LABORATORY HELIUM RECOVERY SYSTEM MANUAL

REVISION 2.0

Designed and built by:

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Manual last updated on 6/15/2017

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PREFACE

Many U.S. researchers have suffered from the increased helium prices over the last decade. The initial inclination from the sudden price shocks was to throttle the number of low-temperature experiments, or to emphasize or switch to less cryogenically hungry projects. Some institutions mitigated the problem by pooling resources to install large centralized helium recovery systems. Those at institutions that did not have such collective foresight were forced to consider laboratory-scale solutions. At UMD, some of the larger research groups began buying individual closed-loop “dry” systems, one at a time. This further solidified the mindset that a central system was not worthwhile. In the end, the cost of these individual systems far exceeded the cost of a large centralized recovery system.

Our laboratory has four continuous flow cryostats, two superconducting magnets, and five bolometer detectors. A closed-loop liquefier system on the most frequently used magnet system would have mitigated a substantial percentage of the cost of magneto-optical measurements. However, vibrations from the liquefier cold-head are a big concern. Also, some experiments require constantly sweeping the magnetic field. The boil-off under these circumstances becomes much greater than the condensation rate of liquefier cold heads. A closed-loop system therefore will not work with our magnet system.

Optical cryostats outfitted with cold-heads potentially suffer from similar vibration-coupling issues. Furthermore, none of our existing cryostats have helium reservoirs than can be maintained by a cold-head. Modifications to correct this problem are untenable in light of the cost and loss of portability. Existing cryostats would, at a minimum, need to be replaced.

Continuously running bolometer detectors with small 1L helium reservoirs do not require large amounts of helium, but the liquid helium needs to always be available. The losses from the blow-off from standing dewars and frequent transfers add up quickly.

Most of our measurements concurrently use multiple cryogenic systems. Magneto-optical measurements often require cooling two bolometer detectors, a magnet, and a continuous flow cryostat. Spectroscopy measurements nearly always require cooling a continuous flow cryostat and bolometer detector.

Members of the laboratory made conscious and subconscious decisions to throttle the amount of acquired data, place exploratory measurements on the chopping block, and implement painful measures to reduce the consumption of helium by stringing together multiple 24-hour per day experiments. The increasingly drastic measures led to a decision to build a central laboratory-scale recovery system.

Funding agencies are reluctant to shell out more grant money for the same amount of helium used in the past. However, DOE and NSF recognized the devastating effects of the skyrocketing price of helium on research groups and provided substantial investment for helium recovery. The funding level did not cover our entire expense, but was enough to purchase major components. A shortfall in funding was compensated by building system components and infrastructure. By consensus, this cost was agreed to be shouldered among laboratory personnel. And therein lies a problem!

Although eventually benefitting everyone, the project would immediately penalize those involved by taking time away from other immediate concerns. In a university research environment with transient students and post-docs that are under various pressures to quickly produce “important” results, and research scientists and faculty whose time is constantly under fire, this penalty is burdensome.

I am very thankful for the help I received, and acknowledge those contributions to the project at the end of this manuscript. However, the cumulative amount of assistance I received from students and other current and former members of the laboratory over the course of the project was less than 5% of the total. The shortage of assistance was not solely due to lack of enthusiasm, but involved the sheer number of skills required to engineer and build it, not to mention repairing and modifying existing cryogenic systems that interface with the system.

I attained funding for the project, engineered the system, fabricated components, and built the system. During this time, I generated high quality research and publications, and authored basic research proposals, three of which were awarded. The entire project took about 1 ¾ years spread over 3 ½ years.

The initial goals of the helium recovery system were to deliver nearly free liquid helium to the laboratory with very little time and attention devoted to the recovery process. The system is safe, easy to use, supplies more than enough liquid helium to continuously run experiments indefinitely, and the recovery rate is 98% (averaged over 1 year). A large amount of automation was built into the system practically eliminating technician-level work, relegating the burden on laboratory personnel to an insignificant level.

REVISION NOTES

The original manuscript was posted in PDF on 10/02/2016. Since that time, substantial modifications have been implemented. The description of these changes in this revised manuscript entitled "*Laboratory Helium Recovery System Manual, Revision 2.0"* include the following:

(1) Addition of a second water trap (with two heaters);
(2) Addition of automatic regeneration hardware for the cold trap and water traps. This includes several modifications to the Mechanical Room manifold, addition of many motorized ball valves & solenoid valves, a scroll pump, an air pump (diaphragm compressor), 11 K-type thermocouples, and multiple relief valves;
(3) Addition of a second band heater for the cold trap;
(4) Installation of an additional NI-DAQ card (PCI-6035E) with SCSI connector break-out block with screw terminals that are wired to a DB-25 connector break-out block with screw terminal block;
(5) Addition of a DB-25 connector break-out block with screw terminals that is wired to the NI BNC-2060A that interfaces with the existing NI-DAQ 6361 card;
(6) Installation of a countdown timer with built in relay that actuates a new solenoid valve attached to an industrial grade nitrogen cylinder to automatically shut-off gas flow while purging a cold liquid nitrogen capacitance level gauge when removed from the liquid nitrogen bath;
(7) Addition of a local area network with a new router to harbor an XP windows touch-panel computer (included with the Cryomech LHeP22) since the operating system was banned from the UMD network. The LAN includes the Helium Recovery System (HRS) Windows 7 computer that runs the control software. Drive sharing allows the HRS software to read the LHeP22 logfiles in real-time. Teamviewer provides remote access and control of both computers;
(8) Replacement of 10 PSI relief valves on the 60L and 100L mobile dewars with 15 PSI relief valves;
(9) Addition of an automatic PID-feedback heater to warm the cold helium exhaust gas from the Oxford magnet during liquid helium transfers;
(10) Implementation of a diagnostic Mathematica program that reads LHeP22 log files, iSpy bladder pictures, and Helium Recovery System control software log files and compiles summaries of system performance as well as time-lapse bladder videos (used for leak testing);
(11) Addition of 5 PowerTails, each device housing a 15A@120V relay, to computer control six heaters and a vacuum pump;
(12) Addition of two digital pressure gauges mounted to KF-25 flanges to the mechanical room manifold
(13) Addition of an electronics box that houses 24 relays, three dc power supplies, twelve computer actuated 120V outlets and eight computer actuated 12V outlets with BNC connectors to control PowerTails, amplifiers for 12 k-type thermocouples, two BNC analog input connections for the pressure gauges, and one analog output BNC connector.
(14) Major upgrades of the helium recovery system control software include automatic regeneration of cold and water traps (involving automated control of 13 devices), notification alerts (via SMS, email, and/or Pushetta) from system errors or completed processes, transfer exhaust heater control, and a revised tabbed layout suitable for easy manipulation from touch-panel displays,

HELIUM RECOVERY SYSTEM OVERVIEW

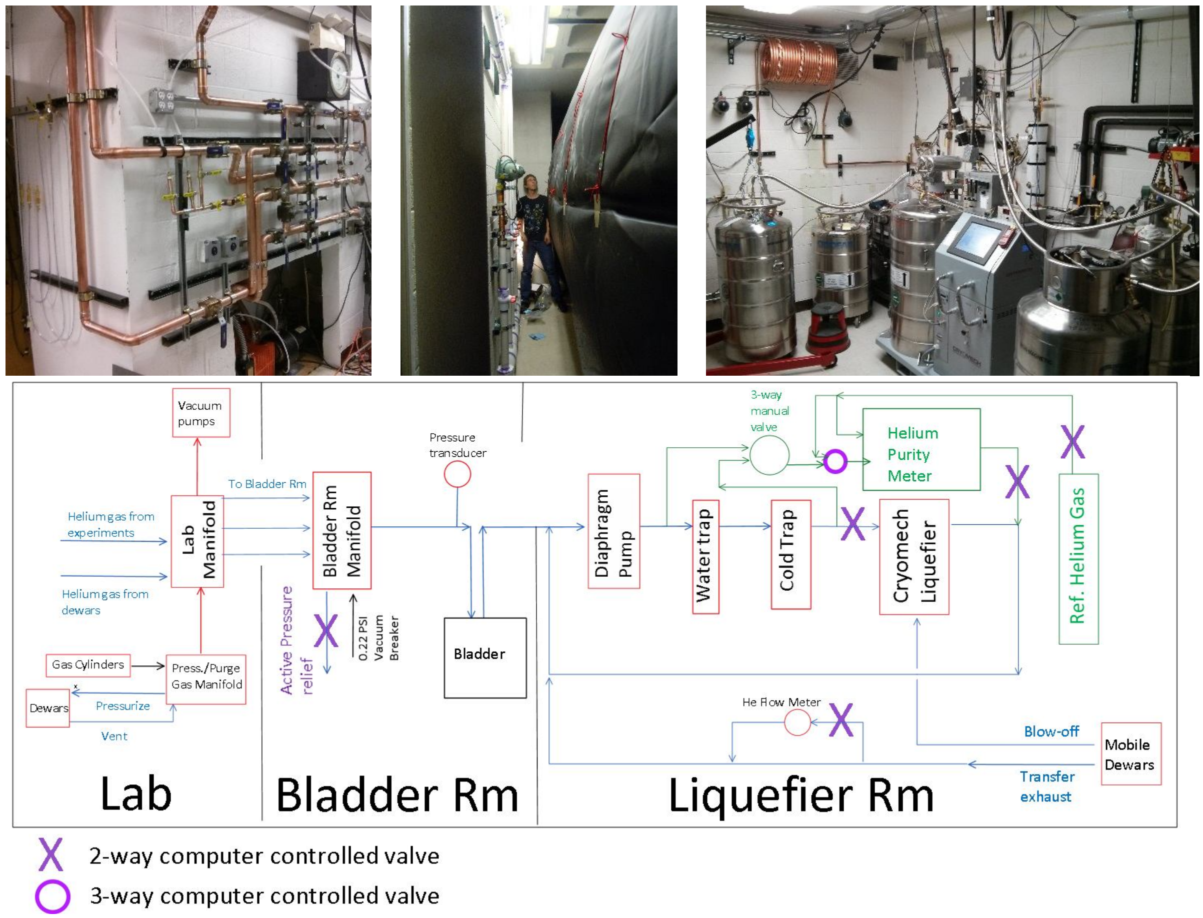


Figure 1: Pictures of the laboratory manifold, bladder room, and liquefier room are shown in the top row. The bottom schematic shows the major components of the system.

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

Figure 1 shows a simplified schematic of the main components of the system. Arrows indicate the flow of helium gas. 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 laboratory exhaust lines into one large line that interfaces with a 3600 cu. ft. helium recovery bladder (Figure 1b). The bladder acts as an accumulator for the 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 (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 helium recovery process begins anew.

The above schematic omits extremely important 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 four main sections: Liquefier room, Bladder room, Laboratory, and Helium Recovery System acquisition and control computer. The purpose and function of the subcomponents are discussed in each of these sections. The final section discusses the Helium Recovery System acquisition and control computer.

LIQUEFIER ROOM

CRYOMECH LIQUID HELIUM PLANT 22 (LHEP22)

The heart of the system is the Cryomech helium liquefier plant, the 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: A helium purity meter is attached to the chassis of the Cryomech Liquid Helium Plant 22.

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 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 (like in a typical 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 the cold head and rests on the bottom of the dewar. An onboard touch-screen 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 by cycling the power to the compressor. When the compressor is off, 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, the dewar heater is turned on to maintain 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 by the heater.

The user supplies purified helium gas to 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 excessive 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 to regenerate the cold head. The process takes about 10 days to naturally warm an empty dewar to room temperature. Cycling warm gas through the dewar would considerably reduce this time. To regenerate, evacuate the warm 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, reorienting the helium gas input to the back of the unit, and mounting a helium purity meter and liquid nitrogen autofill controller to the top.

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

HELIUM PURITY METER

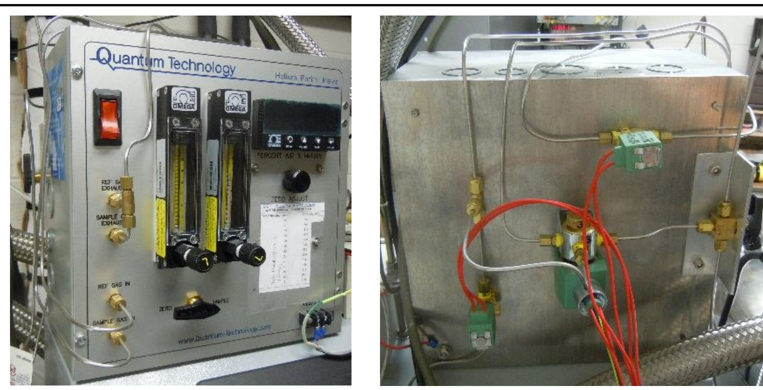


Figure 3: Three computer controlled solenoid valves are mounted to the back of the helium purity meter to automate readings.

Quantum Technology makes the helium purity meter. 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 zero the meter. Once zeroed, a sample gas is then routed through one of the anemometer chambers and compared with the reference gas chamber.

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 rotameters (see Appendix 0 for calibration charts). The gas purifier produces purified helium gas for 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 analog output voltage from the meter is measured by computer. Calibration of voltage output to impurity level was performed (see Appendix 3). 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. An application note on the operation of the meter specific to helium recovery applications was posted by Stanford Research at my request during the construction of the IREAP helium recovery system.

DIAPHRAGM PUMP ASSEMBLY

A Gast MAA-P102-MB diaphragm pump draws helium from the bladder (very near 0 PSIG) and pressurizes upstream components. The diaphragm pump can produce much larger flow rates and pressures than necessary. Upstream 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 output and input to 5 PSI. The diaphragms permanently deform if left under vacuum or pressure for long durations, which eventually causes premature failure (and leaking). When the pump is off, the bypass valve is manually opened to equalize the pressure between the input and output ports and therefore between the two sides of the diaphragms.

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

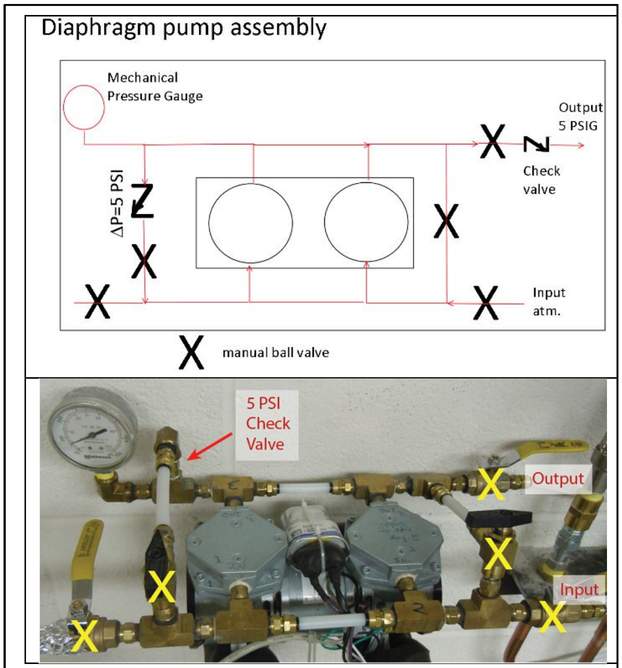


Figure 4: A diaphragm pump assembly draws helium from the bladder and pressurizes components upstream.

The diaphragms are rated for 6 months of continuous use. However, since the pressure differential on the diaphragms is maintained at 5 PSI, the stress on the diaphragms is much less than the rated 120 PSI output pressure of the pump. Therefore, the diaphragms have not yet been replaced after about 2 years of use. 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 checked for leaks. 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 thread 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 connections. Loctite 565 was used to seal some threads where over-tightening fittings is especially problematic. A special surface adhesion layer made by Loctite, 7649 Primer, was pre-applied to the aluminum pump housing. It is required for inactive surfaces like stainless-steel and aluminum.

PURIFICATION OF HELIUM

WATER TRAPS

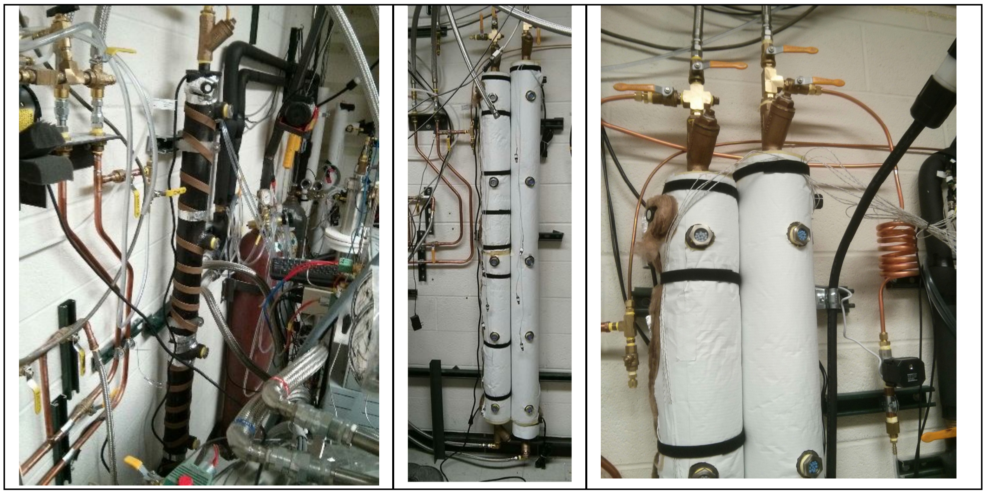


Figure 5: The water traps are filled with activated alumina. (left) A water trap with the fiberglass insulation removed reveals the silicone heater tapes and thermostats. (center) The two traps are mounted side-by-side. (right) Helium gas enters the top of the traps and exits the bottom. During regeneration, a counter flow of air enters the bottom of the trap and exits the top of the trap. This exhaust gas is routed through a cooling coil and then a motorized ball valve.

The helium from the bladder and diaphragm pump is routed through water traps. The traps are filled with beads of activated alumina. Blue 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 can form that block the flow of helium. Also, the zeolites in the adsorbing bed strongly trap polar water at the expense of trapping other nonpolar impurity gasses like oxygen and nitrogen. 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 were welded to a 6ft long 3” diameter black steel pipe. Two 1” NPT Wye 150 mesh filters on either end retain the beads. Each 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 saturated. Each trap is equipped with a 10 PSI relief valve mounted on the manifold.

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, the traps saturate in about 2 weeks in (dry) winter time, and between 1 and 1.5 weeks in (humid) summer time.

The activated alumina is regenerated by baking and supplying a counter flow of air. For each water trap, two 720W (10’ long 1” wide) silicone heater tapes with regulating thermostats are wrapped around the 3” diameter pipes secured with Kapton tape. The heaters are rated to 233C. Effective regeneration temperature for activated alumina is 150C. For each trap, four K-type thermocouples measure the upper and lower pipe and heater temperatures. The traps are wrapped in 1” thick high-temperature glass-fiber insulation. The thermostats are tuned to automatically maintain a pipe temperature above 150C and a heater temperature below 230C.

One trap is actively scrubbing at any given time. When the active trap becomes saturated, the other trap is brought into service and the saturated trap regenerated. The regeneration process involves heating the activated alumina while counterflowing air through the adsorbing bed. The idea is that the heated ambient air has an extremely low relative humidity at 150C, so easily drives the water from the zeolites. A diaphragm pump provides the air flow.

The entire regeneration process has been automated. A computer monitors eight k-type thermocouples mounted to the two water traps, an air exhaust thermocouple, and trap pressure. The computer controls an air exhaust motorized ball valve, evacuation motorized ball valve, purge solenoid valve, vent solenoid valve, and a scroll vacuum pump. The water trap automatic regeneration sequence is about 14 hours long.

COLD TRAP

Quantum Technology make the cold trap. 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 zeolite bed removing impurities like nitrogen and oxygen. An output helium purity is better than the limit of the helium purity meter sensitivity, 99.99%.

Figure 6: The cold trap is removed from the liquid nitrogen bath.

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 water that may accumulate (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 installing the water traps, no ice or 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 liquid nitrogen dewar with a 9.25” diameter neck. Trap pressure should always be maintained above atmosphere, especially during cooling and while cold. An industrial grade helium cylinder ensures that the cold trap pressure never drops below ~2 PSIG except during regeneration. The adsorbing bed requires about 1.5 hours in liquid nitrogen to sufficiently chill from room temperature.

Quantum Technology specifies that the trap capacity is about 1 to 1.5 kg of dry air, which translates into 9 days of continuous flow at 22 LLHe/day and a 99% input helium purity level. Experimentally, the cold trap typically lasts 1.5 to 2 weeks, but depends strongly on helium purity levels in the bladder and therefore on run-time conditions. The heat exchanger in the neck is a poor design causing icing of the neck outside the dewar. The mass of the trap is too large causing copious amounts of LN boil-off when cooling from room temperature as well as excessive warm-up time when regenerating. The lack of a supporting flange requires the trap to continuously hang 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 “output” 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.

Figure 7: Two band clamp heaters quickly warm the cold trap and prevent excessive icing during regeneration.

Cold trap heaters:

During the regeneration process, two 1200 watt @ 120V mica band heaters are warmed and then clamped to the cold trap immediately upon removing from the liquid nitrogen bath. This prevents copious icing that insulate the vessel and therefore greatly reduces regeneration time. The two heaters are wired in parallel and driven by a Variac set at 60V. A k-type thermocouple is mounted to the heater. The temperature of the trap should never exceed the melting point of solder, ~190C.

The cold trap is automatically regenerated by the HRS control computer in about 8 hours.

LN Autofill system:

The liquid nitrogen level of the cold-trap bath is automatically maintained. Optimal level is near the bottom of the 4" diameter cold-trap neck. An American Magnetics LN level capacitance 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 an external cryogenic solenoid valve 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.

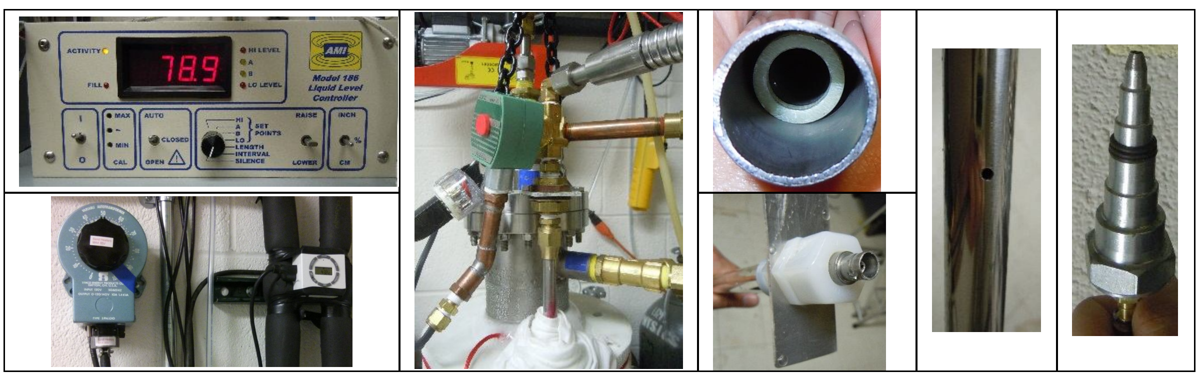


Figure 8: Pictures of liquid nitrogen autofill components are shown: (a) LN level controller, (b) Variac for the cold trap heater, and a countdown timer that actuates a solenoid valve to control the flow of purge gas through the capacitance gauge, (c) LN transfer solenoid valve and transfer line mounted to the cold trap, (d-e) LN level capacitance gauge inside a stainless steel protective sheath, (f) pressure equalization holes in the sheath, and (g) conical tube that interfaces with hoses for purging level gauge.

The capacitance level gauge is a pair of fragile concentric thin-walled stainless-steel tubes. There were several problems implementing this type of level gauge. 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. The gauge can easily become pinched causing bends or dents if the cold trap were accidently bumped. Pressure equalization holes in the outer tube of the gauge are located outside of the LN dewar. Atmospheric water was cryopumped causing icing between the tubes. The capacitance therefore changed and the level readings failed. When the capacitance gauge was removed from LN to regenerate the trap, ice accumulated inside, between, and outside the tubes. The gauge therefore had to be thoroughly dried before re-inserting into the LN dewar to eliminate the accumulated water that caused capacitance readings to fail.

To solve these problems, the fragile capacitance gauge is placed inside a thicker-walled stainless-steel tube (shown in Figure 8). This outer tube is sealed against the gauge at the upper end. Pressure equalizing holes reside inside the cold trap dewar just above the LN level. Upon removing the assembly from LN, a hose is pushed over the outside diameter of the armored sheath allowing dry nitrogen gas to flow through the assembly and out the pressure equalization holes preventing ice and water from contaminating the capacitance gauge. The purging gas is shut off once the gauge is at room temperature.

I have depleted multiple nitrogen cylinders by accidently leaving the purge gas flowing. Therefore, a solenoid valve was installed at the output of the nitrogen cylinder pressure regulator, which is actuated by a countdown timer mounted on the wall. The purge interval is set to 35 minutes.

Figure 9: Styrofoam Lid for the 240L wide-mouthed cold-trap LN dewar.

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 asymmetrical cooling of the trap during LN transfers. The American Magnetics controller actuates the solenoid valve. The control 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 in and out of the 240L 9" wide-mouth LN dewar. The steel crane was MIG welded together. The hoist can potentially 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 prevents catastrophic collision of the cold trap with the ceiling and aluminum pulley. Before hoisting the cold trap out of the dewar, it is imperative to disconnect the liquid nitrogen transfer line and transfer solenoid power cable, and remove the capacitance LN level gauge. While raising and lowering the trap in and out of the dewar, careful alignment of the cold trap and dewar mouth is necessary to prevent damaging the dewar neck.

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 ~110C to dry in inert atmosphere and is not damaged from water exposure. The regeneration should therefore be quicker and easier to fully regenerate the trap. The capacity to adsorb nitrogen and oxygen is very similar at LN temperatures. Since the implementation of the water traps, I have found it unnecessary to replace the zeolites.

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.

LIQUEFIER MANIFOLD

Figure 10 shows the mechanical room manifold. The yellow X's mark the location of manual ball valves. Red arrows indicate flow path of helium gas during liquefaction, sequentially numbered 1 through 12.

The manifold has been built to position nearly all the valves in one accessible location. The gas flow from the bladder is drawn into the diaphragm pump, and sent through the water trap and cold trap. The gas is sampled with a helium purity meter at the point the gas flows into the helium liquefier. The essential gas flow of the system is easy to lay out diagrammatically in a linear fashion, but to position all the valves in one area required "folding" the manifold. Additional lines are required to route helium exhaust gas (from dewar-to-dewar liquid helium transfers and standing dewar blow-off) back to the bladder. Optimizing the configuration for ease of use makes the diagram appear complicated, but the flow is conceptually very simple.

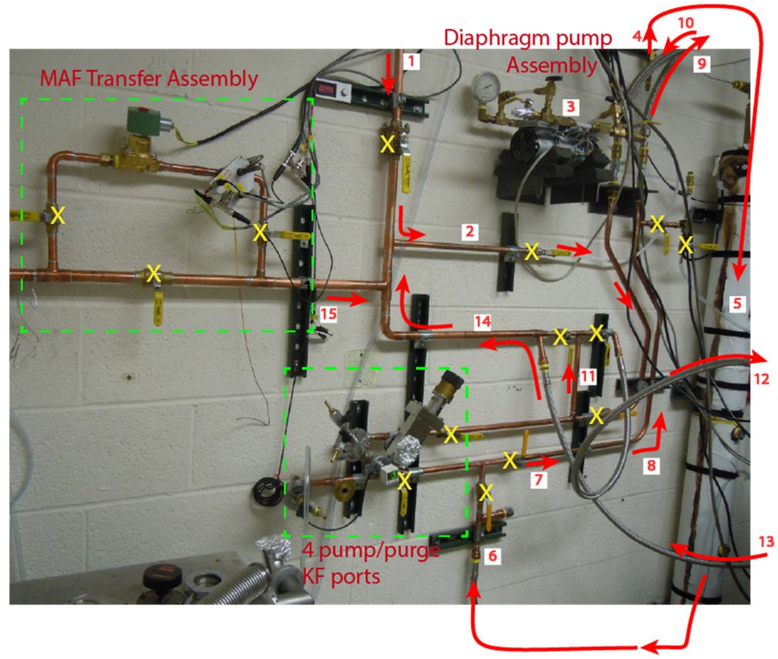


Figure 10: The main sections of the liquefier room manifold are shown. The red arrows and sequential numbers show the helium gas flow from the bladder through the system under normal run-time conditions, and the yellow x's demarcate manual valves.

The manifold depicted in Figure 10 is used to describe the flow through the system to limit the clutter from annotations, but two manifold modifications have subsequently been implemented that are not depicted: (1) a second cold trap was installed, and (2) an automatic regeneration manifold section has been built that replaces the “4 pump/purge KF ports” section labelled in Figure 10. These two modifications (shown in Figure 14) are inconsequential to the description of the helium flow under normal liquefying run-time conditions, and therefore will be described later in this section.

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 when the pump is off. The helium then flows through a flexible corrugated stainless-steel hose, and to the top of the water trap.

The top of each water trap has two manual ball valves as shown in Figure 11: the top valve is an input isolation valve, and the side valve is an exhaust valve. During regeneration, the top valve is closed and the exhaust valve is opened to direct the hot water-saturated exhaust gas through a small cooling coil and a motorized exhaust ball valve.

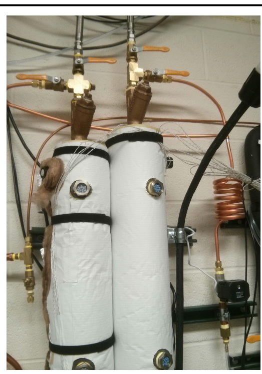


Figure 11: The top of each water trap has an input isolation valve (top) and a manual exhaust port valve (side).

The helium 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).

As shown in Figure 13(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 13(a) is the attachment from the mobile dewar exhaust allowing direct venting into the 150L dewar, which will be discussed in more detail in the next section.

Figure 13(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 10 is the MAF Transfer Assembly. Cold helium exhaust gas from mobile dewars during a liquid transfer, as shown in Figure 12, is heated to room temperature. Two 900W @ 120V heater-tapes driven by Variacs (set at 70V and 40V) are wrapped around several loops of a copper coil heat exchanger. The gas then travels into the MAF Transfer Assembly that directs the flow through the transfer solenoid and helium mass-flow sensor (see Section *Helium gas mass flow meters*). The gas flow rate is used to regulate the rate of liquid transfer. The liquid level in the dewar is calculated from the measured dewar weight during transfer. When the dewar is full, the control automatically closes the transfer solenoid valve. (see Section *Automated dewar-to-dewar transfer shut-off* for details). The exhaust gas from dewar-to-dewar transfers is routed (15) back into the bladder (1).

Figure 12: (left) Weighing and venting a 60L dewar immediately before inserting the transfer line from the 150L liquefier dewar. (right) During the transfer, the helium exhaust passes heated copper coil.

Figure 14 shows the manifold with the latest modifications. The numbered annotations correspond to the numbered sequence of Figure 10. Since there are two water traps, two manifold junctions now exist from the attached corrugated hoses at 6-1 (from water trap #1) and 6-2 (from water trap #2). Next to these junctions are 10 PSIG vent-to-atmosphere relief valves to prevent water trap over-pressurization. Two ball valves straddle each junction to the left and right. Opening the left valve gives the automatic regeneration section of the manifold access to the trap. Opening the right valve allows the helium flow to continue through to the cold trap.

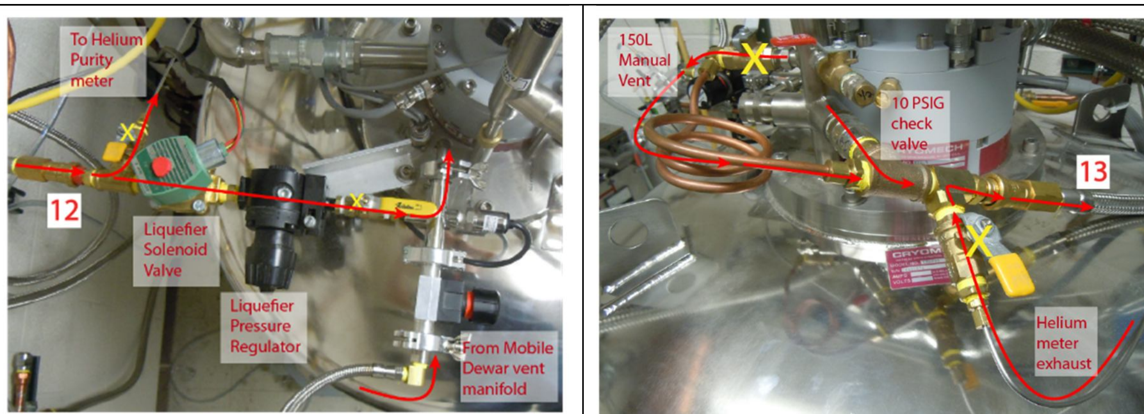


Figure 13: (a) The purified gas enters the liquefier input assembly on the 150L dewar. The point marked "12" corresponds to the same point on the liquefier manifold diagram in Figure 10. (b) The 150L dewar liquefier exhaust assembly sends gas to point number "13" on the liquefier manifold diagram in Figure 10. The coil allows for thermal expansion and contractions without stressing rigidly attached joints.

The Automatic Regeneration section is highlighted in Figure 14. The trap regeneration process requires a sequence of steps involving heating, venting, purging, and evacuating. This manifold section mainly consists of two very similar horizontal parallel lines: the top line provides access to the cold trap, and the bottom line provides access to the water traps. Each line consists of a manual isolation ball valve, KF-40 and KF-25 flanged access ports, helium purge solenoid valve, vent-to-atmosphere solenoid valve, vent-to-atmosphere 3 PSI relief valve that can be isolated by closing a manual ball valve, and a motorized ball valve that isolates the line from a scroll vacuum pump. Pressure gauges occupy the KF-25 ports. Small diameter copper tubing connects the purge solenoid valves to an industrial-grade helium cylinder.

A Gast MOA-P22-AA diaphragm air compressor, with mesh filters and output regulator, forces air through the water trap. During water trap regeneration, the output of the air compressor passes through the water trap motorized ball valve, labelled “WT air pump BV” in Figure 14.

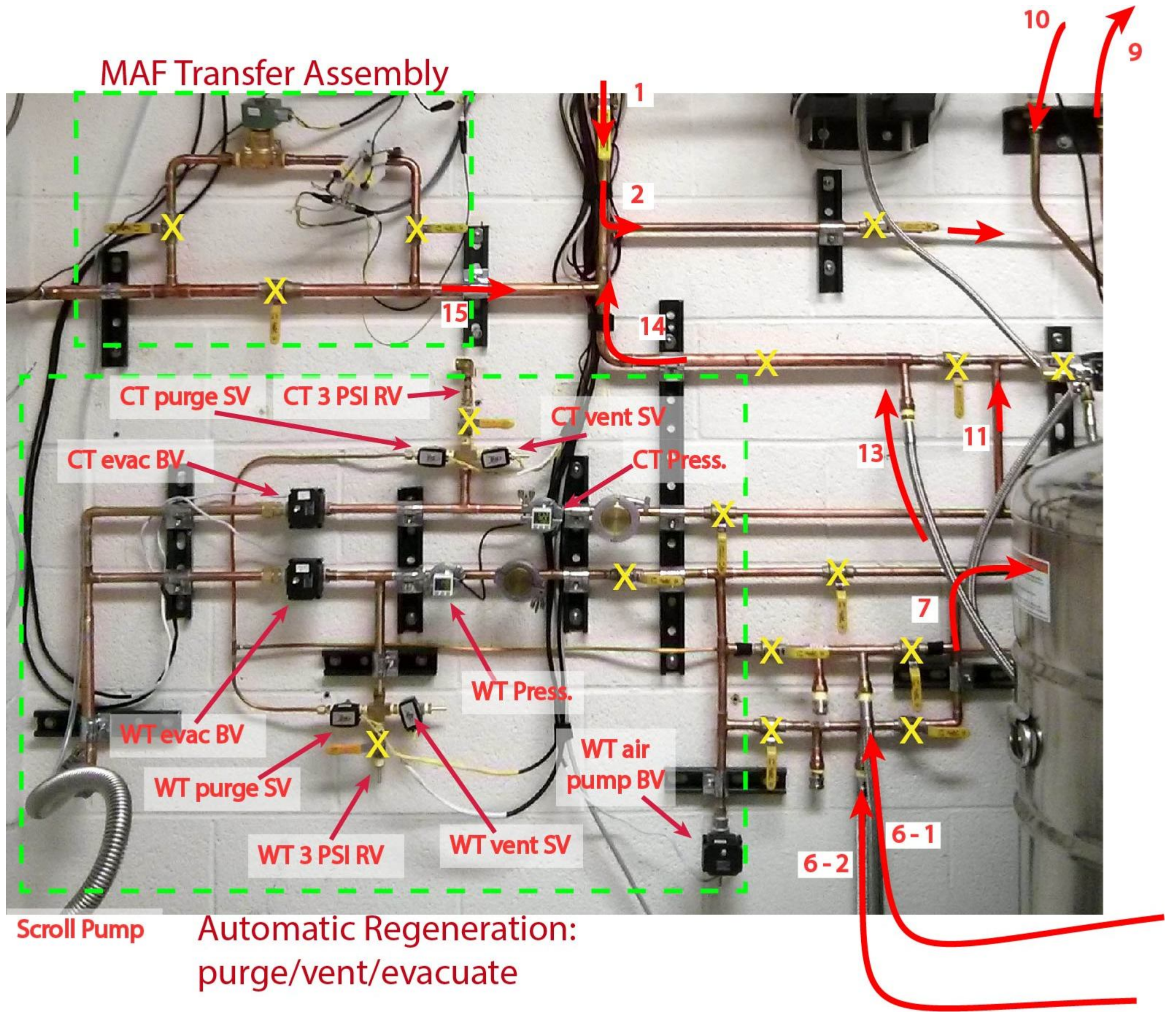


Figure 14: The newly revised mechanical room manifold sections are highlighted. Since there are two water traps, there are two junctions, one at 6-1 from water trap #1 and the other at 6-2 from water trap #2. The helium continues through the system as described earlier, steps 7-14. One trap can be isolated from the system and be regenerated while the other trap is in service.

The diverse design of the manifold allows many other configurations. All pipelines in the manifold can be pumped and purged. The gas from the bladder can be continuously purified by cyclically flowing gas through the traps without entering the liquefier. This configuration also allows flushing lines that are contaminated. An industrial grade helium cylinder ensures the cold trap remains under positive pressure when the diaphragm pump is off. The diaphragm pump is easily checked for leaks (see Section *Diaphragm pump assembly*) by closing appropriate valves and monitoring a pressure gauge. Pressure testing the manifold and other system components for leaks is easy with the digital pressure gauges.

MOBILE DEWAR HELIUM BLOW-OFF CAPTURE MANIFOLD

One of the mobile helium dewar exhaust ports consists of a ball valve, an in-line 2 PSI check valve, and Swagelok B-QC4 brass quick-connects (Figure 15a). The exhaust flows into the 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

13(a). A KF port is also included on the manifold for pumping and purging. Two dewars simultaneously connect to the blow-off manifold.

Figure 15: (a) The dewar blow-off exhaust port vents through a 2 PSI check valve and a Swagelok quick connect. (b) The mobile dewars vent into the dewar helium blow-off capture manifold. This manifold attaches directly to the liquefier 150L dewar reservoir.

HELIUM GAS MASS FLOW METERS

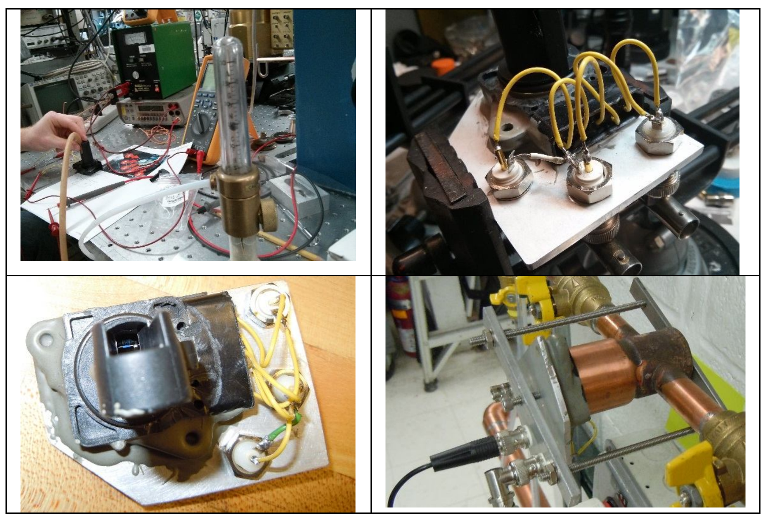


Figure 16: Modified automotive Mass-air-flow sensors are used as adjustable helium flow sensors and the Laboratory and Liquefier manifolds

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, which maintains the hot wire at constant power. The lid was replaced with an aluminum plate with three BNC connectors: 12 V dc input power, signal voltage, and the voltage across an RTD thermometer. An o-ring 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 insignificant for short duration, like for liquid helium transfers. The meters have accompanying isolation valves on both the lab and liquefier room manifolds. The dynamic range and sensitivity of the meter is designed to be adjusted by rotating the meter to different angles inside the copper housing. In practice, the meters placed at 45 degrees offer an optimal dynamic range for all liquid helium transfers.

An LED display shows the voltage signal that relates to flow rate. Calibration of the signal voltage to a volumetric flow rate (CFH) of helium is given in Appendix 3, and wiring charts are provided in Appendix 10.

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 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 17: A Coherent LaserPure 20 chiller supplies chilled water to the Cryomech LHeP22. It is a closed-loop circulator chiller with a water pump and heat exchanger. The physics building supplied chilled water cools the heat exchanger.

The total capacity of the chilled water lines and reservoir is 7.8 gallons. A change of an inch of coolant level in the reservoir corresponds to ½ gallon. The coolant is a mixture of pure water with 25% (by volume) BioFrost, 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. RTD thermometers are mounted on the physics building supply line and the closed cycle chiller supply line.

OXYGEN SENSORS, ALARMS, AND REMOTE DISPLAYS

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.

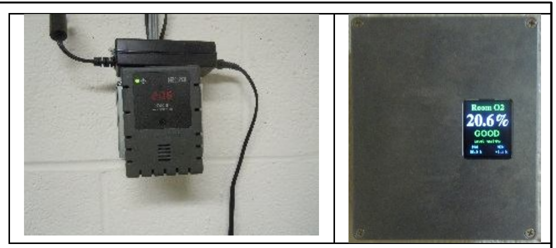


Figure 18: Room oxygen sensors with remote displays and visual and acoustic alarms are located in the Liquefier and Bladder rooms.

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 0), 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

Two mobile helium dewars are in service, and a third in storage: 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 2 PSIG pressure relief valve. The Swagelok connectors are valves on both the male and female ends. The valves seal shut when disconnected, and open when connected. The male connectors are on the dewars with protective caps. The interface with the laboratory and liquefier room manifolds is simple, quick, and foolproof.

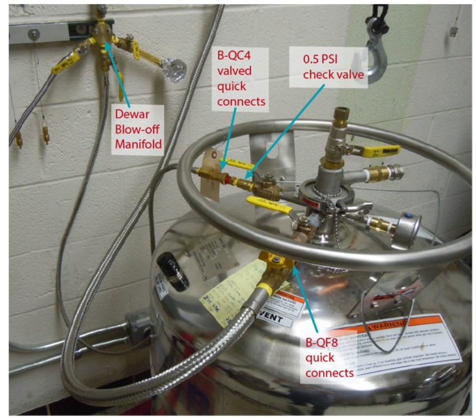


Figure 19: A Cryofab 60L dewar with hoses attached to the vent and exhaust ports. The 0.5 PSIG relief valve has been replaced with a 2 PSIG check valve.

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.

Each dewar was originally equipped with 15 and 10 PSIG relief valves. However, the Cryomech LHeP22 150L is equipped with a 10 PSIG inline relief valve. When the cold head turns off, the dewar pressure rises to 10 PSIG and vents into the bladder. Since the reservoirs of the mobile dewars attach directly to the LHeP22 150L dewar through a 2 PSIG inline relief valve, the mobile dewar pressures potentially can rise to ~12 PSIG. The original 10 PSIG relief valve would vent the mobile dewar helium gas blow-off directly into the room. Therefore, the 10 PSIG relief valves on the mobile dewars were replaced. Each mobile dewar is now equipped with two 15 PSIG relief valves.

DEWAR PLATFORM SCALE

An Adam Equipment CPWplus 200L Large Platform Floor Scale with an RS-232 port measures the liquid level of the mobile helium dewars during liquid transfers (see Appendix 4). The dewar is wheeled onto the scale via an aluminum ramp. The liquid level is calculated from the weight by the HRS computer. During a transfer, the weight is graphed in real time. When the weight of the liquid reaches the set-point (or the LHeP22 is low on liquid helium, or the temperature of the exhaust line is too low), the transfer is automatically shut off and the user notified.

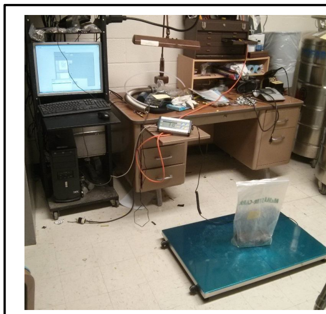


Figure 20: A 440-lb capacity platform scale with an LCD display and RS-232 port connects to the helium recovery system computer.

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 21, 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.

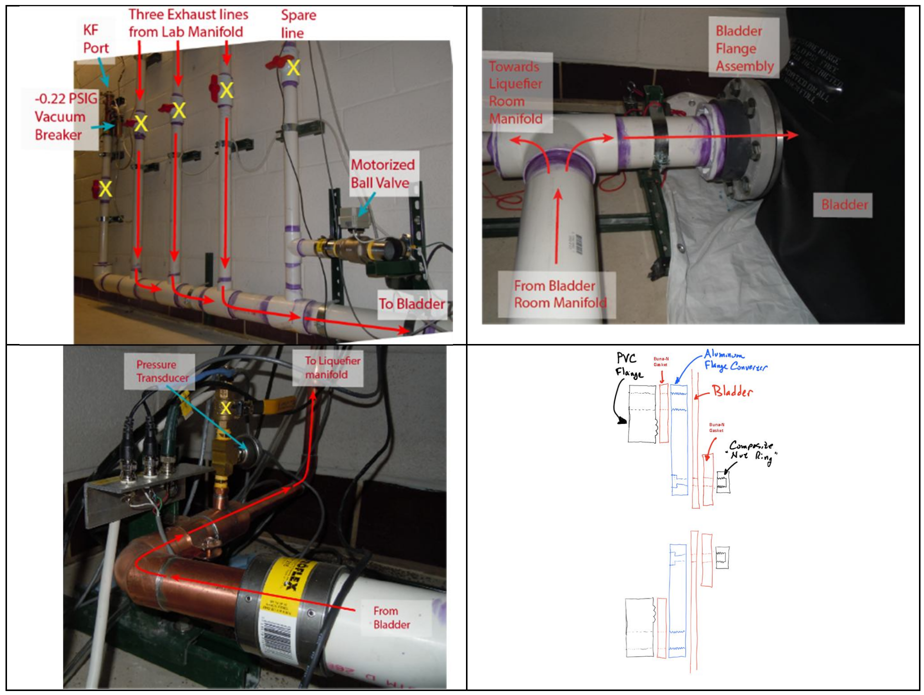


Figure 21: Pictures show (a) the Bladder room manifold, (b) the Bladder room manifold interface with the bladder, and (c) the Bladder send line to the Liquefier manifold showing the pressure transducer and connectors. (d) A sketch of the custom-designed bladder flange assembly.

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. The high capacity lines allow capture of helium from magnet quenches.

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 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

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

Figure 22: The three hanging overinflation switch mechanisms are shown with a half-filled bladder. The liquefier manifold is against the left wall.

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 over the surface area of our large bladder.

A 3" diameter pipe interfaces with the bladder via a PVC flange as shown in Figure 21. 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 21.

As shown in Figure 22, three switches mounted on three PVC bumpers press against hanging steel paddles when the bladder becomes over-inflated. The bumpers are tunable, tied to the wall by red paracord with slipknots that were set during an air inflation test. 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. All the surfaces exposed to the bladder were made smooth, including removing electrical panels, plumbing, ducts, switches, shelving etc.. All walls were scraped to remove rough and sharp protrusions, and heavy paint. Spackle smoothed out any remaining rough areas. The rough concrete ceiling was covered with a suspended tarp. The floor is covered with a 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 tends to damage when traumatically creased, so do not step on or otherwise pinch the bladder. Since entry into the room must be performed with care to avoid damaging the bladder, a paracord door-stop prevents the door from fully opening.

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 when the bladder is around half-full. The measurement of losses was 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 loss rate is much less than 0.5 LLHe/day with an emptier bladder $\lesssim$ 30 LLHe (liquid liters worth of helium in the bladder) where the PVC bladder-weight-pipes lay on the floor.

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.

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, can explode if the pipe fails. 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. This type of fittings is not rated to very high pressures but are fine for helium recovery and are 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 23: Bladder camera

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

LABORATORY MANIFOLD

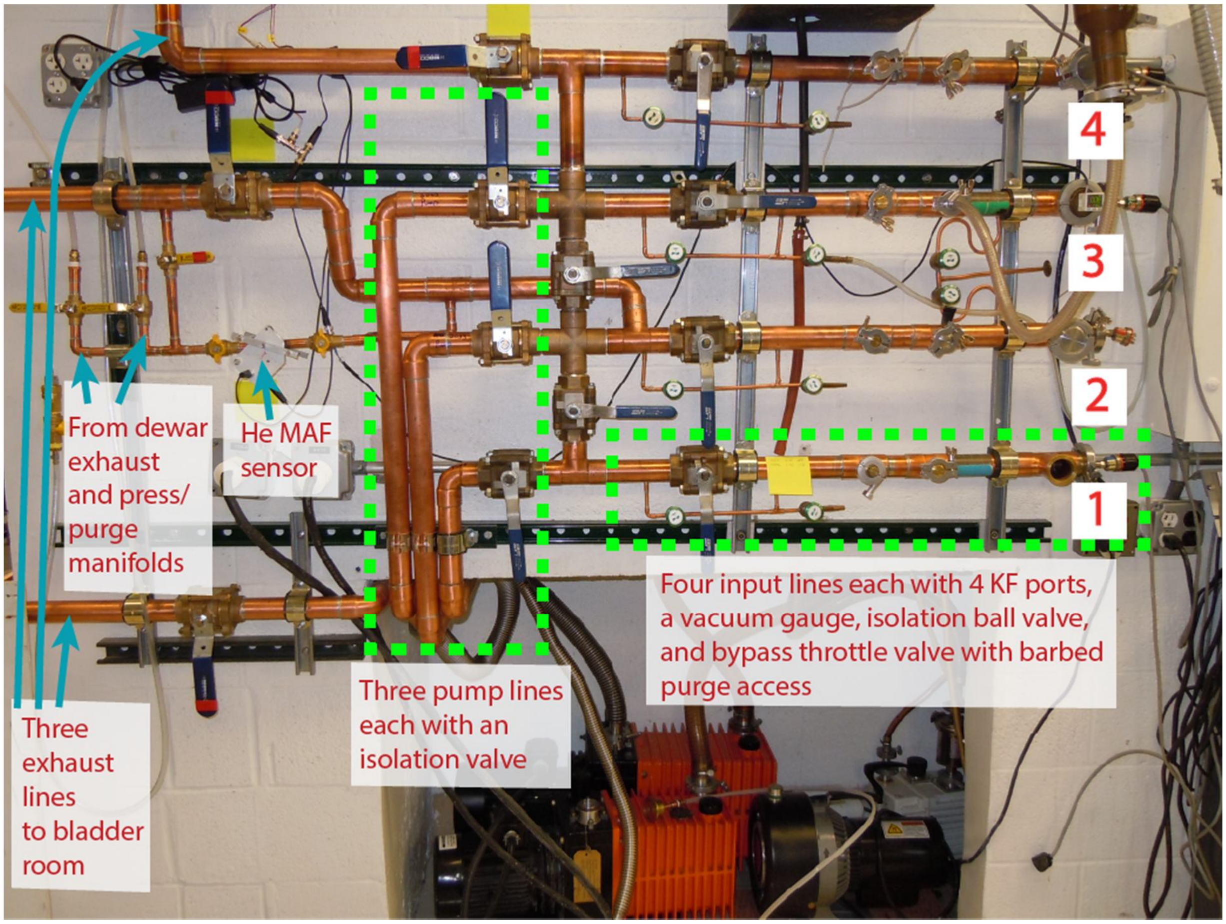


Figure 24: The laboratory manifold is extremely versatile.

The laboratory manifold provides an 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 24, 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 and vacuum 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 has a shut-off valve and a barb convenient for attaching of ¼" ID hose, typically 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 sealed rotary-vane pump.

Three helium exhaust lines run to 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 mass-flow meter. The meter is used to monitor dewar-to-dewar transfer exhaust flow rate in the laboratory. The middle exhaust line is used to exhaust two other laboratory manifolds, the dewar blow-off manifold and the pressurization/vent manifold as shown in Figure 24.

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. The temperature of helium reservoirs can be lowered to below 2K by pumping and recapturing the backline of 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 25. The top of this spine has a plastic exhaust tube that vents into the main laboratory manifold. The ends of each manifold line are barbed for easy attachment of compressed gasses, usually helium or nitrogen.

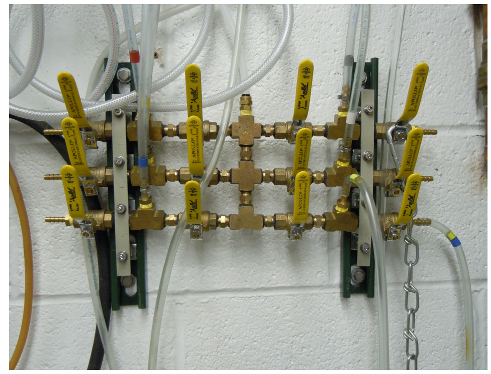


Figure 25: Pressurization/vent manifold

Therefore, either nitrogen or helium can be directed to any of the six stations. Any dewar or experimental vessels can be pressurized or purged. Dewars may be vented and the exhaust routed to the main laboratory manifold for helium recovery.

Six stations located at various places around the laboratory are each equipped with a B-QF8 Swagelok quick connect and shut-off ball valve, like the one shown in Figure 26. 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.

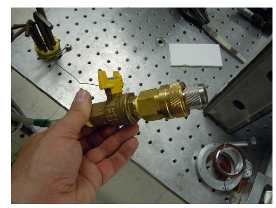


Figure 26: Press./vent station

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 swage lock B-QC4 quick connects, each attaching to a mobile dewar vent port through a 2 PSI check valve. Each line has an isolation valve. The combined exhaust from dewars is connects to the main laboratory manifold for recovery.

Figure 27: Lab dewar blow-off manifold

Mobile dewars therefore exhaust into the bladder from the laboratory. This is different than the liquefier room where dewars exhaust directly into the liquefier.

LASER AREA PIPELINE

Many 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.

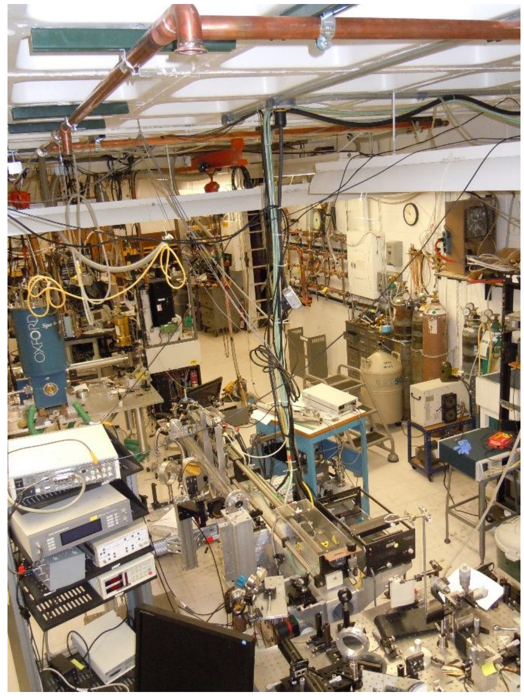


Figure 28: Laboratory laser-area pipeline with five KF-40 ports that interfaces with flexible hose that hang from the ceiling and attach to experiments.

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 cut a groove at the joint, 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 dozens of times.

Figure 29: The top view of an Oxford 8T magnet showing the magnet current leads and pressure equalization tubes (copper).

The magnet exhaust is either directed to the helium recovery bladder through fully open large-diameter pipes or directed through a 0.2 PSI check valve.

The exhaust gas from the Oxford magnet is reheated to prevent freezing of plastic exhaust/vacuum hose. An Omega CN4431 temperature controller regulates a 900W @ 120V heater wrapped around a corrugated stainless-steel hose. The controller cycles the power to the heater by switching a Variac on and off via a Crydom solid state relay model D4850 (Input: 3-32V Output: 280/480V 50A). A k-type thermocouple measures the heater temperature, which is used as the process variable. The temperature controller cycle time is set to 30 seconds and the on-board autotune algorithm was used to set the PID parameters. The Variac is currently set at 75 Volts, and the temperature set-point is 200C. An RC-snubber circuit was built and placed across the terminals of the solid-state relay output (a resistor and capacitor in series where R=2kOhms rated to 1.25W and C=0.22 μF).

HELIUM RECOVERY SYSTEM (HRS) ACQUSITION AND CONTROL COMPUTER

Very little time is required to operate and maintain the system. A high level of automation and interlocks allow the operator to stay focused on experiments and other tasks without added concern associated with helium recovery. Examples of automated tasks include trap regeneration, helium purity readings, notifications via e-mail/SMS/Pushetta to remote computers and cell phones, cold trap LN refill, helium transfers, overfill and high vacuum interlocks protecting the bladder, and mobile dewar liquid level measurements. An array of telemetry from sensors, the state of relays, and software flags are displayed and graphed in real-time and logged. Powerful diagnostics and system performance benchmarks are derived from this data when analyzed in existing scripted Mathematica notebooks.

To accomplish this high level of automation, a sophisticated Labview acquisition and control program controls power to equipment and actuates valves while reading sensor telemetry. The Helium Recovery System (HRS) computer utilizes National Instruments multi-purpose data acquisition (NI-DAQ) cards with analog and digital IO's, and other standard PC ports (USB, Ethernet, and RS-232). Cables from the computer rack go to various sensors as well as two custom-built electronics boxes that contain power supplies, relays, and thermocouple amplifiers.

SENSOR AND CONTROL HARDWARE DESCRIPTION

There are two NI-DAQ cards installed in the HRS computer, a PCIe-6361 and a PCI-6035E. Mounted to the computer rack are two break-out boxes for the SCSI cables that connect to the cards: a white rack-mounted NI BNC-2090A connector block (for the PCIe-6361), and a home-built blue box that houses a generic SCSI screw terminal connector block (for the PCI-6035E card) that is wired to a DB-25 screw terminal connector block.

Two electronic boxes were fabricated and mounted in close proximity to sensors and controlled devices as shown in Figure 30. The first electronics box installed in the system, labelled Electronics Box #1, allows control of essential functions of the helium recovery system. A DB-15 cable links the electronics box to the computer rack. The electronics box contains a single bank of 8 optically isolated relays, six of which control power to six 120V outlets of a power strip mounted to the side of the box. These outlets control the helium diaphragm pump power, transfer solenoid valve, helium purity meter power concurrently with two helium purity meter 2-way solenoid valves, 3-way solenoid valve for selecting between reference or sample gas flow into the helium purity meter, and a large motorized bladder relief ball valve. A seventh relay controls the chiller low voltage power switch circuit. This relay is wired in parallel with the manual power switch on the chiller front panel.

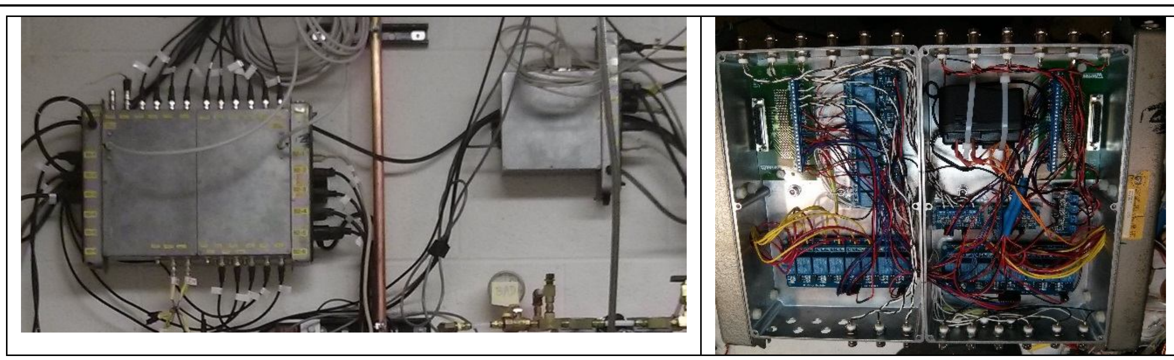


Figure 30: (Left) Electronics box #2 is the larger box on the left, and electronics box #1 is the smaller box on the right. (Right) Inside electronics box #2 are two DB-25 screw-terminal connector blocks, three 8-channel relay boards, three 4-channel k-type thermocouple amplifiers with virtual cold junction offset correction, three dc power supplies, and two 6-outlet power strips.

Electronics Box #2 automates various aspects of maintaining the system. Its main purpose is to measure and control cold trap and water trap regeneration sequences, and regulate the dewar-to-dewar transfer exhaust heaters. Two DB-25 cables link the electronics box to the computer rack. The box contains three banks of 8 optically isolated relays and three four-channel k-type thermocouple amplifiers with cold junction compensation. The outlets of two 6-outlet power strips attached to the sides of the box are controlled by two banks of relays, labeled Bank #2 and Bank #3. These relays actuate low power 120V devices. Bank #2 controls the Water trap and Cold trap vent and purge solenoid valves (a total of four) as well as the water trap diaphragm air pump concurrently with a motorized ball valve. Bank #3 controls evacuation of the water trap and cold trap via two motorized ball valves, and the water trap air exhaust motorized ball valve.

For high current devices, a bank of 8 relays selectively applies 12V to PowerTails. These devices each contain an optically isolated relay rated at 15A @ 120V. There are currently five PowerTails that control a vacuum scroll pump, water trap heaters (one power tail for each trap), cold trap heater, and the helium transfer exhaust heaters. The 12 V control voltages connect to the PowerTails via the BNC connectors along the bottom right edge of the box.

Eleven k-type thermocouples measure the temperature of the water traps (8 total), water trap exhaust (1), cold trap heater (1), and helium transfer exhaust (1). BNC connectors arrayed along the top edge of the box are thermocouple inputs.

Two pressure gauges, mounted to KF-25 ports on the mechanical room manifold, monitor the cold trap and water trap. They connect to analog inputs at the bottom left edge of the box.

Some sensors are not wired to remote electronic boxes, but instead connect directly to the NI BNC-2090A connector block on the computer rack: mass-flow sensor that monitors helium transfer exhaust gas, bladder pressure transducer, analog output from the helium purity meter, and three RTD thermometers that monitor the physics building supplied chilled water, chiller supplied water to the LHeP22, and temperature at the mass flow sensor. The three over-inflation bladder switches are attach directly to the rack via a DB-15 connector, and three of these pins are wired to three PFIO lines configured as digital inputs.

Other computer ports are also used to monitor sensors. A USB connected uninterruptible power supply (UPS) monitors the status of the power. RS-232 ports connect to the dewar platform scale and the LN level controller that measures the LN Level of the cold trap bath. The log files recorded by the Cryomech LHeP22 XP windows computer are read over the LAN/Ethernet connection providing access to onboard sensor and status telemetry: liquid helium level, dewar pressure, cold head temperature, dewar heater power, state of the compressor, state of the run-time mode, the high and low-pressure sides of the compressor, and the temperature of the closed-cycle helium gas, compressor oil, and the supply and return chilled water.

A summary of all the sensors and controlled devices and their associated NI-DAQ card, ports, lines, connectors, and pin numbers are summarized in three tables in Appendix 2.

The HRS Windows 7 computer and the LHeP22 Windows XP computer are accessible remotely via Teamviewer. Both software packages are conveniently manipulated by touch screens. Charts and indicators are easily viewed and equipment manually controlled remotely from computers, tablets, and phones. Log files are automatically uploaded to WebDAV cloud storage for easy download and analysis.

The bladder level is remotely monitored in real-time by accessing the bladder security camera. The HRS 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 HRS 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 helium purity meter solenoid valves are closed, and the helium purity meter powered off. The chiller and bladder over-/under- inflation interlocks remain active. The cold trap is maintained above atmospheric pressure. *Safe Mode* can be configured to return to normal operating mode after waiting a designated amount of time.

The *Emergency Safe Mode* lasts indefinitely, and can only be cleared manually by the user.

MAIN CONTROL PANEL

Figure 31 shows a screenshot of the HRS computer control software. The main categories are defined by the tabs along the top: *Configuration*, *Run-time Controls*, *Regeneration Controls*, *Transfer Controls*, and *Notification Controls*. Each of these tabs have submenu tabs arrayed along the left edge.

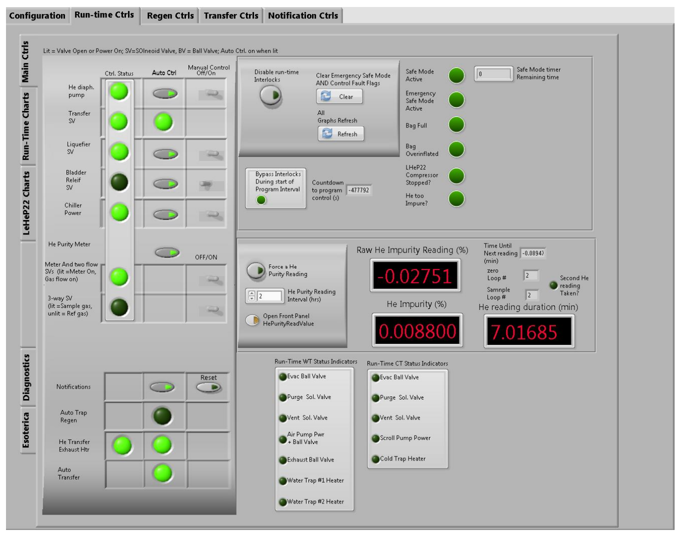


Figure 31: The Main Control panel of the Labview software running on the Helium Recovery System acquisition and control computer.

The *Run-time Ctrl/Main Ctrl* panel summarizes the state of the recovery system and allows toggling controls: status of all controlled processes and devices; user toggling of automated processes; helium purity meter control and readout; and essential system faults and manual clearing of these fault flags.

The left subpanel contains a grouping of indicators and controls. Each row is a controlled process that is labeled along the left side. The controlled processes labeled from top to bottom are helium diaphragm pump power, transfer solenoid valve, liquefier solenoid valve, bladder relief solenoid valve, and chiller power. The next two rows are associated with the helium purity meter: helium purity meter in conjunction with two 2-way solenoid valves, and a 3-way solenoid valve. The last four rows are associated with controls that relate to the *Regen Ctrls*, *Transfer Ctrls*, and *Notification Ctrls* tabs.

There are three columns of indicators and controls on this subpanel. The left column contains LED's that indicate the status of the controlled process (on/off, or open/closed). The middle column contains buttons that the user presses to activate the automatic control of the process. The right column contains manually actuated toggle switches that control the process.

The two clusters of LED's at the bottom are labelled "Run-Time Water Trap Status Indicators" and "Run-Time Cold Trap Status Indicators" that indicate whether the labeled valves, heaters, or pumps are energized.

Above these two clusters of LED's is a grouping of indicators and controls that relate to the helium purity meter. The time between measurements can be set by the user (usually two hours under normal run-time conditions). A meter reading can be immediately instigated by pressing the "Force Reading" button.

Above the helium purity meter group of indicator and controls are various system status LED's. An important button to note is near the bottom of this cluster, *Clear Emergency Safe Mode and Fault Flags*. When the system is in *Emergency Safe Mode*, the user must correct the problem and then depress this button to restart computer control. If the program is stopped and then restarted, automatic controls will not start for 90 seconds. This permits the operator time to check and adjust software settings before computer control of processes start. A countdown timer shows the time remaining until automatic control begins, and a green lit LED indicates that automatic control and interlocks are being bypassed.

Figure 31 is a screenshot of the HRS control software when the system is liquefying (diaphragm pump, helium meter, and liquefier solenoid valve are in automatic mode), performing a dewar-to-dewar automatic transfer (auto transfer LED active, and the transfer exhaust heaters LED indicates that the heaters are on), and taking an automated helium purity reading (LED's indicate that the zero is currently being calibrated with reference gas). Automatic control of the bladder under-/over- inflation relief valve and the transfer exhaust heater are always active. Notifications are currently active.

AUTOMATED PURITY READINGS AND INTERLOCKS

The HRS program controls the power to the helium purity meter and three solenoid valves that control gas flow. They are mounted to the back of the meter. A 3-way solenoid valve allows switching the S*ample Gas* anemometer chamber between reference gas and sample gas. The 3-way valve is configured to allow reference gas to flow when de-energized. One 2-way solenoid valve controls the flow of the reference gas. Another 2-way solenoid valve controls the combined sample and reference exhaust gasses that eventually flow into the liquefier manifold (as shown in Figure 13b) and routed to the bladder. One relay controls the meter power and the two 2-way solenoid valves simultaneously. A second relay controls the 3-way valve.

The meter should be coarsely zeroed manually before beginning automating purity measurements to ensure the bridge readings correspond the voltage signal-to-impurity level calibration and that the dynamic range of the output amplifiers are not near their saturation limits. The zero will drift a little over time. The automated measurements include calibrating this small zero offset.

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-offset 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 signal voltage is out of range or the maximum number of readings has been breached (set to 3). Otherwise, the new zero-offset impurity level voltage V_z is recorded.

Next, the 3-way solenoid valve is energized so that sample gas flows through the *Sample Gas* anemometer chamber. The sequence is the same as before: flush the helium lines and *Sample Gas* 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 V_S by $m_C \times (V_S - V_z)$ where m_c is the calibrated slope (see Appendix 3).

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

Using this algorithm, the systematic time drift of the meter (due to the anemometers gradually outgassing/warming) over the time interval between attaining V_z and V_S give a consistent offset to the final impurity reading. Usually the offset is between 0.010% to 0.015%. A reading in this range is regarded as 0% impurity level. Experimentally, I have witnessed no degradation of liquefaction rates and therefore no significant cumulative impurity contamination coating the cold-head over two continuous years of operation.

Automated measurements are typically performed every 2 hours. A single 300 cu. ft. cylinder of 5.0 reference helium gas is estimated to last 1 year before requiring replacement. The flow rates through the anemometer chambers must be approximately equal and adjusted so that the ball bearings in the rotameters are at 1/2 to 2/3 of full scale.

AUTOMATED DEWAR-TO-DEWAR TRANSFER SHUT-OFF

Figure 32: The *Transfer Ctrls* tab of the HRS control software.

A liquid helium transfer from the LHeP22 150L dewar to a 100L or 60L mobile dewar is automatically shut-off if either the mobile dewar is full, the temperature at the mass flow meter is too low, or the LHeP22 is nearly out of liquid helium. The operator is then notified.

Dewar-to-dewar transfers take between 40 minutes and 1.5 hours. They only take about 5 minutes of manual labor to start, and about 10 minutes of user time after the transfer to vent the mobile dewar, remove the transfer line, and warm and disconnect the exhaust line from the mobile dewar.

The steps to follow for automatic dewar-to-dewar transfers are outlined on the *Transfer Ctrl* tab shown in Figure 32.

Starting with Step 1, the user manually opens the transfer exhaust solenoid valve and the flow sensor's isolating manual ball valves, and verifies that the helium exhaust heaters are being automatically regulated by the computer.

Step 2, the user measures the level of helium in the dewar. Set the platform scale and dewar ramp on the floor, zero the scale, and wheel the dewar onto the scale leaving the braided corrugated stainless-steel hose that connects to the 0.5 PSI vent port of the mobile dewar connected. When the dewar is placed on the scale, rotate about 1/8 of a turn to point all the casters tangentially to prevent the dewar from rolling off the scale. In the software, select the dewar size (100L or 60L) from the drop-down menu, verify a checkmark is next to the 0.5 PSI vent port connection option, and depress the *Calculate* button. The amount of helium in the dewar in lbs. and Liters, and the depth the transfer line needs to be inserted into the dewar to touch the liquid in the mobile dewar is displayed. The most important calculated parameter is the weight of helium required to fill the dewar, which is the set-point weight that will be used to stop the transfer. Proceed to Step 3 and depress the *Clear* button that clears any existing flags shown under the *Transfer Flags* cluster displayed in Step 5. Activate notifications, and test to verify that your cell phone or tablet rings.

Attach the helium exhaust vent hose and vent the dewar through the flow meter. Either using Teamviewer to access the LHeP22 or directly on the LHeP22 touch screen, configure the log files to update every 1 minute and the helium level reading interval to 1 minute. Make sure to *Force a Helium Level Reading* and *Log Update.* Mark or note how far the transfer line will protrude out from the dewar when the tip is about 1-2 inches from above the liquid. Open the transfer line valve on the LHeP22 so that a small flow emanates from the tip, and insert the transfer line into the dewar far above the liquid level. Allow about 3 minutes for the line to cool before fully inserting the line. Zero the scale (TAR).

Step 5, verify the *Dewar Wt*., *LHeP LHe Level*, and *MAF temp* are activated as parameters that will be used for automatic control of the transfer shut-off. Depress *Start Transfer Auto Control*.

The computer will automatically shut-off the transfer if the dewar is full, the LHeP22 is almost empty (5L), or the mass-flow thermometer too cold. The user will be notified in case of a shut-off event. The dewars should be vented within about 15 minutes after automatic shut-off to prevent pressure building in the mobile dewar that may cause helium to transferring back into the 150L dewar.

When the transfer is finished, shut-off the transfer line valve. Vent the mobile dewar by manually opening the transfer solenoid valve, wait for the flow rate to become small, and remove the transfer line and immediately close the dewar. With a heat gun, warm the mobile dewar exhaust port ball valve until it is easy to shut-off. Reconfigure the LHeP22 log files to update every 5 minutes and the LHe level to update every 60 minutes.

Leave the dewar in this configuration to save time. The iced exhaust line and quick connect will warm up naturally. After an hour or two, shut off the quick connect ball valve, disconnect the high flow quick-connect exhaust line from the mobile dewar, close the transfer solenoid valve and the ball valves on the MAF assembly that isolate the flow meter, and remove the dewar from the scale. The dewar should remain connected to the 150L reservoir via the 0.5 PSI check valve vent port through the entire process.

A maximum transfer time interval as well as a maximum flow rate can be selected as control parameters in Step 5, but I have not found them useful.

AUTOMATED NOTIFICATIONS

The notifications tab is very self-explanatory. The operator chooses which processes triggers notifications. The notifications are recurrently sent as long as the flag remains active. This interval is configurable as well as the method of transmission (email, SMS, &/or Pushetta). The clocks associated with these intervals remain active even if the user deselects the notification methods. This can lead to some unexpected delay in receiving notifications if the user interactively selects/deselects notification methods. All the clocks can be reset on the *Run-Time Ctrls/Main Ctrls* page. Automatic notifications are activated/deactivated on this page as well.

AUTOMATED REGENERATION OF WATER TRAPS AND COLD TRAP

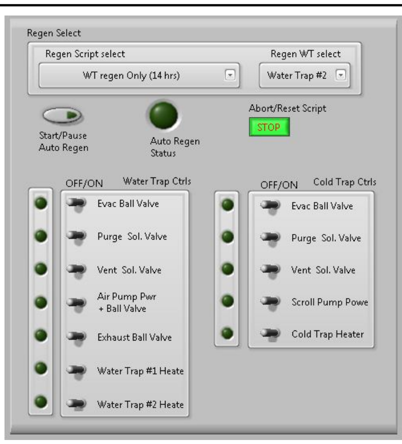


Figure 33: The *Regen Ctrls* tab of the HRS control software.

Regeneration of the water traps and cold trap was described in section *Liquefier room* subsections *Water traps* and *Cold trap*. Both traps during the regeneration process are heated, purged with industrial grade helium, vented, and evacuated. The water traps are flushed with a counter flow of ambient air while hot.

A prescribed script is run for the auto regeneration sequence. These scripts are written as rows into an excel spreadsheet (*RegenScriptFiles2.xlsx*). Each command and parameters are labeled in the spreadsheet. These scripts are placed into service by copying them into the HRS control program (array) text window.

To regenerate a water trap, the user first configures manual valves. The manual input ball valve located at the top of the trap is closed and the manual exhaust ball valve opened (see Figure 11). Two manual valves associated with the water straddle the hose connection to the mechanical room manifold (see Figure 14, sequential step 6-1 and 6-2): the valve on the right should be closed to isolate the water trap from the cold trap, and the one on the left opened which allows access to the water trap pressure gauge, motorized evac ball valve, and purge and vent solenoid valves. The isolating manual ball valve for the *WT 3 PSI RV* (relief valve) should remain open. In the software, the user selects the script and the water trap number (1 or 2) to regenerate. To start the script, depress the *start/pause auto regen* button.

The water trap automatic regeneration script summary:

1. Open water trap exhaust ball valve and turn on heaters
2. monitor the heaters while heating for 12 hours:
    a. if the wrong heater is on, stop script and return and error
    b. If the pressure breaches 5 PSI max, then the user did not open the 3 PSI relief valve so stop
    c. If the heater temperature breaches 250C, stop script and return error
    d. turn on the air pump counter flow when the upper and lower pipe temperatures are above 90C
3. Turn off heaters and air pump, close exhaust valve, turn on scroll pump, vent to between 0 and 0.2 PSIG;
4. Open the evacuation valve and pump on the trap for 3 hours
5. Close the evac valve, turn off the scroll pump, and purge the water trap with helium
6. Maintain the pressure in the trap between 0.2 and 1.2 PSIG for a long time (10000 minutes) – user stops script

To regenerate the cold trap, close the valve that maintains the cold trap with pressurized helium from an industrial grade cylinder, and close the valve that shuts off flow at the manifold prior to the braided stainless-steel hose that connects to the input of the liquefier (both shown in Figure 10). Open the valve that gives access the regeneration portion of the manifold access to the cold trap. Make sure that the *WT 3 PSI relief valve* is active.

Remove the capacitance LN level gauge and begin purging with dry nitrogen gas. Disconnect the autofill LN transfer line and the power chord to the cyrogenic valve. Remove the cold trap from the LN bath, start the script (which turns on the heaters), and immediately clamp the heaters to the cold trap. The warming trap will immediately begin venting to atmosphere through the 3 PSI relief valve.

The cold trap automatic regeneration script summary:

1. Heaters on
2. Monitor the heaters while heating for 5.5 hours
    a. If the pressure breaches 5 PSI max, then the user did not open the 3 PSI relief valve so stop
    b. If the heater temperature breaches 200C, stop script and return error
3. Heaters off, scroll pump on, vent trap to between 0 and 0.2 PSIG
4. Open evac valve and pump on trap for 1 hour
5. Close evac valve, turn off scroll pump, and purge the water trap with helium
6. keep pressure between 0.2 and 1.2 PSIG for 30 minutes
7. scroll pump on, vent trap to between 0 and 0.2 PSIG
8. Open evac valve and pump on trap for 1 hour
9. Close evac valve, turn off scroll pump, and purge the water trap with helium
10. keep pressure between 0.2 and 1.2 PSIG for a long time (10000 minutes) – user stops script

If scripts stop due to an error, trap regeneration valves are closed and heaters turned off.

CHILLER PUMP OVERHEAT PREVENTION INTERLOCK

The chiller operates continuously under normal conditions. However, if the chilled water supplied by the physics building is turned off or no longer cold, then the small closed-loop coolant continuously heats. The LHeP22 compressor will automatically turn off when the temperature is too high. The coolant will continue to heat up due to the heat generated by the water pump. To protect the pump from 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.

BLADDER OVER- AND UNDER- INFLATION PREVENTION INTERLOCKS

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

Active interlocks are also required. 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 has a sensitivity of 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. Passive interlocks only operate to pressures down to around 0.1 PSIG. A single cinderblock (16 in. x 8 in.) this generates an outward force of 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 that can potentially overwhelm interlocks cannot happen by any other mechanism due to flow restrictions.

Active interlocks guard against over-inflation. Three switches safety switches are shown in Figure 22. 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.

LIQUID NITROGEN LEVEL INTERLOCK

If the LN level drops too low 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 of a very low LN level are high helium impurity levels, this interlock is somewhat redundant since helium purity readings are now automated.

POWER OUTAGE INTERLOCK

The UPS (uninterruptable power supply) connected through the USB port monitors the status of the power in the room. 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

Many interlocks are built into the LHeP22. If the compressor oil temperature becomes too high (>126F), then the compressor controller turns off the compressor 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.

FIBRILLATION INTERLOCKS

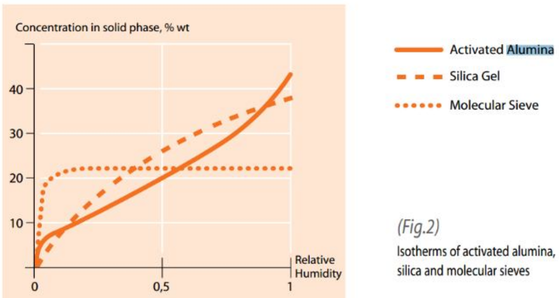
Automatic controls tend to automatically screw up. An extra safety mechanism prevents rapid cycling of relays for any computer controlled process. The *logic evaluation and control* section of the program cycles rapidly, many times per second. Rapid on-off conditions can damage equipment. Longer time scale on-off conditions integrated over many unattended hours or days can be extremely detrimental to electronics, valves, and pumps. 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:

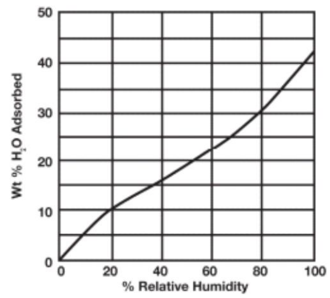
The National Science Foundation, Department of Energy, Center for Nanophysics and Advanced Materials, and the Department of Physics provided funding. Undergraduates Remington Carey and Garret Sutherland helped write the initial version of the Labview control software, set-up the first relay board, and 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. ELECTRONIC BOX WIRING CHARTS

In the below charts, the acronyms are used to aid in legibility.

- P#1.#2 describe the digital port (#1) and line (#2) of the NIDAQ card
- AI = analog input, AO = analog output, Diff. = differential
- SV = solenoid valve, BV = (motorized) ball valve
- PT = PowerTail
- TC = k-type thermocouple, RTD = platinum resistance thermometer
- UPS = uninterruptible power supply
- MAF = mass air flow sensor calibrated to measure helium flow rate
- PG = pressure gauge

Electronics Box #1					
NIDAQ PCIe-6361 (DEV1)					
	Description	**NIDAQ Pin**	**Box Connector**	**Rack NI-breakout pin**	**Equipment**
	Relay Bank 1	P0.0	wired to chiller	P0.0	Chiller power
	Relay Bank 1	P0.1	Pwr Strip Outlet 1	P0.1	He diaph. pump pwr
	Relay Bank 1	P0.2	Pwr Strip Outlet 2	P0.2	Transfer SV
	Relay Bank 1	P0.3	Pwr Strip Outlet 3	P0.3	He purity+two SV's
	Relay Bank 1	P0.4	Pwr Strip Outlet 4	P0.4	Liquefier input SV
	Relay Bank 1	P0.5	Pwr Strip Outlet 5	P0.5	He pur. meter 3-way SV
	Relay Bank 1	P0.6	Pwr Strip Outlet 6	P0.6	Bladder relief BV
	Relay Bank 1	P0.7	blank	P0.7	<none>

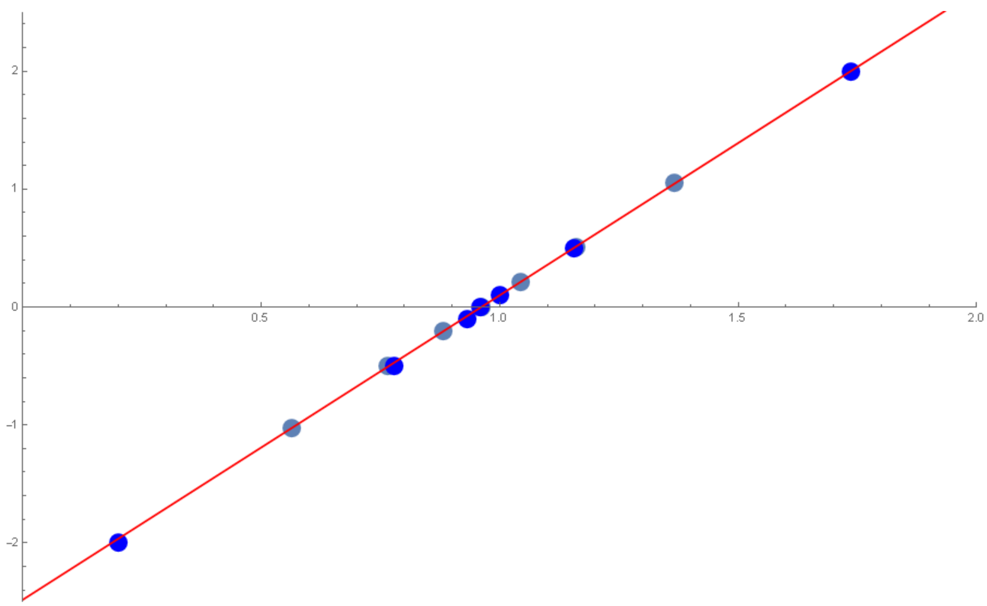
Electronics Box #2

NIDAQ 6035E (DEV2)					
db 25 Pin #	**Description**	**NIDAQ Pin**	**Box Connector**	**SCSI Pin #**	**Equipment**
1	Ground, 5V P.S.	Digital GND		33, 18	
2	Relay 5V reference	5V Digital Ref		14 or 8	
3	12V Relay	P0.0	PT 1	52	Scroll pump on/off
4	12V Relay	P0.1	PT 2	17	Water Trap #1 Heaters
5	12V Relay	P0.2	PT 3	49	Water Trap #2 Heaters
6	12V Relay	P0.3	PT 4	47	Cold Trap Heaters
7	12V Relay	P0.4	PT 5	19	He Transfer Exhaust Htrs
8	12V Relay	P0.5	PT 6	51	<unused>
9	12V Relay	P0.6	PT 7	16	<unused>
10	12V Relay	P0.7	PT 8	48	<unused>
11	Blank				
12	Blank				
13	Blank				
14	Amp1, TC3	AI11	TC #12	63	WT Exhaust
15	Amp1, TC2	AI10	TC #11	31	CT Htr
16	Amp1, TC1	AI9	TC #10	66	He Transfer Exhaust
17	Amp1, TC0	AI8	TC #9	34	<unused>
18	Amp2, TC3	AI7	TC #8	57	WT-2 Upper Pipe
19	Amp2, TC2	AI6	TC #7	25	WT-2 Upper Htr
20	Amp2, TC1	AI5	TC #6	60	WT-2Lower Pipe
21	Amp2, TC0	AI4	TC #5	28	WT-2 Lower Htr
22	Amp3, TC0	AI3	TC #4	30	WT-1 Upper Pipe
23	Amp3, TC1	AI2	TC #3	65	WT-1 Upper Htr
24	Amp3, TC2	AI1	TC #2	33	WT-1Lower Pipe
25	Amp3, TC3	AI0	TC #1	68	WT-1 Lower Htr
NIDAQ PCIe-6361 (DEV1)					
db 25 Pin #	**Description**	**NIDAQ Pin**	**Box Connector**	**Rack NI-breakout pin**	**Equipment**
1	Ground, 5V P.S.	Digital ground		Digital ground	
2	Relay 5V reference	5V Digital Ref		5V Digital Ref	
3	Relay Bank 3	P1.1	Pwr Strip Outlet 1	PFIO 1	Evac WT BV
4	Relay Bank 3	P1.2	Pwr Strip Outlet 2	PFIO 2	Evac CT BV
5	Relay Bank 3	P1.6	Pwr Strip Outlet 3	PFIO 6	Exhaust WT BV
6	Relay Bank 3	P1.7	Pwr Strip Outlet 4	PFIO 7	<unused>
7	Relay Bank 3	P2.0	Pwr Strip Outlet 5	PFIO 8	<unused>
8	Relay Bank 3	P2.1	Pwr Strip Outlet 6	PFIO 9	<unused>
9	Relay Bank 3		blank		
10	Relay Bank 3		blank		
11	Relay Bank 2	P2.2	Pwr Strip Outlet 1	PFIO 10	He Purge CT SV
12	Relay Bank 2	P2.3	Pwr Strip Outlet 2	PFIO 11	He Purge WT SV
13	Relay Bank 2	P2.4	Pwr Strip Outlet 3	PFIO 12	Vent CT SV
14	Relay Bank 2	P2.5	Pwr Strip Outlet 4	PFIO 13	Vent WT SV
15	Relay Bank 2	P2.6	Pwr Strip Outlet 5	PFIO 14	Air Pump + BV WT
16	Relay Bank 2	P2.7	Pwr Strip Outlet 6	PFIO 15	<unused>
17	Relay Bank 2		blank		
18	Relay Bank 2		blank		
19	Diff. AI	AI 4	PG1	AI input 4	Pressure Gauge WT
20	Diff. AI	AI 12	PG1	AI Input 12	Pressure Gauge WT
21	Diff. AI	AI 7	PG2	AI input 7	Pressure Gauge CT
22	Diff. AI	AI 15	PG2	AI input 15	Pressure Gauge CT
23	AO	AO 0	AO 0	AO 0 BNC	<unused>
24	AO	AO 1	AO 1	AO 1 BNC	<unused>
25	blank				

NIDAQ PCIe-6361 (DEV1)					
	Description	**NIDAQ Pin Desc.**		**Rack NI-breakout pin**	**Equipment**
	Diff. AI	AI0,8	Wired direct to rack	AI 0 and 8 BNC	MAF sensor
	Diff. AI	AI1,9	Wired direct to rack	AI 1 and 9 BNC	Temp at MAF (RTD)
	Diff. AI	AI2,10	Wired direct to rack	AI 2 and 10 BNC	Temp ofChiller Supp (RTD)
	Diff. AI	AI3,11	Wired direct to rack	AI 3 and 11 BNC	Temp of House Supp (RTD)
	Diff. AI	AI5,13	Wired direct to rack	AI 5 and 13 BNC	Bladder Press. Tranducer
	Diff. AI	AI6,14	Wired direct to rack	AI 6 and 14 BNC	He Purity Meter AO
		P1.0	N/A	PFIO0	nothing
		P1.3	Wired direct to rack	PFIO3	Bladder Overfill Switch 1
		P1.4	Wired direct to rack	PFIO4	Bladder Overfill Switch 2
		P1.5	Wired direct to rack	PFIO5	Bladder Overfill switch 3
	Computer Port	**Equipment**			
	USB	UPS			
	RS232	LN Level Ctrlr			
	RS232	dewar scale			
	ethernet (LAN)	LHeP22			

3. 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.



HELIUM PURITY METER ROTAMETER 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

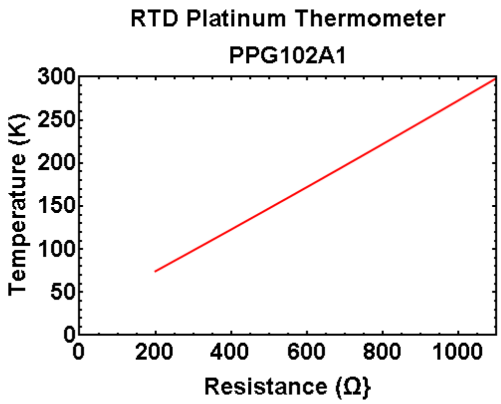
4. PERTINENT FACTS (CONVERSIONS ETC.)

- 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 (Cryomech 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 + 2.555751569177865*^-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: <redacted>
Password:<redacted>

Login: <redacted>
Password: <redacted>

phantom power through network
75' ethernet
gigabit switch

7. QUAD-CHANNEL ANALOG THERMOCOUPLE AMPLIFIER / CONDITIONER

K-Type, based on AD8494/AD8495)

Description:
With temperature data acquisition and conditioning needs in mind, we introduce the SEN-30103, an analog thermocouple amplifier board based on the AD849x series from Analog Devices! The AD849X series is an improved lineup based on the popular AD595 and similar devices from Analog. This quad-channel thermocouple board converts the very low voltage signal from a thermocouple to a highly-linear, 0.005V/°C output with either 0V or 1.245V offset (both configurations stocked) while removing unwanted noise from the signal. Many supply and output configurations are available with this board, though the PCB was designed with Arduino in mind. Specifically, the output header will plug directly into a standard Arduino Uno or Mega, with a pin-for-pin match for power supply, ground and analog outputs. With a 5V Arduino, temperatures from 0°C to 1,000°C are possible with the 0V offset board and -249°C to 750°C with the 1.245V offset board. If using a 3.3V microcontroller (Due, etc), the board must be supplied with no more than 3.3V to avoid damaging the microcontroller. External references, including application notes, pinouts and schematics can be found by visiting the product page on our website. It is also possible to supply the board with higher voltages to allow temperature measurement over the entire operating range of the K-Type and J-Type thermocouples, allowing use with more capable data acquisition equipment.

Applications:

- Automotive data acquisition (exhaust, coolant, brakes, etc)
- Industrial instrumentation
- Oven temperature measurements and control
- Home brew setups
- Other hobby projects!

Features:

- K-Type or J-Type amplifiers get the most out of your analog application
- Wide temperature range dependent on supply and offset - options to 1,000°C for 5V Arduinos
- Ttc = (Vout / 0.005)°C (0V offset version)
- Ttc = ((Vout – 1.245) / 0.005)°C (1.245V offset)
- Analog output with high cutoff frequency signal conditioning
- Measure rapid changes in temperature, such as exhaust temp during a drag race, that most sensors can’t detect
- Analog filtering to remove higher frequency EMI from signal is included in the design (both differential and common mode filtering)
- Supply voltage range: 3.3V - 10V+
- See AD849x datasheet for linearity and correction tables
- Mounting holes for 4-40 sized screws (see Related Products below)
- Screw terminals sized for PH0 phillips screw driver

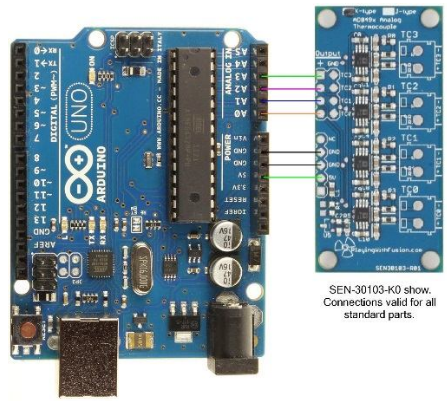
Purchase includes one SEN-30103 Quad Channel Thermocouple Amplifier Board with screw-terminal connectors soldered on. A short segment of 0.1" breakaway header is included (minimum 10 pins)

Table 3: Absolute Maximum Ratings

Parameter	Rating
Supply Voltage (operational)	4.75V to 32V
Reverse Supply Protection	-32V across supply pins
Output Short Circuit Duration	Indefinite
Operating Temperature	-25°C to 85°C
Storage Temperature	-40°C to 125°C

Table 4: Optimized Operating Characteristics

Parameter	Rating
Supply Voltage	5.0V to 32V
Operating Temperature (Tamb)	0°C to 50°C
Absolute Accuracy (initial)	3°C
Storage Temperature	-40°C to 125°C



SEN-30103-K0 show. Connections valid for all standard parts.

8. K-TYPE THERMOCOUPLES

Nine k-type thermocouples were fabricated. Thermocouple wire was purchased rated between -30C to +400C. The wire was cut into lengths, and an oxyacetylene torch was used to weld the junction. A BNC screw terminal is mounted to the other end, and BNC cabling connects the thermocouple to Electronic control box #2.

9. 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).

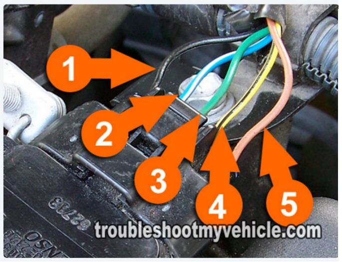
The computer also does not begin to regulate the digital output voltages until a program tells it to do so. This means that when the computer turns back on, the voltage readings are still equal and the devices remain off. This is also what we want.

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

10. 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

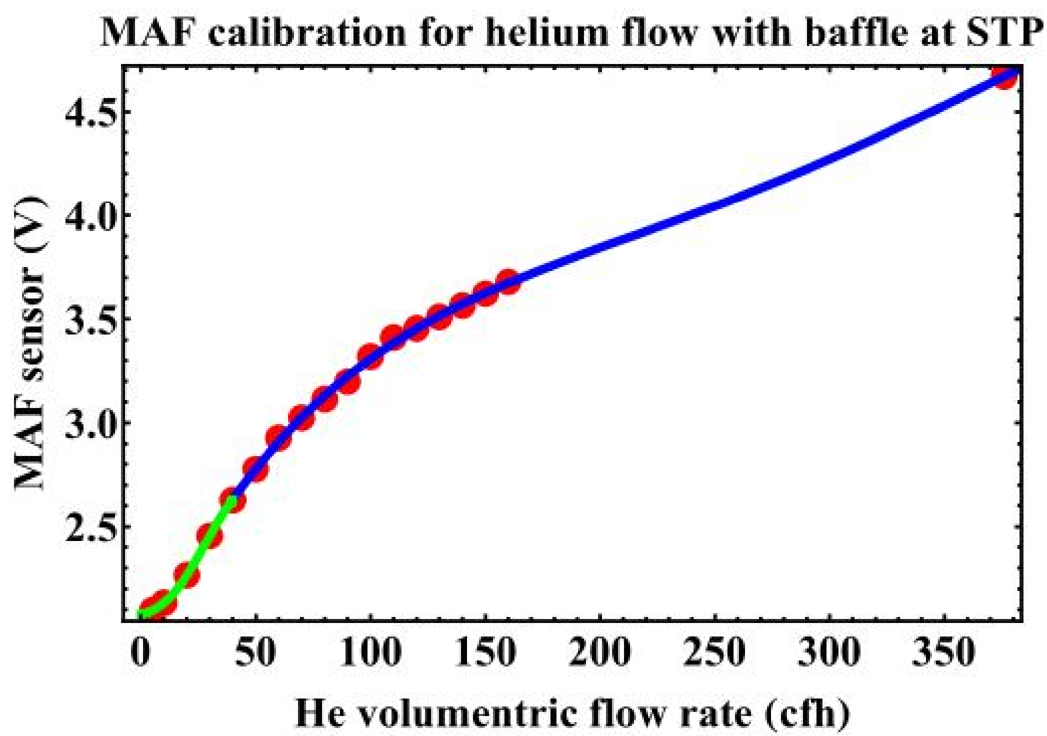
Fit data

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: $1.87809 + 0.0228673\,FR - 0.000110887\,FR^2 + 2.77145\times10^{-7}\,FR^3 - 2.43243\times10^{-10}\,FR^4$

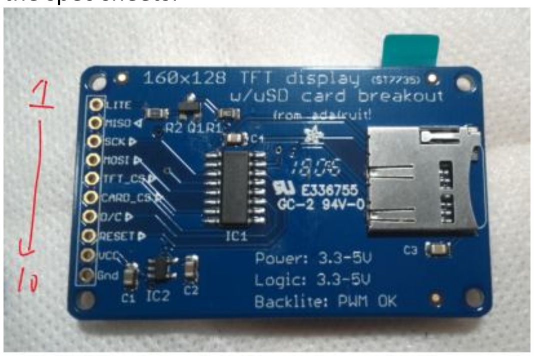
Lo flow rate fit: $2.07695 + 0.00264762\,FR + 0.000216667\,FR^2 + 0.0000106952\,FR^3 - 2.28952\times10^{-7}\,FR^4$

Out[148]=

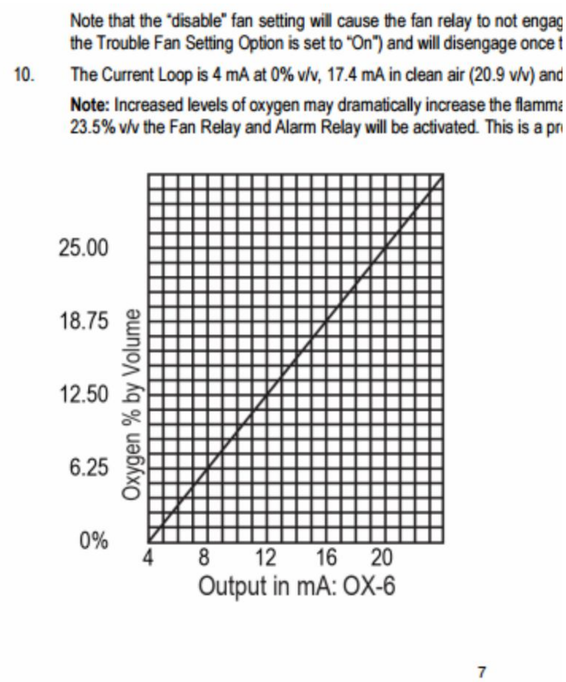


ARDUINO 1.8" TFT DISPLAY WIRING CHART O2 SENSOR CALIBRATION CHART

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:



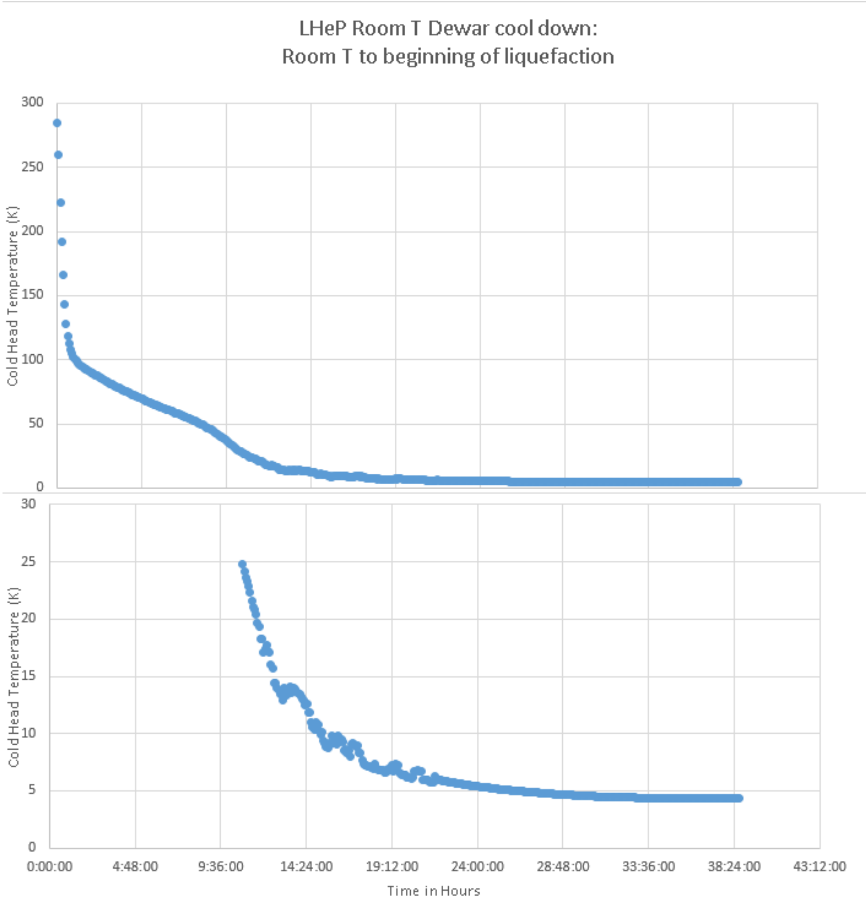
1.8" TFT Display Pin #		Arduino Pin #
Lite	1.	3.3V
MISO	2.	xxx
SCK	3.	Pin 13
MOSI	4.	Pin 11
TFT-CS	5.	Pin 10
Card-CS	6.	XXX
D/C	7.	Pin 9
Reset	8.	Pin 8
Vcc	9.	5V
GND	10.	GND


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

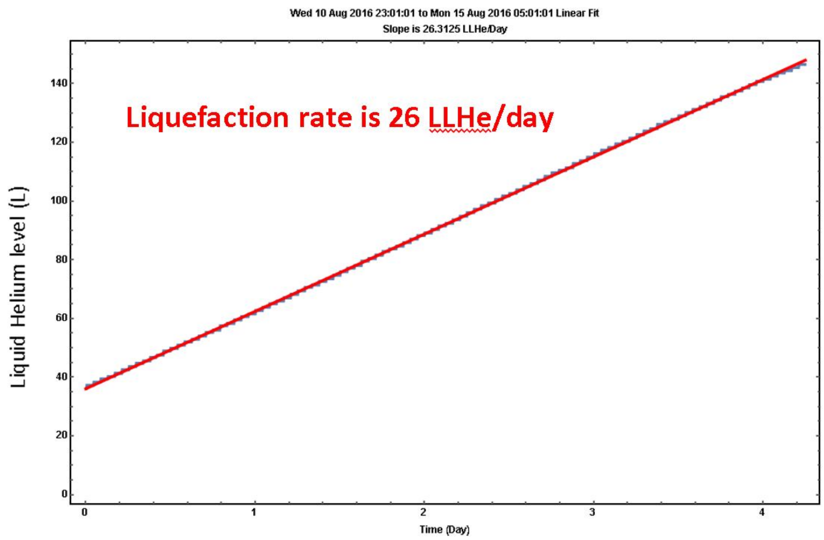
Note: Increased levels of oxygen may dramatically increase the flamma
23.5% v/v the Fan Relay and Alarm Relay will be activated. This is a pr

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

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



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

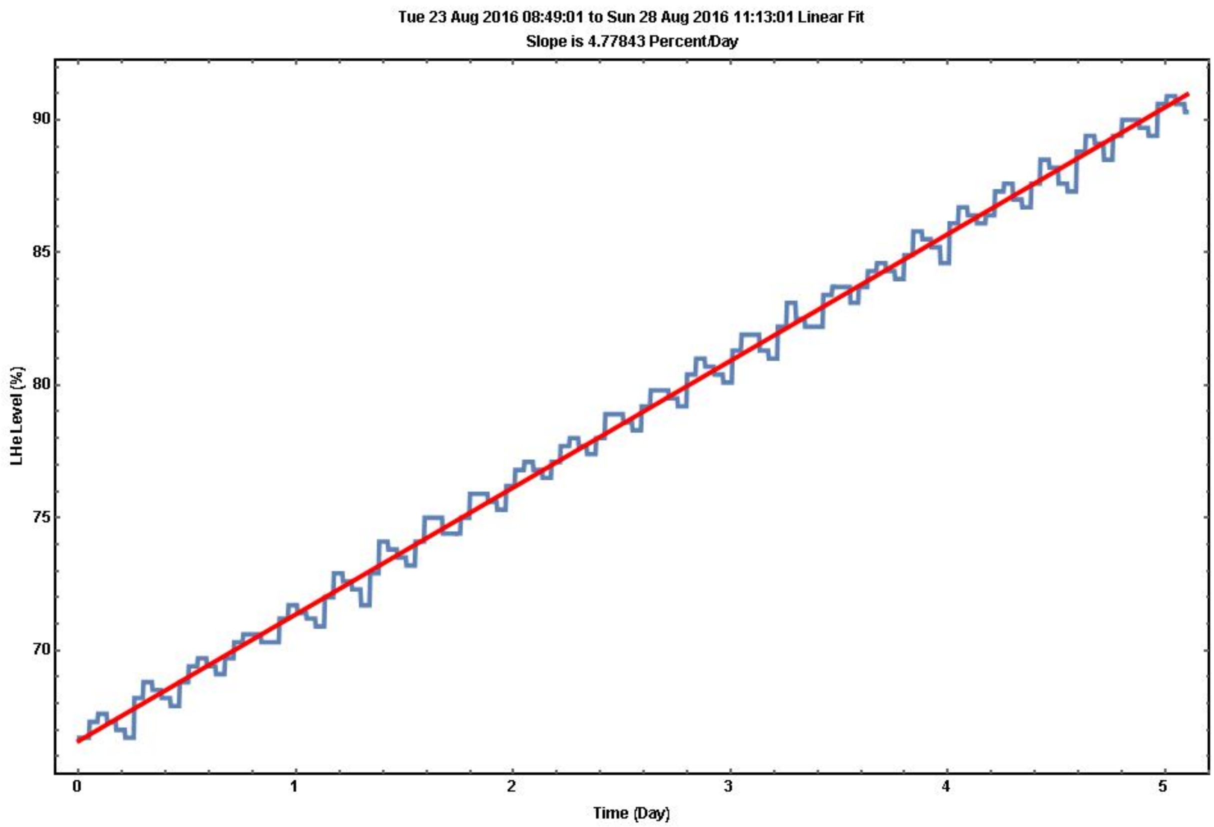
Since the bladder leaks helium at a rate of around 0.5 liquid liters/day, an order of magnitude larger than expected based upon earlier test bladder leak rates which agreed with the calculated bulk permeability of the material, it is not feasible to recover helium dewar blow-off into the bladder. The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

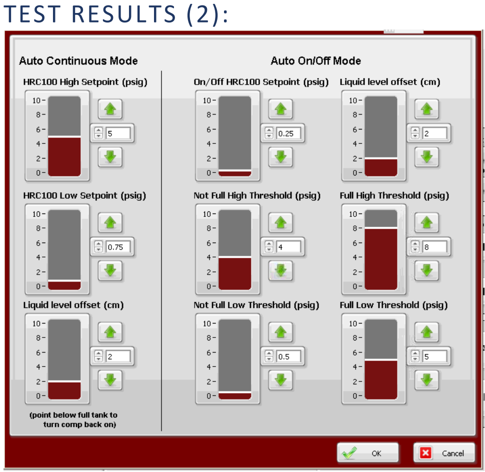
In all three conditions, note that the pressure in the mobile dewars is 0.5PSI higher than the 150L dewar due to the check valve.

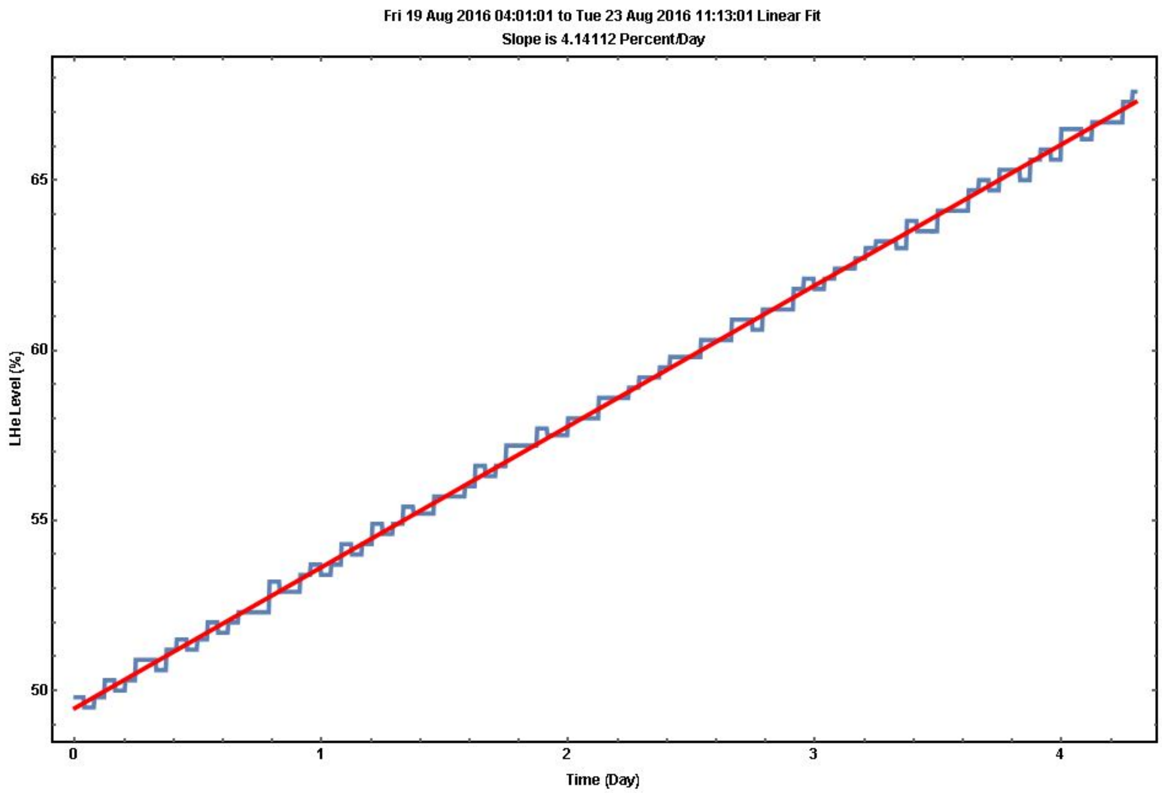
TEST RESULTS (1):

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 not labeled correctly here (Level was measured in liquid liters, not percent)

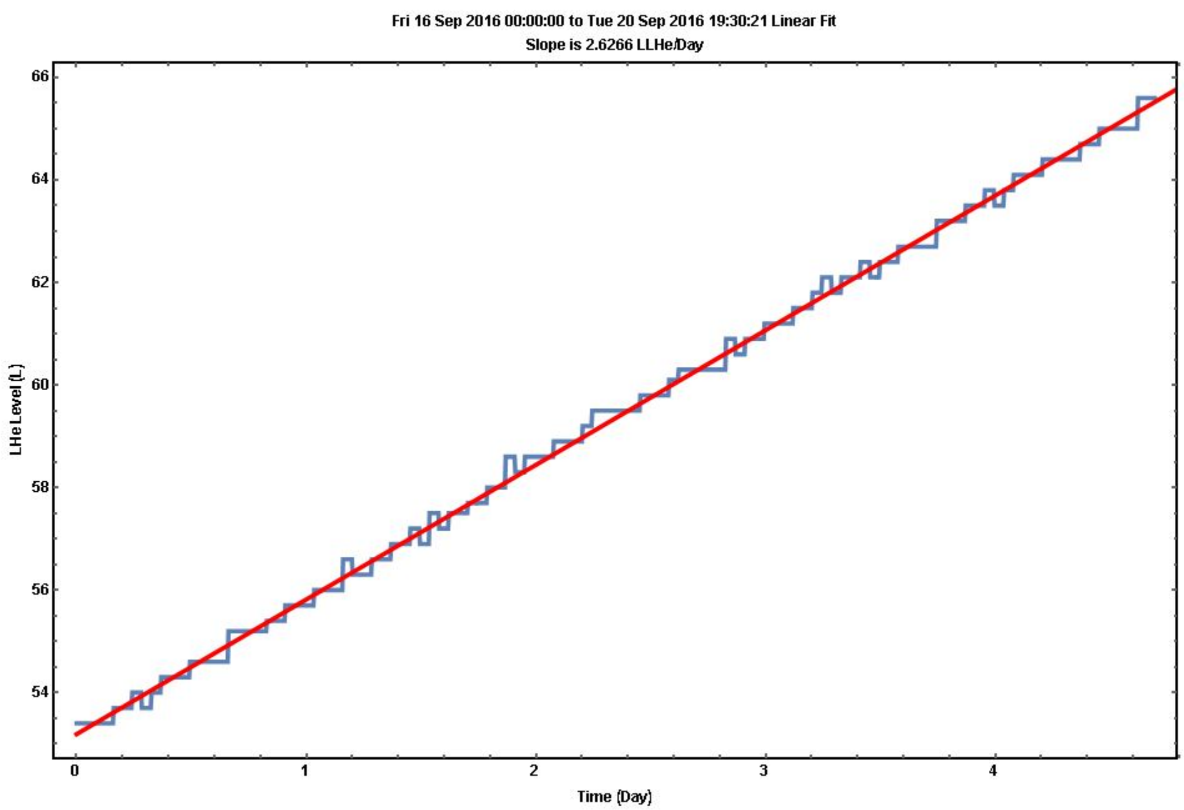


TEST RESULTS (2):





TEST RESULTS (3):



13. LEAK TESTING

Leak testing the plumbing is most efficiently 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.

14. VARIOUS ITEMS THAT SHOULD BE IMPLEMENTED AS OF 6/2017

- Pump interlocks on lab manifold to prevent pumping on the bladder with the lab vacuum pumps

Possibly implement:

- A way to salvage/scavenge LN from wide-mouth 240L dewar

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.