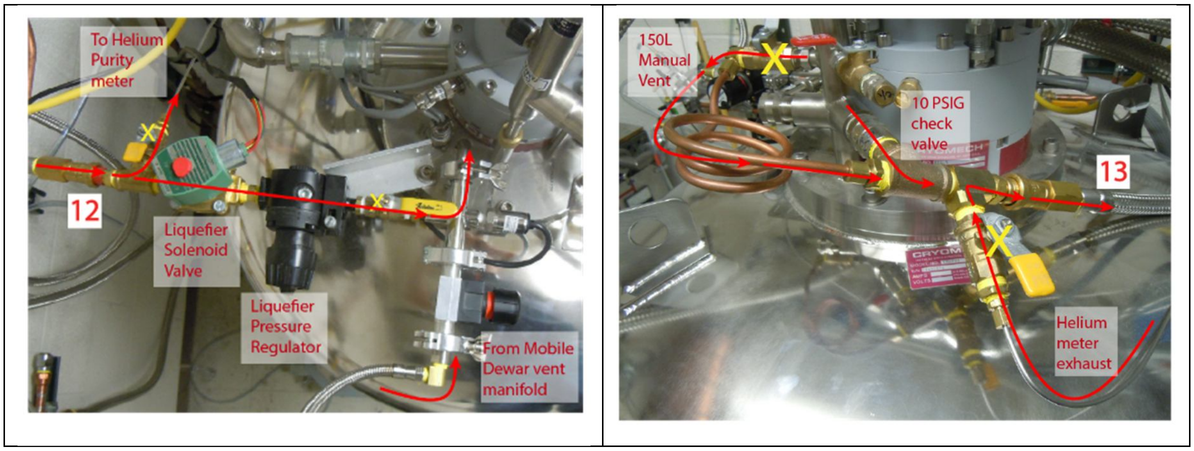


Figure 11: (a) The purified gas enters the Liquefier input assembly on the 150L dewar. Point number "12" is demarcated on the Liquefier Manifold in the previous Figure. (b) The 105L dewar liquefier exhaust assembly sends gas to point nmber "13" on the previous Liquefier Manifold Figure.

As shown in Figure 11(a), the helium passes through the liquefier solenoid valve, pressure regulator, and into the liquefier 150L dewar. A tee at the input diverts some of the flow into the helium purity meter. Also shown in Figure 11(a) is the attachement from the mobile dewars that vent directly into the 150L dewar that will be discussed in the next section.

Figure 11(b) shows two venting ports from the 150 L dewar that exhaust into the liquefier manifold (13). One is a manually operated ball valve, and the other is an inline 10 PSI check valve. The helium exhaust from the helium purity meter is also merged into the exhaust line. The combined exhaust is routed into a corrugated stainless steel hose, into the manifold (14), and then to the bladder (1).

Also shown in Figure 9 is the MAF Transfer Assembly. Helium exhaust gas from mobile dewars during a liquid transfer, as shown in Figure 12, is heated to room temperature. A copper coil with three 900W heater-tapes with variacs are wrapped around several loops. The gas then travels into the MAF Transfer Assembly, which can be routed through the transfer solenoid and helium MAF sensor (see Section *Helium gas Mass Flow meters*). The sensor measures the gas flow rate used to control the rate of liquid transfer. Another useful parameter is the liquid level in the dewar which is derived from the dewar weight during transfer. In the adjoining picture, the weight is measured by suspending the dewar from an engine hoist with a hanging scale. A platform scale with an RS-232 has recently replaced this scale allowing transfers to be automatically shut off by a computer based on weight, time of transfer, or temperature of the MAF sensor (see Section *Liquid Helium dewar-to-dewar transfer shut-off interlock* for details). The exhaust gas from dewar-to-dewar transfers is routed (15) back into the bladder (1).

Figure 12: Transfering liquid helium from the 150L liquefier dewar to a 60L mobile dewar.

The four pump/purge ports on the Liquefier manifold provide great flexibility to perform a variety of tasks at one easily accessible location. The water trap and cold trap are independently isolated with ball valves, independently regenerated with backflow of nitrogen or air (by attaching a squirrel cage motor to the KF flange), evacuated with a pump station, and backfilled with helium. All pipelines in the manifold are pumped and purged. The pipelines between the diaphragm pump and liquefier can also be flushed with gas from the bladder by running the diaphragm pump, or the gas from the bladder can be continuously purified without liquefying. The cold trap can be maintained under pressure while cold for long periods of time by pressurizing with helium from a cylinder. The diapharagm pump is easily leak checked (see Section *Diaphragm pump assembly*) by closing appropriate valves and attaching a pressure sensitive pressure gauge and pressurizing cylinder to the manifold.

MOBILE DEWAR HELIUM BLOW-OFF CAPTURE MANIFOLD

Figure 13: (a) The dewar blow-off exhaust port (b) dewar helium blow-off capture manifold

One of the mobile helium dewar exhaust ports consists of a ball valve, an in-line 0.5 PSI check valve, and Swagelok B-QC4 brass quicklock connectors (Figure 13a). The exhaust flows into Mobile Dewar Blow-off Capture Manifold via a ¼" corrugated stainless steel flex hose. The manifold connects to the Liquefier 150L dewar as shown in Figure 11(a). A KF port is also included on the manifold for pumping and purging. Two dewars simultaneously connect to the blow-off manifold.

HELIUM GAS MASS FLOW METERS

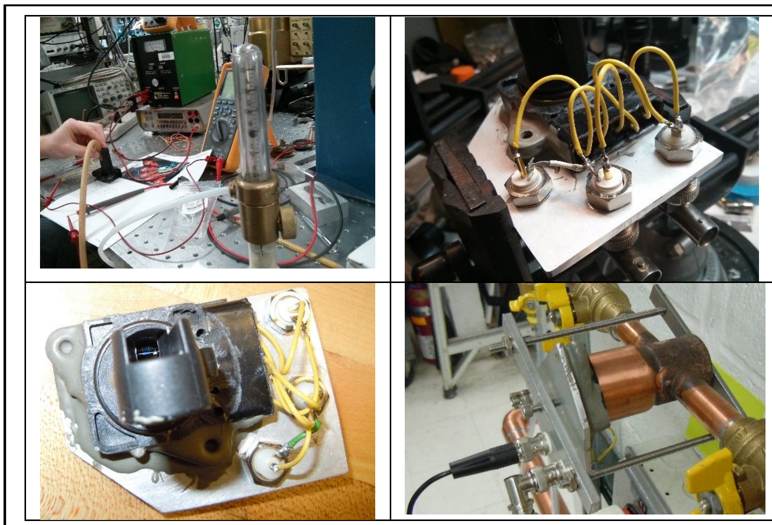


Figure 14: Modified automotive Mass-air-flow sensors are used as adjustable helium flow sensors and the Laboratory and Liquefier manifolds

An automotive mass air flow (MAF) sensor was modified for use as a helium mass flow sensor. The sensor is a hot wire anemometer with onboard electronics that maintains the hot wire at constant power. The lid was replaced with an aluminum plate to attach three BNC connectors to apply 12 Vdc, and read the signal voltage as well as an RTD thermometer. An oring gland was modified to adequately seal between the plastic housing and a copper fittings that is part of a brazed housing. The o-ring seal slowly leaks due to imperfections in the plastic. The leaks are insignifcant for short duration like for transfers. The meters have accompanying isolation valves on both the Lab and Liquefier Room Manifolds. The sensitivity of the meter is adjusted by rotating the meter to different angles inside the copper housing. An LED display shows the voltage that relates to flow rate. Calibration of the meter voltage to a volumetric flow rate (CFH) of helium is given in Appendix 2, and wiring charts are provided in Appendix 8.

CHILLER

A closed-cycle chiller, a Coherent LaserPure 20, removes heat from the compressor of the LHeP22. A heat exchanger in the LaserPure unit transfers the heat from the closed-cycle coolant to the building chilled water system. The cooling power is adjustable: a coolant-reservoir bulb thermometer actuates a bypass diaphragm valve that is adjustable. This allows some tuning of the coolant temperature.

Figure 15: A Coherent LaserPure 20 chiller

The total capacity of the chilled water lines and reservoir is 7.8 gallons. Every inch of coolant level in the reservoir corresponds to ½ gallons. The coolant is a mixture of pure water with 25% BioFrost (by volume), polypropylene glycol with corrosion inhibitors.

The front panel power switch is a low-voltage circuit, which has been wired in parallel with a computer controlled relay. The chiller is automatically turned off if the coolant temperature rises above a user defined set point preventing the water pump from overheating.

A stand was welded together to raise the chiller off the ground for easy draining.

O2 SENSORS

The room oxygen levels in the Liquefier and Bladder Rooms are separately monitored by Macurco OX-6 Oxygen detectors. Each wall mounted unit is powered by a 12V power supply and includes a digital readout of the oxygen concentration, a 4-20mA oxygen sensor output, two alarm relays with programmable set points, and an internal buzzer.

Figure 16: Room oxygen sensors with remote displays and alarms are located in the Liquefier and Bladder rooms

The Department of Environmental Safety at UMD required remote oxygen level displays as well as audible and visual alarms exterior to the two rooms. An Arduino Uno controls a 1.8" Color TFT LCD display ST7735 (a wiring diagram is provided in Appendix 9), and homebrewed software uploaded to the Arduino Uno. Custom 12Vdc remote buzzers and flashing-light alarms were also implemented.

The flashing lights are connected to the ALARM relay with an oxygen concentration set point of 19.5%. Buzzers are connected to the FAN relay with a set point of 18%. Lifetime of the oxygen sensor is rated between 2 and 3 years. Calibration of the sensor is recommended at 2 years.

MOBILE DEWARS

Three mobile helium dewars are used in the recovery system: a new Cryofab 60L dewar, a Cryofab refurbished 100L dewar, and an older 100L dewar that came from IBM and manufactured in the early 1980's. Each dewar is outfitted with a Swagelok quick connect (B-QC4) with an inline 0.5 PSIG pressure relief valve. The Swagelok connectors are valves on both the male and female ends. The valves seal shut disconnected, and open when connected. The male connectors are on the dewars with protective caps. The interface with the lab manifolds is simple, quick, and foolproof.

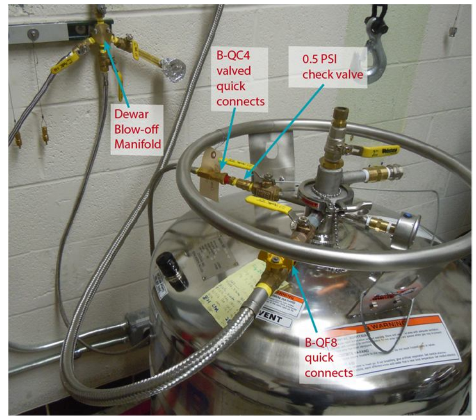


Figure 17: A cryofab 60L dewar vent ports

A Swagelok high flow quick connect (B-QF8) is located on each dewar on a separate vent port. This provides a convenient way to connect/disconnect to pressurize or vent the dewar during LHeP22 liquid helium transfers.

DEWAR PLATFORM SCALE

All liquid helium and nitrogen dewars are weighed to measure the liquid level (see Appendix 4). An engine hoist with a hanging scale lifts dewars.

Recently, a platform scale with an RS-232 connection has been added to measure the liquid level of the mobile helium dewars during liquid transfers. The weight is graphed in real time on a computer. When the weight of the liquid reaches a user defined set-point, the transfer is automatically shut off.

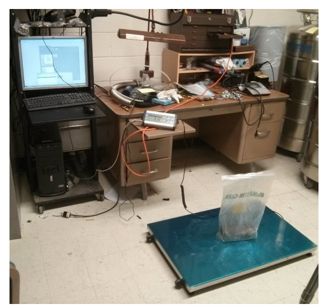


Figure 18: A 440-lb capacity platform scale with an LCD display and RS-232 port connected to the liquefier computer.

BLADDER ROOM

BLADDER ROOM MANIFOLD

The Bladder Room Manifold routes captured gas from the Laboratory Manifold to the recovery bladder and Liquefier Room Manifold.

As shown in Figure 19, three helium exhaust lines from the Laboratory Manifold are merged into a 3" diameter PVC pipe. The flow is then directed into the helium recovery bladder and the liquefier manifold.

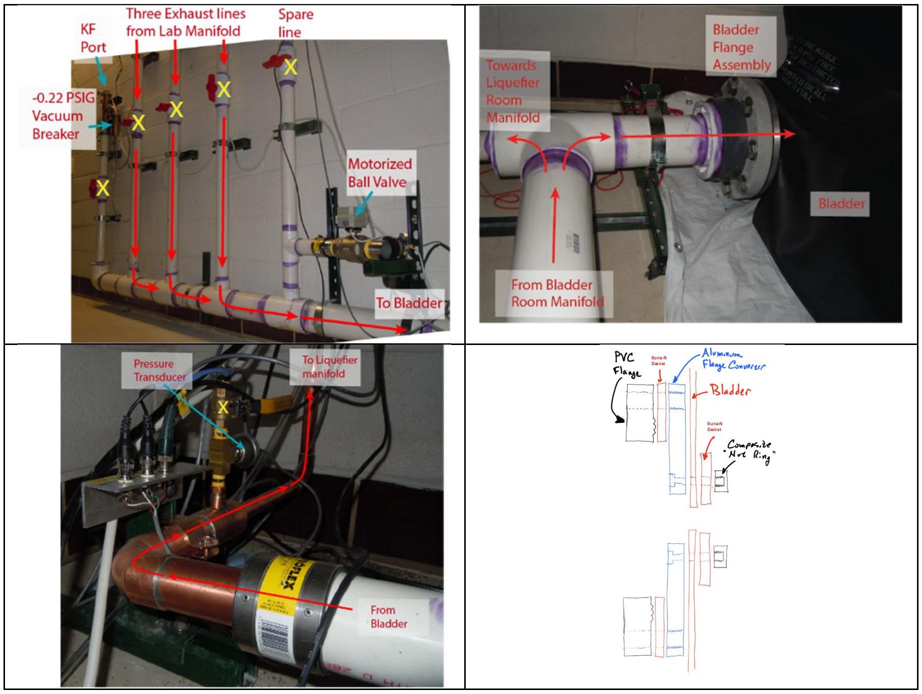


Figure 19: (a) Bladder room manifold (b) Bladder room manifold interface with the bladder (c) Bladder send line to the Liquefier Manifold showing the pressure tranducer and connectors (d) A sketch of the bladder flange assembly.

The large diameter pipe ensures that pressure pulses from pumping on helium reservoirs in the laboratory do not propagate back to sensitive (bolometer) IR detector helium reservoirs. The low impedance line couples to an atmospheric bladder, further minimizing pulses.

A spare line is available for future connections to other laboratory spaces. An extra KF access port is available. A -0.22 PSIG high-flow vacuum breaker ensures the bladder is not be damaged by accidental evacuation. Also, a nylon rope is tied down inside the 3" pipe near the flange assembly and thrown into the helium recovery bladder. The rope prevents the bladder from sealing against itself across the flange opening while inadvertently pumping.

A pressure transducer is located near the flange assembly used as part of an active interlock preventing underinflation of the bladder. A computer controlled motorized ball valve opens if the bladder becomes overinflated (bladder switches activated) or underinflated (the pressure inside the bladder is too low).

BLADDER

Figure 20: A half-filled bladder with the three overinflation switch mechanisms. The liquefier manifold is against the wall on the left.

The bladder is approximately 3600 cu ft in volume (a capacity equivalent to 135 LLHe), providing a ballast in the system. No company that manufactures helium bladders qualifies leak rates. A few report the bulk permeability of the material.

AeroTech Laboratories (ATL) fabricated four small test bladders that we qualified in our lab. The measured leak rates of the 0.040" thick rubberized polyurethane matched the estimated bulk permeability rates. The rate of diffusion of helium through the test bladder extrapolate to about 15 LLHe/year for the surface area of our large bladder.

A 3" diameter pipe interfaces with the bladder via a PVC flange as shown in Figure 19. A custom aluminum flange converter is sandwiched between the bladder and a stock PVC flange. An ATL composite "nut ring" clamps the bladder to the flange converter. The assembly is sketched in Figure 19.

As shown in Figure 20, three switches mounted on three PVC bumpers press against hanging steel paddles when the bladder becomes over-inflated. If any two of the three switches are activated (closed), a relief valve is opened.

Great effort was expended to ensure that the bladder is not abraded or punctured in the entire room. All the surfaces exposed to the bladder were made smooth, including the electrical panels, plumbing, ducts, switches, shelving etc.. All walls were scraped to remove rough and sharp protrusions, and heavy paint and spackle smoothed out any remaining rough areas. The rough concrete ceiling was covered with a suspended tarp. The floor is covered with protective tarp. The bladder is suspended half-way up the bladder to ensure full deflation. Two PVC pipes are strapped to two top edges of the bladder to help minimize wrinkling during the deflation process. The rubber bladder is damaged when creased (you can see it begin to crack), so do not step on or pinch the bladder. Entry into the room must be performed with care to avoid damage to the bladder from rolling underneath the door.

The largest amount of stress occurs near the flange. When the bladder is fully inflated as was performed with air inflation tests using a blower motor, quite a bit of force was observed at the flange area due to bulging of the bladder. An effort was made to tie down the corner in way to alleviate some of the stresses.

To minimize creasing of the bladder, inflation/deflation tests showed that the pvc pipes tied along two edges provided enough weight to prevent undue folding of the top of the bladder upon deflation. Also, the pipes provide more reproducible inflation permitting installation of overinflation switches.

Current measured bladder loss rate is 0.5 LLHe/day. The measurement of losses were performed in two ways: (1) a known volume of helium gas was injected into the bladder while performing time-lapse photography. The pictures are correlated to a known amount of helium. Barometric pressure and temperature changes were taken into account. The slow loss integrated over many days is translated into a gas volume. (2) After recording this estimated loss, a known volume of gas was slowly re-injected into the bladder over the course of many hours. The pressure in the cylinder was recorded with the time. The closest picture that matched the initially filled condition of the bladder was then correlated to the loss of pressure in the cylinder.

The flange assembly is suspected to leak. I could not locate the leak with a helium sniffer probe. I would recommend coating the outside area of the bladder with silicone grease to attempt to seal the leak. Also, removing the composite nut ring and replacing with a larger-area backing ring inside the bladder would allow a larger diameter seal. Pressure intensifier rings at the larger diameter may do the trick.

A NOTE ABOUT PVC PIPE AND COMPRESSION COUPLERS

PVC pipe is used to reduce cost. The solid-core PVC pipe is rated to many 10's of PSI, but warnings from manufacturers state that you should never pressurize PVC pipe with gas. The compressed air inside the pipe, contrary to incompressible water pressure tests, can explode if the pipe fails at some point. The plastic pipe tends to splinter into dangerous shards. I find it odd that the internet is full of people making air pressurized guns and launchers from PVC pipe despite warnings. I pressurized the system to 10 PSI to test for leaks late in the evening when no one was around. Out of all the PVC joints, none of them leaked. The method of cleaning, using solvent (primer), and then gluing (cement) as instructed by the manufacturer is nearly full proof. Joining plastic to copper or steel pipe is done utilizing a ProFlex coupler, a rubber seal with a compression collar. These type of fittings are not rated to very high pressures but are fine for helium recovery and leak tight.

BLADDER SECURITY CAMERA

A Dahua DH-IPC-HFW4300S IP camera is installed in the bladder room (see Appendix 6). The camera provides an estimate of the helium level. It is accessible on Android and Windows systems. I use ISpy software on Windows and the Dahua App on my Android phone. The liquefier computer is configured to capture a picture every hour. This is useful for assessing leak rates of the bladder.

Figure 21: Bladder camera

Time lapsed photography has also been instrumental in tuning the inflation/deflation of the bladder with minimal creasing.

LABORATORY

LABORATORY MANIFOLD

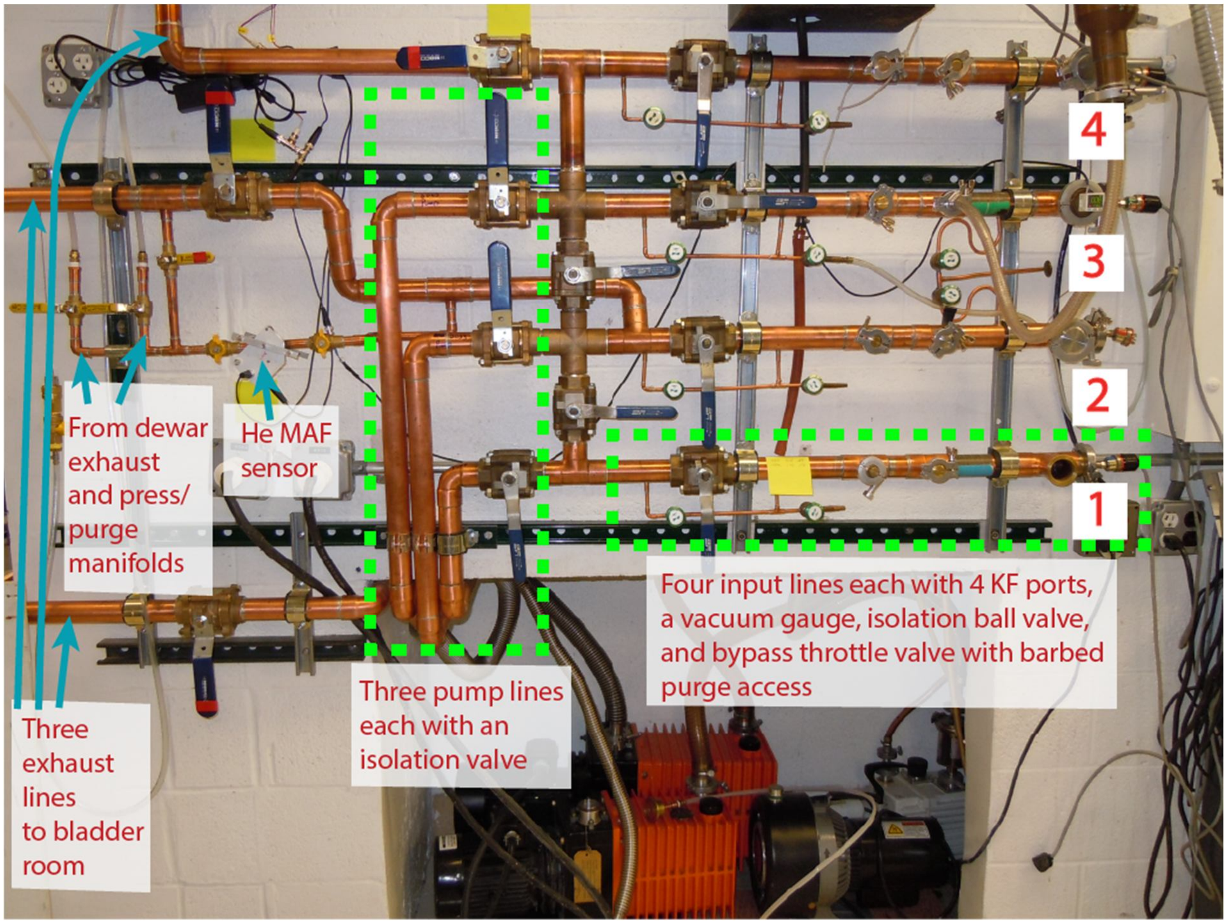


Figure 22: Laboratory manifold

The Laboratory Manifold provides and easy way to pump and purge back and fore lines, measure transfer exhaust flow, and route gasses from various experiments to the Bladder Room Manifold. As shown in Figure 22, the main laboratory manifold has four main input lines that collect helium from experiments. Each input line has four KF ports for connecting helium exhaust lines, relief valves, pressure gauges, or vacuum systems, for example. Each input has a large isolating ball valve and a bypass line with throttle valve. This small bypass line also provides an access with a barb and shut-off valve, usually used for connecting purge gasses.

There are three pumping lines. Two lines are connected to a 2063 and 2033 Alcatel rotary vane pumps. One line is connected to a scroll pump.

Three helium exhaust lines run to the bladder room and interface with the Bladder Room Manifold. Each exhaust line has a large isolation valve. The middle helium exhaust line has a bypass line with an inline helium flow meter. The meter is used to monitor dewar-to-dewar transfer exhaust flow rate in the laboratory. The middle exhaust line is also to exhaust line two other laboratory manifolds, the Dewar Blow-off Manifold and the Pressurization/Vent Manifold as shown in Figure 22.

Any of the four input lines can be pumped with any of the three pumps or routed to any exhaust port. All fore- and back- lines can be evacuated and purged from the Laboratory Manifold.

Furthermore, the temperature of helium reservoirs can be lowered to below 2K by pumping with the scroll pump and recapturing the backline helium gas exhaust.

PRESSURIZATION/VENT MANIFOLD

The Pressurization/Vent manifold is a set of 6 lines each with two ball valves that straddle a tee. Each of these tees has a tube that runs to various experimental stations around the laboratory. The six manifold lines attach to one another along the central “spine” as shown in Figure 23. The top of this spine has a plastic exhaust tube that attaches to the main Laboratory Manifold. The ends of each manifold line are barbed allowing users to attach compressed gasses from a cylinder, usually helium or nitrogen.

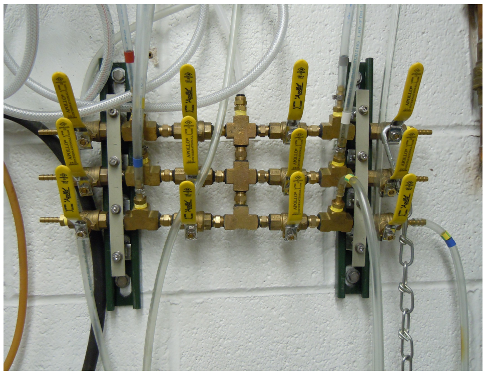


Figure 23: Pressurization/vent manifold

Therefore, either nitrogen or helium can be directed to any of the six stations. Any dewar or experimental vessels can be pressurized or purged. Pressurized helium vessels or dewars are vented and the exhaust routed to the middle helium exhaust line of the main Laboratory Manifold recovery line.

Each station is equipped with a B-QF8 swagelok quick connect and shut-off ball valve, like the one shown in Figure 24. Connection to the mobile helium dewars for pressurizing and venting during transfers are foolproof. Converters to other connectors have been made for other specialized purposes.

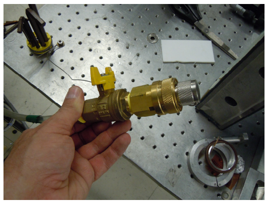


Figure 24: Press./vent station

The manifold was assembled with XPando. It is not possible to modify it, but it will never leak!

LAB DEWAR BLOW-OFF MANIFOLD

The Laboratory Dewar Blow-off Manifold has three swagelock B-QC4 quick connects, each attaching to a mobile dewar 0.5 PSI vent port. Each line has an isolation valve. The combined dewar exhaust is directed through a plastic tube at the top of the manifold, which connects to the middle exhaust line on the main Laboratory Manifold.

Figure 25: Lab dewar blow-off manifold

Therefore, mobile dewars exhaust directly into the bladder from the laboratory. This is different than the Liquefier Room where dewars exhaust directly into the liquefier.

LASER AREA PIPELINE

A number of connections to the recovery system are possible around the laboratory. A pipe is run on the ceiling above our laser area to various experimental locations. Six KF ports allow connection to cryostats and detectors for helium recapture. The exhaust from the pipeline feeds into input line #2 of the main Laboratory Manifold.

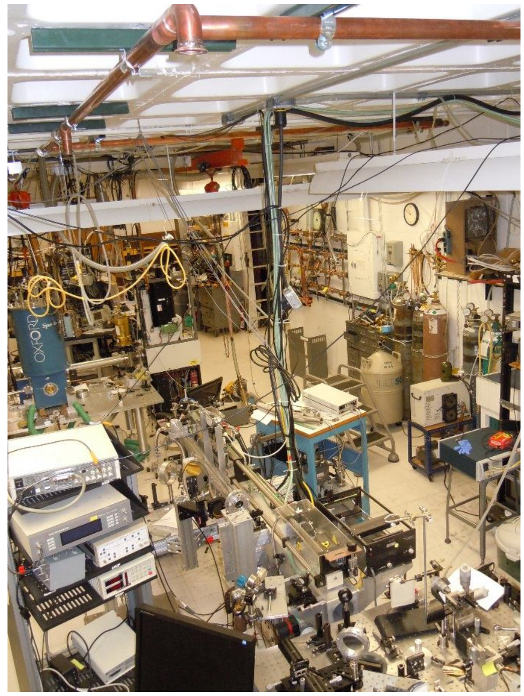


Figure 26: Laboratory laser-area pipeline

MAGNET AND HELIUM RECOVERY

The large amount of helium boil-off from our 8T split-coil magnet with optical access was one of the motivating factors to install a laboratory helium recovery system. While installing the recovery system, I designed and implemented a new cold shield and sample actuator design that dramatically lowered helium blow-off.

The helium reservoir leaked to atmosphere precluding the possibility of recovering the helium. The many leaks were repaired. Brass NPT fittings and compression fittings with copper tubing replaced several plastic hoses. The magnet leads leaked at every interface (4 of them) and were repaired: a dremel tool was used to cut a groove at the joint, an epoxy was applied, and a vacuum pulled on the helium reservoir which pulled the epoxy into the joints. The seals remain helium tight after thermally cycling the cryostat.

Figure 27: Top of 8T magnet showing the magnet current leads and pressure equalization tube (copper).

The magnet is operated with the exhaust fully open to the recovery system. When the magnet is not scanning, a low-pressure inline check valve is placed between the helium reservoir and the recovery system. This is accomplished with check valve connected between two of the main input lines of the main Laboratory Manifold.

LIQUEFIER ACQUSITION AND CONTROL COMPUTER

A summary of the current data acquisition card (NIDAQ) IO's and computer serial ports are listed in Figure 28. Sensors are read through the analog inputs (AI), digital inputs (PFIO), and serial (USB and RS-232) ports. Control of system components is actuated through a relay box using digital outputs (D out).

I/O	I/O Description	Notes
AI0	Mass Air Flow Sensor (CFH of helium)	
AI1	T at MAF sensor housing (K)	
AI2	T of LaserPure Chiller Supply (K)	
AI3	T of House Supply Chilled Water (K)	
AI4	T of transfer line (K)	not implemented
AI5	Bladder pressure transducer (PSI)	
AI6	He Purity Meter (% impurity level)	
AI7	<none>	
D out 0	Chiller power	Relay box (no outlet)
D out 1	diaphragm pump power	"1" outlet Relay Box
D out 2	transfer solenoid	"2" outlet Relay Box
D out 3	He purity Meter: Meter power+ two shut-off solenoids	"3" outlet Relay Box
D out 4	liquefier solenoid	"4" outlet Relay Box
D out 5	He purity meter: 3-way solenoid	"5" outlet Relay Box
D out 6	bladder relief motorized ball valve	"6" outlet Relay Box
D out 7	<none>	Unused Relay in box
PFIO0	Bladder motorized valve closed switch	
PFIO1	Bladder motorized valve open switch	not working
PFIO2	Bladder Overfill Switch 1	
PFIO3	Bladder Overfill Switch 2	
PFIO4	Bladder Overfill switch 3	
PFIO5	<none>	
PFIO6	<none>	
PFIO7	<none>	
USB	UPS for computer rack	
RS232	LN Level (%)	
RS232	Dewar platform scale (lbs)	
RS232	Liquefier compressor	not implemented

Figure 28: A table of NI-DAQ analog inputs (AI), Digital outputs (D out), and Digital inputs (PFIO) as well as serial inputs (USB and RS232).

A Labview program measures analog inputs from the helium mass flow (MF) sensor, multiple 1kOhm RTD thermometers (MF thermometer, chiller coolant supply, and House chilled water supply), bladder pressure transducer, and Helium purity meter. The status of the power to the battery backup system on the computer rack is monitored over a USB connection. The LN level of the cold trap dewar is measured over a serial connection to the American Magnetics LN level controller. The liquid level of mobile dewars is monitored by acquiring scale readings (in lbs) over the serial port.

The motorized over/under- inflation bladder valve has onboard switches to indicate when the valve is fully opened or closed. The status of these switches are read by digital inputs. The status of three bladder overfill switches are similarly measured.

The computer controls solenoid valves and power to equipment using digital outputs that set the state of eight 120V relays. Power to the chiller, diaphragm pump, and helium purity meter is computer controlled. Two-way computer controlled solenoid valves are mounted on the Transfer MAF Assembly (see Figure 9), the input of the LHeP22 (see Figure 11a), and to the helium purity meter (2 of them). One three-way solenoid valve is also mounted to the helium purity meter (see Figure 1b). The computer also controls a motorized ball bladder-relief valve (see Figure 19a).

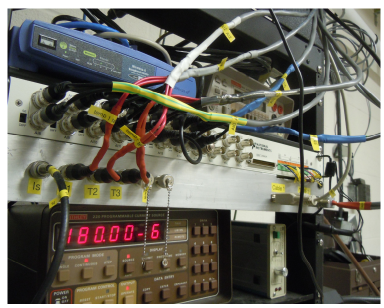


Figure 29: NI-DAQ card break-out board with AI and Digital wiring. Constant current source for RTD thermometer is also shown.

Teamviewer is installed on the Liquefier computer and the LHeP22 computer. Both machines are accessible remotely. Charting and status indicators are remotely viewed, logfiles downloaded and analyzed, and equipment manually controlled remotely.

The bladder level is remotely monitored in real-time by accessing the bladder security camera. The Liquefier computer uses ISpy security software to take snapshots of the bladder every hour. Downloading the time-lapse history of the level of the bladder is a powerful diagnostic which can be remotely accessed and analyzed.

Mathematica software reads the log files from both the Liquefier and LHeP22 computers for charting and diagnostics.

SAFE MODE AND EMERGENCY SAFE MODE

A Safe Mode is instigated by the program under certain conditions. In this mode, the liquefier solenoid valve closes protecting the LHeP22 from impurities. The diaphragm pump is turned off. The purity meter solenoid valves are shut stopping helium flow, and the meter power is de-energized. In this mode, the chiller and bladder over-/under-inflation interlocks remain active.

The Emergency Safe Mode can only be cleared manually by the user.

CONTROL SECTION OF SOFTWARE

The control tab of the Labview program is shown in Figure 30. The conditions depicted in The rows are, from top to bottom, the diaphragm pump, transfer solenoid, liquefier solenoid, bladder relief solenoid, and chiller power. The remaining two rows are associated with the helium purity meter. These are the controlled processes.

The first column is the status of the process. The second column contains a switch that, when lit, allows the computer to control the process (automatic mode). The third column is a manual switch that the user toggles to control the process. Automatic readings of the helium purity meter are activated with one switch.

An important button to note is at the bottom, “Clear Emergency Safe Mode”.

Figure 30 shows the normal operating configuration while liquefying. The computer controls the diaphragm pump, liquefier solenoid, bladder relief solenoid, and chiller power. Reading of the helium purity meter is automatically controlled.

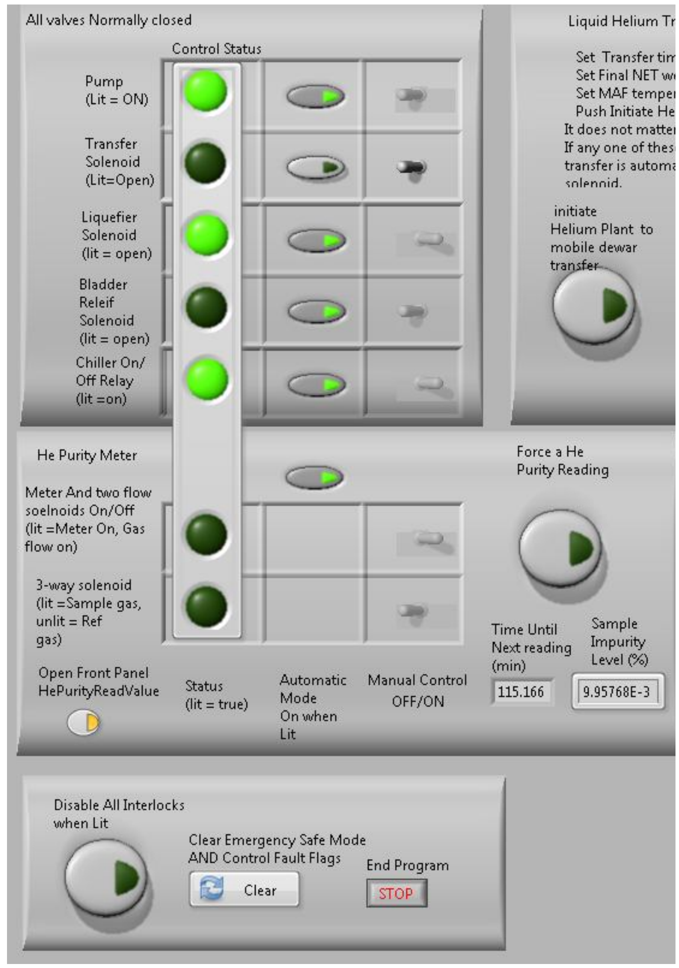


Figure 30: Control tab of the Liquefier Labview software

AUTOMATED PURITY READINGS AND INTERLOCK

A computer program controls the power to the meter and three solenoid valves to control the flow. A three-way solenoid valve allows switching one chamber (labelled “sample gas” on the meter) between reference gas and sample gas. The three-way valve is normally open for the reference gas channel but normally closed for the sample gas. One on/off solenoid valve controls the flow of the reference gas. Another on/off solenoid valve controls the combined sample and reference exhaust gasses that eventually flow into the Liquefier Manifold (see Figure 11b) and routed to the bladder. The meter power and the two on/off solenoid valves are controlled by one relay. The three-way valve is controlled by a second relay. With the automated measurements every 2 hours, a single 300 cuft cylinder of 5.0 reference He gas is estimatead to last 1 year before requiring replacement. The flow rate through the anemometer chambers must be approximately equal and adjusted so that the ball bearings in the rotometers are at ½ to 2/3 of full scale.

Note that the meter must be manually zeroed before automating purity measurements. The zero will drift some amount, so automated measurements include calibrating the zero. However, the zero must be coarsely correct, otherwise the dynamic range of the amplifiers that output the voltage at the analog output could become saturated which would throw off impurity measurements.

The sequence of the automated reading is as follows. The meter is turned on concurrently with the pure helium reference gas flow, and the helium exhaust ports (for both sample and reference gasses) is opened. A user defined delay (90 seconds) allows the lines and anemometer chambers to be flushed and the hot-wire anemometers to warm up. Reference gas flows through both anemometer chambers to measure the zero impurity voltage. The impurity level, averaged over some user defined interval, is consecutively measured with a delay between readings. The user defines the settling tolerance required between consecutive measurements (set to 0.01%). The meter continues to take impurity readings until the criteria is met by the last two readings. Fault flags are set if either the voltage is out of range or the maximum number of readings has been breached. Otherwise, the new "zero" impurity level voltage Vz is recorded.

Next, the 3-way solenoid valve is energized so that sample gas flows through the Sample anemometer. The sequence of impurity level is the same as before: flush the helium lines and Sample anemometer chamber, take and average readings, delay, etc., until the meter has settled within a user defined tolerance. If no fault occurs, then the impurity level is found from the new sample voltage Vs by $m_C \times (V_S - V_z)$ where m_c is the calibrated slope (see Appendix 2).

If the impurity level of the sample gas is greater than a threshold defined by the user (currently 0.021%), then the program instigates Emergency Safe Mode and liquefaction stops.

CHILLER INTERLOCK

The chiller operates continuously under normal conditions. However, if the house supplied chilled water supply is turned off or no longer cold, then the small closed-loop coolant continuously heats up due to the heat generated by the water pump even with the LHeP22 compressor off. To prevent excessive temperatures, a computer controlled interlock has been implemented.

The chiller's on/off switch is wired in parallel to a computer controlled relay. With the power switch off, the computer controls the power to the chiller. If the temperature of coolant breaches a user defined threshold, the chiller is powered off. The threshold is sufficiently high that the LHeP22 compressor automatically turns off before the chiller is powered off.

LIQUID HELIUM DEWAR-TO-DEWAR TRANSFER SHUT-OFF INTERLOCK

A dewar-to-dewar liquid helium transfer is automatically controlled when the user presses the "instigate a helium plant to mobile dewar transfer" button shown in Figure 30. Selecting the button enables the interlock. When activated, breaching a maximum dewar weight, minimum temperature measured by the MAF thermometer, or a maximum time duration closes the transfer solenoid (see Figure 9).

Closing the transfer solenoid valve terminates the transfer since the pressures in the 150L dewar and the mobile dewar equalize.

BLADDER INTERLOCKS

The bladder is outfitted with a high flow -0.22 PSIG vacuum breaker relief valve that prevents catastrophic evacuation that may damage the bladder.

Active interlocks are also required as the system is liquefying. Without an active interlock, the diaphragm pump continues to pump even when the bladder has been emptied and the relief valve is open, dumping large amounts of air into the system and quickly saturating the water and cold traps. A pressure transducer near the bladder measures pressure to 0.01 PSIG. An under-pressure of -0.15 PSIG triggers Safe Mode. By shutting off the diaphragm pump, creasing of the bladder and stress on the bladder near the flange from evacuation is also minimized.

After a user defined time interval passes, the Safe Mode is revoked and the system begins liquefying again. This allows the system to periodically empty the bladder of any helium that was recaptured in the interim.

Over-inflating the bladder is problematic in a closed room. A small pressure integrated over the entire area of a cinderblock wall can be enormous. Therefore, interlocks are required but passive interlocks only operate to pressures down to around 0.1 PSIG. Such a pressure on a single cinderblock is $16in \times 8in$ is therefore 13 lbs. One of the bladder room walls is about 200 cinder blocks, so this small pressure could potentially create about 1.3 tons of outward force.

To guard against over-inflation conditions, the bladder should never be nearly full when the magnet is in use in case of a quench. The reservoir of the magnet is 20LLHe, or about 15% of the bladder capacity. Large catastrophic rapid release of helium into the recovery system cannot happen by any other mechanism.

Active interlocks also guard against over-inflation. Three switches are located in the bladder room. If the bladder over inflates and trips one, an automated alert message is emailed to the user. If any two of the three switches are tripped, a 2" motorized Ball valve is opened until all three switches are closed.

LN LEVEL INTERLOCK

If the LN level drops below a user defined level due to a fault in the refill system or perhaps an empty LN refill dewar, then an Emergency Safe mode is triggered. Since the effects due to low LN level are high helium impurity levels, this interlock is somewhat redundant since helium purity readings are now automated.

POWER OUTAGE INTERLOCK

The power to the room is monitored by the UPS (uninterruptable power supply) connected through the USB port. If the power goes out, Safe Mode is instigated. If the power remains off and the UPS batter level drops to a critical threshold (set in the windows operating system), the computer institutes an Emergency Safe Mode and then powers itself down.

LHEP22 INTERLOCKS

Cryomech has built into the LHeP22 a number of interlocks. If the compressor oil temperature becomes too high (>126F), then the compressor controller shuts off and reports errors. If brown outs occur, then the compressor may shut down and report odd error codes. Under these conditions, the LHeP22 will beep until the system is reset. To reset, switch the main breaker on the LHeP22 off and then on. Read the Cryomech manual regarding other interlocks.

DEFIBRILLATION CHECKS

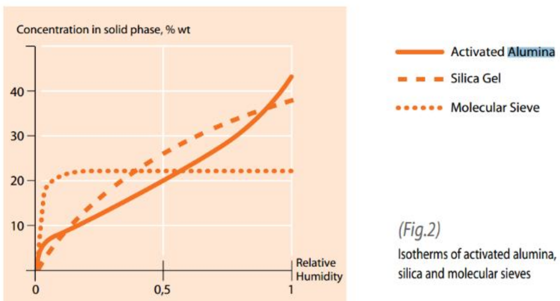
Automatic controls tend to automatically screw up. An extra safety mechanism prevents rapid energization and de-energization of any computer controlled process. The logic evaluation and control section of the program loops rapidly, many times per second. Rapid on-off conditions can damage equipment. Longer time scale on-off conditions integrated over many unattended days can be extremely detrimental to electronics. Therefore, the status of each controller is monitored and evaluated. The user defines the maximum number of on/off cycles that can occur over three time scales, currently set at half a second, 30 seconds, and an hour. If any of these three conditions are breached, the Emergency Safe Mode is instigated.

ACKNOWLEDGEMENTS:

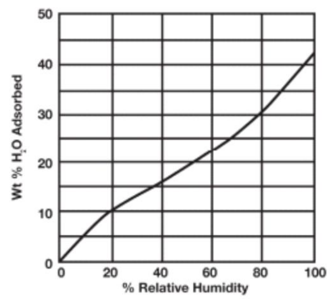
Undergraduates Remington Carey and Garret Sutherland helped write the initial version of the Labview control version, set-up the relay board, and build the mass air flow sensors. Remington Carey, Brendan Bennett, and Tamar Lambert helped with some of the pipe work and preparation of the bladder room. Post-doc Fengguang Liu helped build the water trap and O2 remote sensor displays. Don Schmadel characterized leak rates of test bladders from ATL.

APPENDIX

1. WATER TRAP CONSIDERATIONS



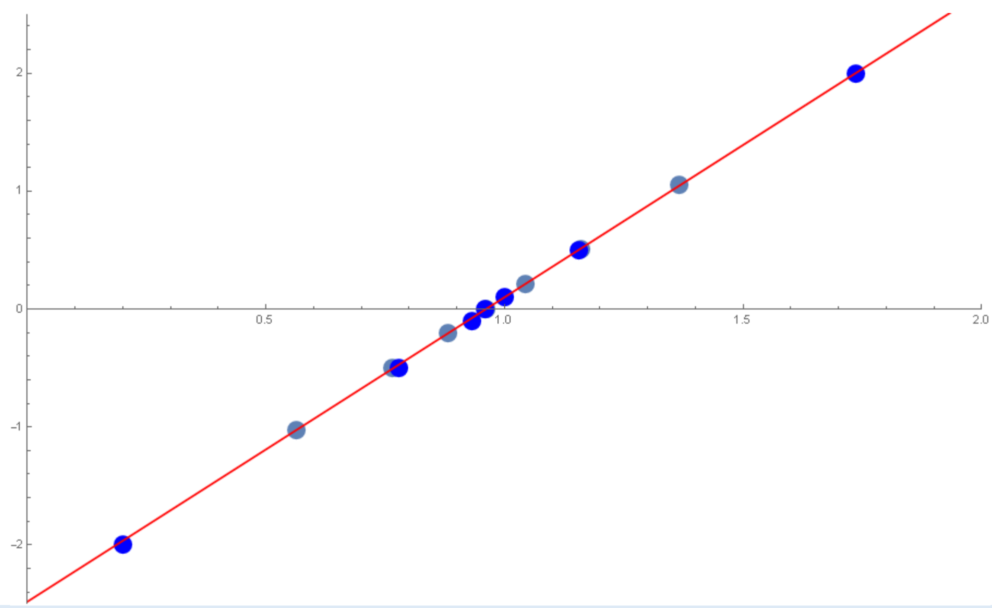
(Fig.2)
Isotherms of activated alumina, silica and molecular sieves



Activated alumina was chosen over silica gel, activated charcoal, and zeolites/molecular sieves. At low relative humidity, the case for recovered helium, zeolites are the most efficacious for adsorbing water. However, the extremely high bake temperature (>300C) makes regeneration difficult. Activated alumina is better than silica gel at low relative humidity and regenerate at relatively low temperatures, >150C. Also, the water capacity of activated alumina is high.

2. HELIUM PURITY METER CALIBRATION FOR AUTOMATED READINGS

In the below graph, the abscissa is the analog output voltage from the helium impurity meter (V) and the ordinate is the impurity level (%). The zero is attained experimentally so only the slope is needed for impurity measurements. The red line is a least-squares regression fit with a slope of 2.583 %impurity/V.



3. HELIUM PURITY METER ROTOMETER CALIBRATION CHART FOR HELIUM GAS: (MM -> ML/MIN)

Supplied by Harry Oyarvide on 5/9/2016, Omega Engineering, Inc., Application/Sales Engineer , Flow Department, Phone: 800-872-9436 ext 2536, hoyarvide@omega.com

012-10-ST FLOWMETER CALIBRATION DATA 012/88

CUSTOMER	CUST. P.O. No	REF. CURVE NUMBER
		0913-02-10

Max. Flow	Min. Flow	Units	Metering Fluid	Date
665	61.0	std. ml/min	HELIUM	09-Sep-2013

Model Number		**Metering Temperature**	70.0 °F
Tube Number	012-10-ST	**Metering Pressure**	14.70 psig
Serial Number		**Metering density**	0.0001656 g/ml
Float Material	ST.STEEL	**Metering Viscosity**	0.01980 cp
Float Density	8.04 g/ml	**Density at STD.Cond**	0.0001656 g/ml
STD. Conditions	STP: 1 atm @ 70 °	**Accuracy**	+/-2%FS
Room Temperature	70.0 °F	**Barometric Pressure**	14.70 psig

SCALE READINGS AT CENTER OF FLOAT

Scale Reading (mm)	Flow
65	665
60	584
55	515
50	449
45	390
40	330
35	276
30	230
25	188
20	149
15	117
10	88.0
5	61.0

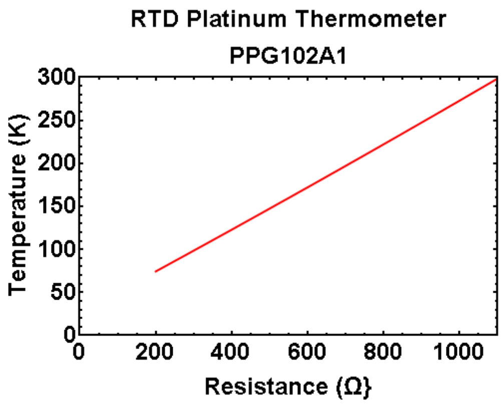
4. PERTINENT FACTS (CONVERSIONS ETC.)

- 0.2754 lbs liquid helium = 1 liter liquid helium, 1.777 lbs liquid nitrogen = 1 liter liquid nitrogen
- 1/2% per day of impurities for about 10LLHe in bladder; LN trap increased total purity in bladder by 1%/day
- conversions ~770 for expansion of liquid into gas at 298K ~ 76F (crymech says 754)
- 1 L LHe --> 27.3567 ft^3 gas, 1 L LHe --> 0.774656 m^3 gas
- “A” cylinder volume ~ 250 ft^3 --> 9 LLHe, 300 cuft cylinder ~ 11 LLHe
- 300K to 4K costs 74x the energy than to liquid-solid energy
- For 2nd stage cooling power of (1.5 J)/s, gas at 4.22K can be liquified at rate of (50.087 L)/day
- The cost of using only latent heat of vaporization of LN to precool Helium gas from room temperature to 77K = (1.28721 Dollars)/LHeLiters
- The power required to heat 100L of helium gas from 4.4K to 295K in 3 hour is (151.364 J)/sec producing a volume of gas equivalent to 8.65487 L of liquid helium. Note that for real mobile dewars, there exists thermal gradients from room T at top to 4.4K at bottom which will cut the power and volume of gas released ---- very approximately say half.
- To fill a 3.068 in^2 ID pipe that is 6 ft long with equal sized spheres of alumina requires 14.7853 lbs of alumina, and can hold approximately 1.0 L assuming ~ 10% relative humidity
- The LN cold trap with zeolites is quoted as able to adsorb 1 Kg of air. Assuming N2, a flow rate of 23 LLHe/day and 5% impurity level gives 1.8 days run time.
- 14’x24’x10’; Bladder is 3400 cuft volume ---> 125 LLHe, .040" thick, 350 lbs; Extrapolation of test bladder leak rate ---> ~15 LLHe / year
- With LHeP compressor off, ~45L LHe inside 150L dewar, boil off averaged about 0.3 LLHe/hour over 21 hours
- From McMaster “Also known as instrumentation fittings (York), they are compatible with Swagelok®, Parker A-Lok, and Let-Lok fittings. “
- If water output > 126F measured by LHeP22, the compressor will shut down and produce an “error” (as opposed to warning). The compressor will stay off until user manually resets software. Note that for oil>130F or He>149F, the compressor will shut off.
- It took about 44 hours to go from Room T empty 150L dewar to producing measurable level of liquid helium accumulation in dewar.

- The level is sensitive to conditions in the dewar like pressure and whether cold head is on or off regardless of actual level. This variation appears to be about ~3L.
- An empty 150 L dewar with T=4K gas will be 150L*295K/4K ~ 14.5 liquid liters worth of helium.

5. RTD THERMOMETERS

RTD PART NUMBER PPG102A1 (RESISTANCE VS. TEMPERATURE TABLE) _ U.S. Sensor Corp_files




```
InputForm[TempF[r]]
-411.63749697085484 + 0.4272674699314844*r + 0.0000161106126050349l3*r^2 + 2.55575156917786 5*^-13*r^4

Clear[TempF2, res];
TempF2[res_] = Fit[TdataF2, {1, res}, res]
-468.12 + 0.493113 res
```

6. DAHUA ETHERNET CAMERA INFO: DH-IPC-HFW4300S

ethernet jack in Phys Room 2315
3c241/3c242

Dahua
Model DH-IPS-HFW4300S-V2-0360B
PN 1.0.0.01.04.4847
SN 1G01D94PAU00231
MAC 4C:11:BF:CE:51:8F
Network Name: IPC

Login: <my UMD user ID>
Password:<usual lab password>

Login: admin
Password: <usual lab password>

phantom power through network
75' ethernet
gigabit switch

7. RELAY BOARD AND COMPUTER CONTROL NOTES:

How to wire up the relays and computer so that devices remained powered down in case of power outages (and subsequent restoration of power):

The program will send a signal of either 0 or 1 to the relay, which will either turn something ON or OFF depending on the relay's mode. The relay has two modes. Under both modes, the relay compares the voltage reading of the +5V output and the digital output from the computer.

- Normally Closed
    - If the inputs are EQUAL, then the switch is closed and the device is powered ON.
    - If the inputs are UNEQUAL, then the switch is open and the device is OFF.
- Normally Open
    - If the inputs are EQUAL, then the switch is open and the device is powered OFF.
    - If the inputs are UNEQUAL, then the switch is closed and the device is powered ON.

Normally the computer regulates the digital outputs against the +5V output. However, when it shuts down, this regulation stops and the digital outputs become equal to whatever the +5V output is (and this output is decaying in accordance with some capacitance time constant). Since we want the devices to shut OFF with the computer, this means we want the device to shut OFF when the voltage readings are EQUAL. This means we must use the normally open setting. (Otherwise, under normally closed, when the computer shuts down the voltage readings would be equal and the pump would turn on).

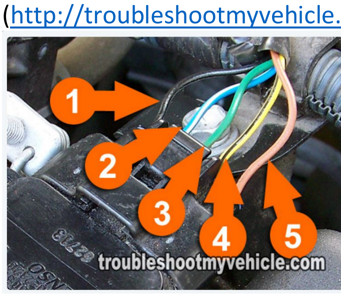
The computer also does not begin to regulate the digital output voltages until a program tells it to do so. This means that when the computer turns back on, the voltage readings are still equal and the devices remain off. This is also what we want.

Finally, under normally closed, if the power to the relay switches off, so does the power to the devices. This is what we want in case of a power outage. So our settings are:

- Normally closed
    - 0V (=0) powers the device ON
    - +5V (=1) powers the device OFF

8. MAF SENSOR (TOYOTA COROLLA 1.8L) WIRING DIAGRAM:

(http://troubleshootmyvehicle.com/toyota/1.8L/how-to-test-the-maf-sensor-1)



MAF Sensor Connector Pin Out

Pin	Wire Color	Description
1	Black	Fused power (12 Volts)
2	Blue w/ White stripe	MAF sensor ground (PCM)
3	Green	MAF sensor signal
4	Yellow w/ Black stripe	Intake Air Temp (IAT) Sensor
5	Brown	Intake Air Temp (IAT) Sensor

Automotive mass-air-flow (MAF) sensor as a helium flow sensor

MAF sensor in series with a calibrated (ball type) flow meter and a throttling valve with gas driven by a helium gas cylinder

Industrial grade helium (>99.9%) flowed through a throttling valve, a flow meter (rotometer, the type with a ball in a glass tube) calibrated for helium gas, and then an automative MAF sensor. The maximum scale of the calibrated He flow meter is 160 cfh.

Historically, the minimum flow rate of helium through an Argon calibrated rotometer, used when adjusing helium flow through the Janis cryostat, has been approximately 5-8 cfh. The conversion to helium volumetric rate is 1.18/0.37=3.2, so the minimum is ~15-25 cfh. Maximum flow rates estimated from the magnet transfer are as follows: 50L transfered out of a helium dewar filling a 20 L reservoir over 1.5 hours gives an average gas flow rate of 30L liquid/(1.5 hr) * (780 L gas)/(L liquid) * 1 cuft/ 28.3L = 550 cfh.

Two geometries were characterized: one with the automative MAF sensor inserted directly in the flow stream unmodified, and the other with a peice of tape (baffle) covering the central hole in the meter which deflected more gas flow over the hot wire. A signal of 3V generated in both geometries corresponded to helium flow rates of 160 and 80 cfh respectively, or an increase in the baffled helium flow across the hotwire which is a factor of 2 times larger.

The baffle lowered the minimum measurable flow rate by this factor, and was determiend that this geometry best suits the (adjustable) laboratory MAF sensor. The minimum acheivable flow rate is ~15 cfh, cubic feet per hour. The MAF sensor signal saturated at a much higher flow than the calibrated meter maximum of 160 cfh, and found to saturate in the vicinity of ~380 cfh. This higher flow rate was calibrated by filling a large bag for a time ΔT at 160 cfh, and then filling the same volume at the unknown higher flow rate and measuring the time $\Delta T'$. The high unknown flow rate is given by 160 cfh x $\Delta T/\Delta T'$.

Since the range of the meter is about 15-380 cfh with a baffle, without a baffle would give roughly 30-700 cfh. Adjusting the angle of the meter wiht respect to the flow direcion can further tune this dynamic range.

Note that air impurities will tend to lower the MAF sensor reading.

Import data and plot

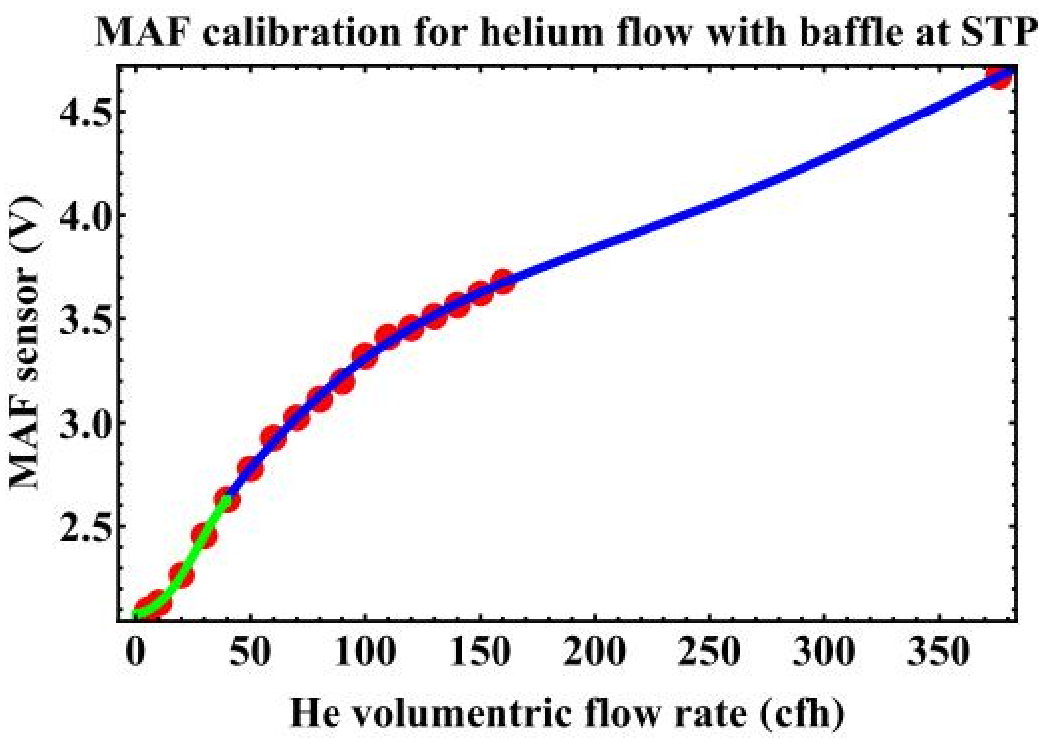
Fit data

In[141]:=
```
splitpt = 5;
maxnum = Length[data3];
fitfHiFR[x_] = Fit[Take[data3, {splitpt, maxnum}], {1, x, x^2, x^3, x^4}, x];
fitfLoFR[x_] = Fit[Take[data3, {1, splitpt}], {1, x, x^2, x^3, x^4}, x];
Print["Hi flow rate fit: ",
  fitfHiFR[(FR)], "\nLo flow rate fit: ", fitfLoFR[(FR)]];
pHiFR = Plot[fitfHiFR[x], {x, 40, 400}, PlotStyle → {Blue, Thickness[.01]}];
pLoFR = Plot[fitfLoFR[x], {x, 0, 40}, PlotStyle → {Green, Thickness[.01]}];
Show[p1, pHiFR, pLoFR]
Show[p1zoom, pHiFR, pLoFR]
```

Hi flow rate fit: $1.87809 + 0.0228673\,FR - 0.000110887\,FR^2 + 2.77145 \times 10^{-7}\,FR^3 - 2.43243 \times 10^{-10}\,FR^4$

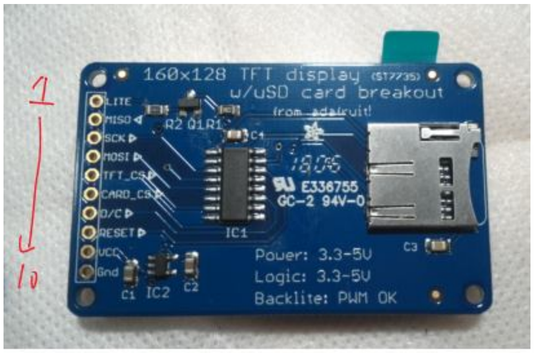
Lo flow rate fit: $2.07695 + 0.00264762\,FR + 0.000216667\,FR^2 + 0.0000106952\,FR^3 - 2.28952 \times 10^{-7}\,FR^4$

Out[148]=



9. ARDUINO 1.8” TFT DISPLAY WIRING CHART O2 SENSOR CALIBRATION CHART

The refresh rate is every second. Analog input #0 measures the voltage across a metal film resistor that is grounded on one end. The O2 concentration current output from the wall mount O2 meter is copied from the spec sheets:

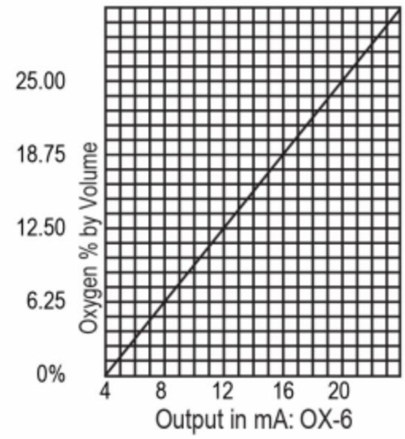


	1.8" TFT Display Pin #	Arduino Pin #
Lite	1.	3.3V
MISO	2.	XXX
SCK	3.	Pin 13
MOSI	4.	Pin 11
TFT-CS	5.	Pin 10
Card-CS	6.	XXX
D/C	7.	Pin 9
Reset	8.	Pin 8
Vcc	9.	5V
GND	10.	GND

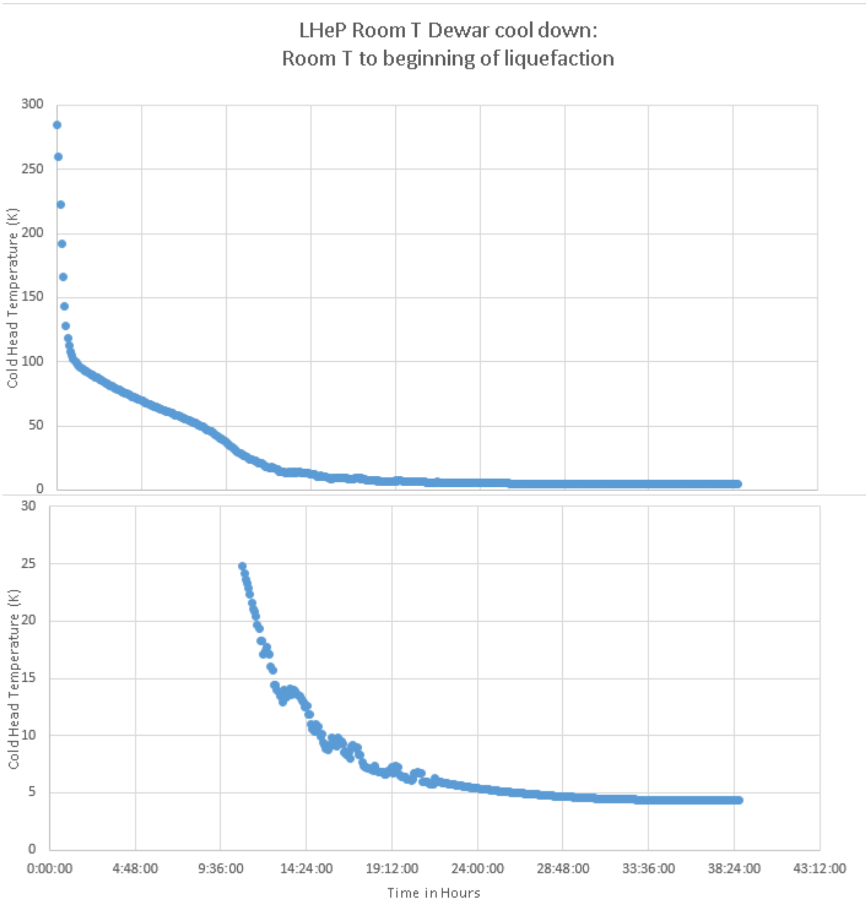
Note that the "disable" fan setting will cause the fan relay to not engag
the Trouble Fan Setting Option is set to "On") and will disengage once t

10. The Current Loop is 4 mA at 0% v/v, 17.4 mA in clean air (20.9 v/v) and

Note: Increased levels of oxygen may dramatically increase the flamma
23.5% v/v the Fan Relay and Alarm Relay will be activated. This is a pr

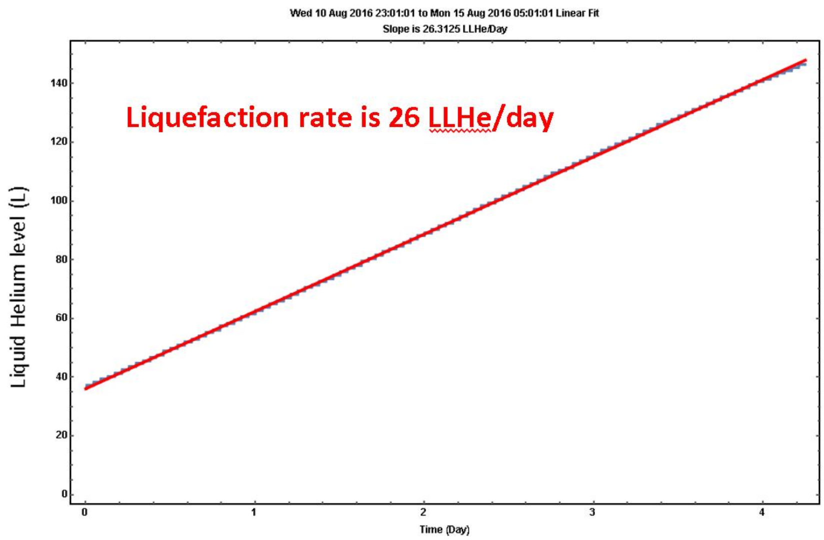


MAY, 2016: COOL DOWN OF LHEP 150L DEWAR FROM ROOM TEMPERATURE TO START OF LIQUEFACTION



August 2016: Top-Off 60 L Dewar, Inject industrial grade Helium from cylinders into Bladder, and transfer from 150L dewar to a Room temperature 100L mobile dewar

10. AUGUST, 2016: LIQUEFACTION RATE OF CRYOMECH LIQUID HELIUM PLANT 22



11. MITIGATING BLADDER LEAKS ---- AUGUST-SEPTEMBER, 2016: DEWAR BLOW OFF RATES

Since the bladder leaks helium at a rate of around 0.5 liquid liters/day, an order of magnitude larger than expected based upon earlier test bladder leak rates which agreed with the calculated bulk permeability of the material, it is not feasible to recover helium dewar blow-off into the bladder. The blow off of the dewars are specified to be less than 0.5 liters/day under the condition that the dewars are maintained at low pressre of around ½ psig.

An alternative configuration is connecting the mobile dewar vent valve (with ½ psi check valve) directly to the cryomech liquid helium plant dewar. The following tests show this configuration. The cold head re-liquefies the mobile dewars helium blow-off into the 150L dewar. The blow off rate can be characterized by measuring the rise of the liquid level in the 150L dewar.

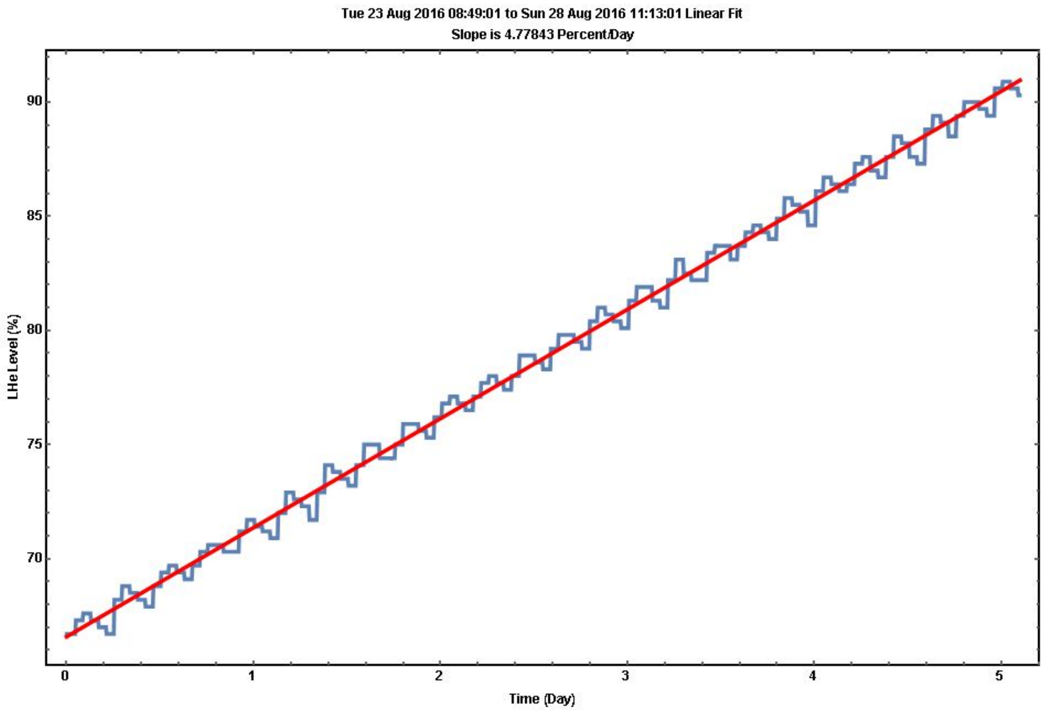
The following three test results show the blow-off rates under three configurations of the liquid helium plant:

(1) Auto on/off mode, where the cold head turns on when the dewar pressure reaches 8 PSI and turns off at 0.5 PSI; results in 4.8 LLHe/day for both mobile dewars.
(2) Auto on/off mode, where the cold head turns on when the dewar pressure reaches 4 PSI and turns off at 0.5 PSI; results in 4.1 LLHe/day for both mobile dewars
(3) Auto-continuous on/off mode, where the cold head turns stays on and heater turns on to maintain the dewar pressure at 0.75 PSI; results in 2.6 LLHe/day for both mobile dewars

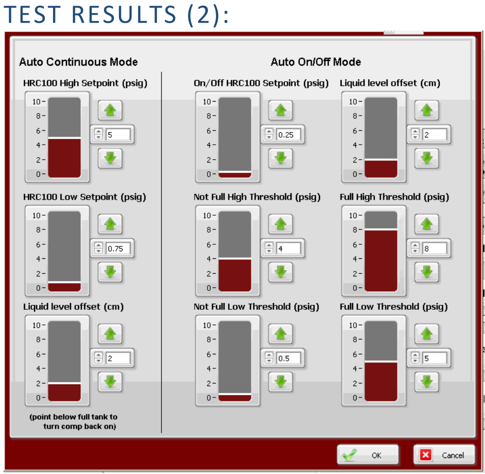
In all three conditions, note that the pressure in the mobile dewars is 0.5PSI higher than the 150L dewar due to the check valve.

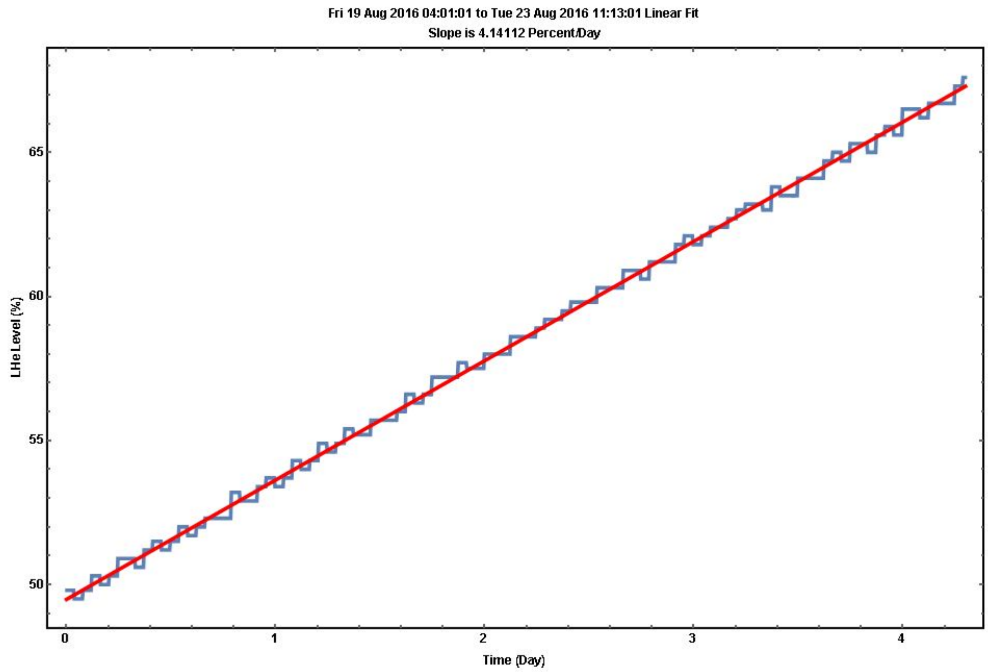
TEST RESULTS (1):

For cryomech liquid helium plant configured at factory settings, blow off of the two dewars (each initially almost full, where 60L dewar has about 50LLHe and 100L dewar has about 90LLHe), into the 150L dewar cryomech is about 4.8 LLHe per day. Note that the graphs are mot labeled correctly here (Level was measured in liquid liters, not percent)

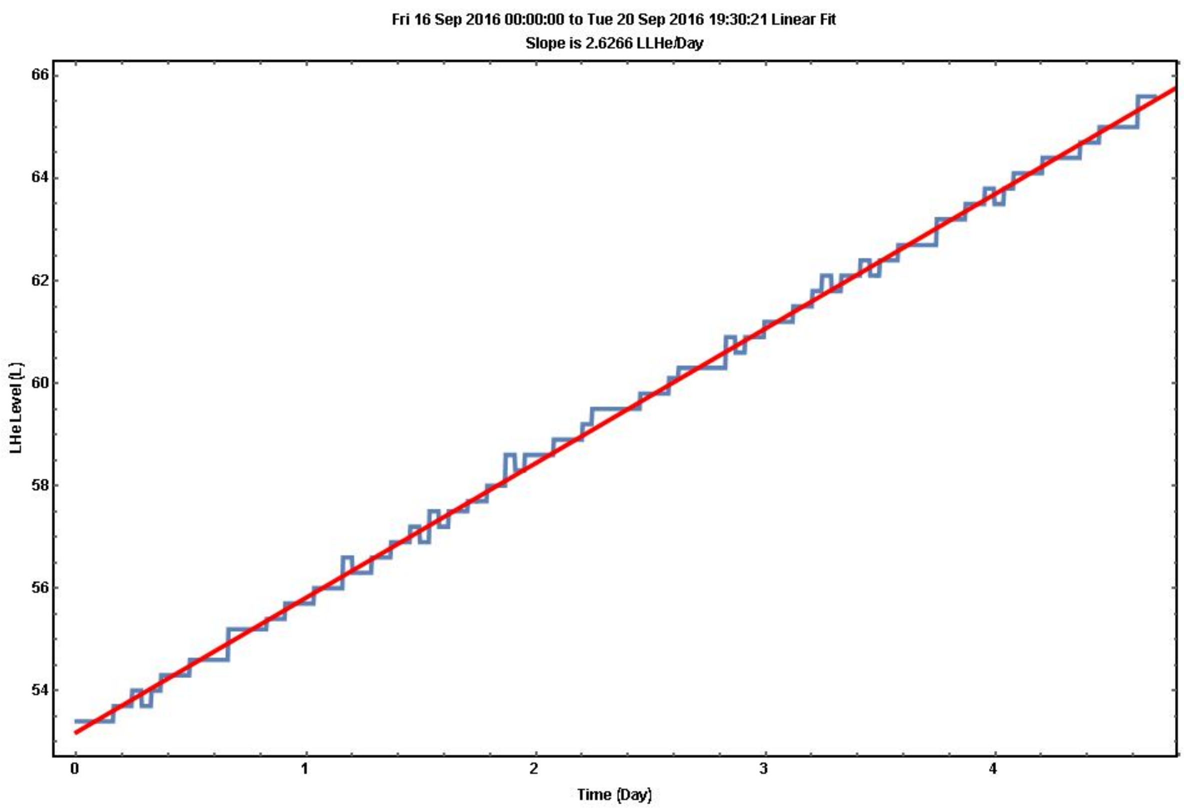


TEST RESULTS (2):





TEST RESULTS (3):



LEAK TESTING

Leak testing the plumbing is most effieciently done by pressuring the pipes and using a soapy water mixture, brushed on the joints. If no bubbles appear within a minute or so, then the leak rate is insignificant for a helium recovery system.

12. VARIOUS ITEMS THAT SHOULD BE IMPLEMENTED AS OF 5/22/2016

- Interface computer with cyromech LHeP22 compressor in order to coordinate chiller with compressor on/off status
- Pump interlocks on lab manifold to prevent pumping on the bladder with the lab vacuum pumps

Possibly implement:

- A way to salvage/scavange LN from wide-mouth 240L dewar
- Mount 240L LN vent pressure regulator to the wall
- Replace scroll pump with sealed pump from He3 system.

Lessons learned: What I would do differently

- Connect a flexible line to the bladder flange instead of using inflexible PVC pipe
- Invest in a large motorized ball valve immediately before the bladder flange to better guard against under and over inflation conditions
- Use smaller diameter pipe for all helium lines --- it was very difficult to plumb all the pipe, contrary to the advice I received. I should not have engineered the system to recapture the helium from magnet quenches.
- Never do business with Quantum Technology --- A much better helium purity meter is now sold by Stanford Research that utilizes speed of sound instead of hot wire anemometry; The Quantum Technology cold trap was not engineered. I could have engineered it and built two of them fairly easily instead of paying an exorbitant amount of money for essentially welded stainless steel pipe.
- Maybe it would have been better to go to a compression system, but was much too expensive for our system when facilities costs are included