

Recirculating Liquid Nitrogen System for Operation of Cryogenic Pumps

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Abstract: Cryogenic pumps are attractive for electric propulsion test facilities due to their pumping speed on propellant gases of interest. Cryopumps utilize a liquid nitrogen-cooled radiation shroud to allow the internal cryosail to reach its operating temperature. Traditional cryopump installations use an open-loop LN₂ feed system which vents evaporated gas to the atmosphere. A closed-loop LN₂ system which employs cryogenerators to reliquify nitrogen gas removes the cost of LN₂ from cryopump operations. The High-Power Electric Propulsion Laboratory at Georgia Tech has implemented a closed-loop LN₂ system with two cryogenerators to provide the cooling necessary for a ten-cryopump vacuum facility with a pumping rate on xenon of 350,000 l/s. The cryogenerator system cools the radiation shrouds to their operating temperature of 107 K within 20 hours of start-up and can maintain the shroud temperatures indefinitely. Projected cost savings of the system will exceed the initial cost within the first 6,900 hours of operation.

I. Introduction

Cryogenically-pumped electric propulsion (EP) facilities achieve very high pumping speeds through the use of multiple pumps simultaneously operated within the same vacuum chamber. Cryopumps are ideal for EP use as they have high pumping speeds (60,000 l/s, 35,000 l/s on xenon for the PHPK TM-1200i pump),¹ can be mounted at any location in a vacuum chamber, contain no oils or greases which may contaminate the thruster or cathode, and can achieve extremely low base pressures on the order of 1.3×10^{-7} Pa (1×10^{-9} Torr). A very high pumping speed is required in EP research in order to maintain a low facility pressure while the thruster operates, which is required for accurate performance and plume measurements.^{2,3} The major disadvantage to cryopumps is that they require a constant supply of liquid nitrogen (LN₂) to operate. Cryopumps function by cooling a cryosail inside the pump to between 12 and 15 K. The temperature of the cryosail allows the surface adsorb gas atoms or molecules that strike it.⁴ These atoms or molecules are trapped on the surface of the cryosail and effectively pumped out of the facility. The cryosail is cooled by a electrically-powered closed-loop helium cryostat and provides less than 30 W of cooling power at the minimum cryosail operating temperature. Without some form of thermal shielding, radiation from the approximately 300 K vacuum chamber walls will prevent the cryosail from reaching its operating temperature. This is seen notionally by equation 1:

$$Q = \epsilon \sigma A (T_h^4 - T_c^4) \quad \text{Eqn. (1)}$$

where Q is the rate of heat transfer from a hot to a cold surface, ϵ is the surface emissivity, σ is the Stefan-Boltzmann constant, A is the surface area of thermal transfer, T_h is the temperature of the hot surface, and T_c is the temperature of the cold surface. Assuming ϵ for both surfaces is 1, A is one square meter, the cold surface is 15 K, and the chamber wall is 300 K, Eqn. (1) gives a heat transfer rate of 459.3 W.

Thermal shielding for the cryosail is provided by a LN₂-cooled radiation shroud, which reduces the radiative heat load on the cryosail. Since the cryosail is no longer warmed by 300 K chamber walls, but by a 105 K

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nitrogen shroud, the heat transfer calculated by Eqn. (1) is reduced to 6.9 W. This near-tenfold decrease in thermal load on the cryosail enables the helium cryostat to maintain the very low operating temperature required for cryogenic pumping. The LN₂ shroud also serves as a gas pre-cooler: the arrangement of vanes on the shroud removes any line of sight path to the cryosail, so gas must strike the shroud before it can strike the cryosail, which cools the gas and reduces the energy deposited on impact with the cryosail.

LN₂ supplied to the shroud is the largest cost of cryopump operation. Figure 1 shows the typical LN₂ feed system which employs an open-loop system where liquid is provided by a dewar and evaporated gas is vented to the atmosphere.

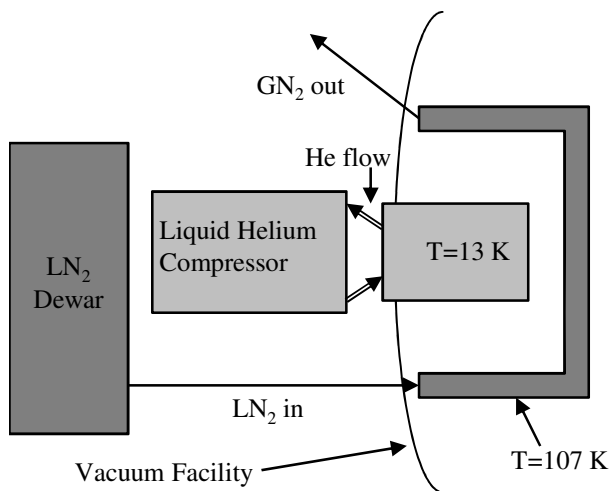


Figure 1: Schematic of a traditional cryopump installation, where the radiation shroud is supplied with nitrogen by a bulk tank.

Since the evaporated LN₂ is vented, the dewar must be regularly refilled. There are three mechanisms by which nitrogen is lost from a dewar: (1) boil-off from the dewar itself, (2) loss during initial cooldown, and (3) nitrogen loss during steady-state cryopump operation. Boil-off from the LN₂ dewar is a constant loss mechanism, and is independent of the operational state of the facility. This loss depends on several factors, including tank volume, insulation quality, and local environment. LN₂ usage during initial cooldown, is highly variable as the radiation shroud temperature is reduced from 300 K. Loss from steady-state operation is due to the fact that the shrouds must be constantly supplied with LN₂ to compensate for boil-off. A single TM-1200i pump requires 22.7 liters per hour of LN₂ at steady-state.¹

A cryopump system that uses ten TM-1200i pumps, for example, requires 227 liters of LN₂ per hour (5,500 l/day) at steady state to maintain the temperature of the radiation shrouds. Such usage requires a large bulk delivery (approximately 26,000 liters) every 4.5 days. This constant resupply of LN₂ is a major addition to facility operating costs. A delay in LN₂ delivery may require shutdown of the vacuum facility and experiment. Clearly, another method of nitrogen supply must be utilized to both reduce steady-state operating costs and the significant additional cost of initial cool-down in environments where tests are short (less than 12 hours at high vacuum), but frequent (full cooldown cycles several times per week).

The High-Power Electric Propulsion Laboratory (HPEPL) at Georgia Tech eliminates the entire expense of LN₂ supply and storage with a closed-loop refrigerator system, similar to the liquid helium loop already employed on the cryosail. Figure 2 shows how gaseous nitrogen (GN₂) exhaust from the radiation shroud, flows to a refrigeration system, is liquefied, and is fed back to the radiation shrouds. Such a closed-loop system eliminates any need for high-volume local LN₂ storage and only consumes electrical and cooling power. Furthermore, the system minimizes the impact of life testing on the environment.

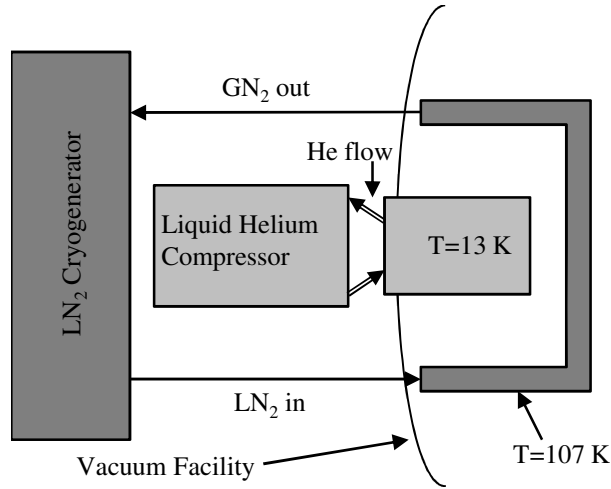


Figure 2: Schematic of a cryopump with a recirculating liquid nitrogen supply.

II. Experimental Facilities

A. Vacuum Facility

Vacuum Test Facility 2 (VTF-2) at HPEPL is 9.2 meters long and 4.9 meters in diameter. Figure 3 is a notional diagram of the facility, and shows the rough layout of LN₂ supply and return lines to the cryopump radiation shrouds. One 6,456 m³/hr blower and one 841 m³/hr rotary-vane pump evacuate the facility to moderate vacuum approximately 0.4 Pa (30 mTorr). To reach high vacuum, the facility employs 10 CVI TM-1200i reentrant cryopumps that give the facility a nominal pumping speed of 600,000 l/s on air (350,000 l/s on xenon) and a base pressure of 2.5×10^{-7} Pa (1.9×10^{-9} Torr). Instead of a traditional large bulk tank of LN₂ the facility utilizes a Stirling Cryogenics SPC-8 RL Special Closed-Loop Nitrogen Liquefaction System with 1,500 liters of LN₂ storage.

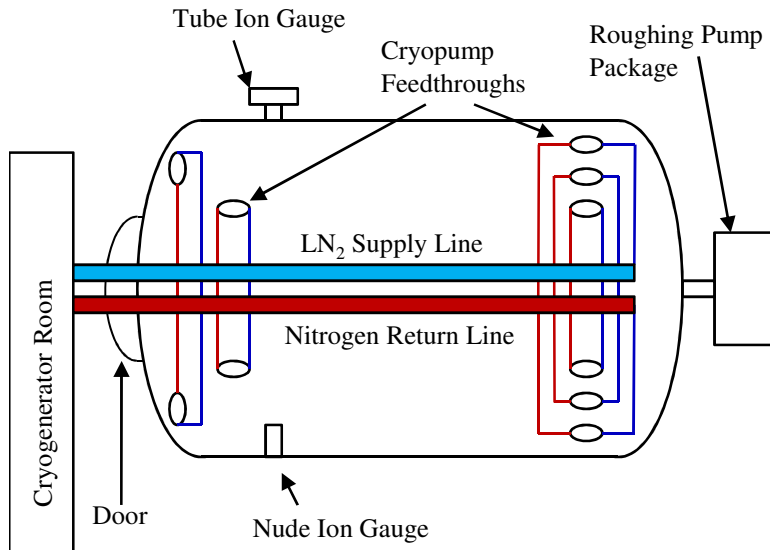


Figure 3: Diagram of VTF-2 and cryopump system.

B. SPC-8 RL Special System

Figure 4 shows the SPC-8 RL Special system. The design places the cryogenerators and storage tank in close proximity to each other to minimize connection line lengths and the physical footprint of the system. The LN₂ pump motor is mounted on top of the storage tank, and shaft-coupled to the impeller inside the tank. There are six

plumbing connections to the storage tank; supply and return to VTF-2, and one input and exhaust line from each cryogenerator. All of the lines which return nitrogen to the storage tank are mounted below the LN₂ level in the tank, which ensures thorough mixing with the stored LN₂. The storage tank has a test pressure of 20 bar and is equipped with two safety release valves set to 14.5 bar. A flow control valve is mounted in the LN₂ output line, downstream of the pump. The nitrogen return line is always open to the storage tank, but has a manual gate valve which can isolate the storage tank from the nitrogen supply and return lines. Cooling water is supplied at or below 20 °C by a dedicated water chiller. The system is designed to be relatively easy to expand; additional SPC-4 units can be added later to cool the system more quickly or support more cryopumps.

The cryogenerators are controlled by a Programmable Logic Controller (PLC) system which monitors the system pressure. As LN₂ at 94 K and 5 bar boils, it expands by roughly 35 times, which increases the pressure of the nitrogen storage tank. When the pressure reaches a set point, the PLC commands the cryogenerators to activate. Once the cryogenerators liquefy sufficient nitrogen to bring the pressure down to the desired level, the cryogenerators deactivate. The system is user-programmable and is typically set to turn the cryogenerators on at a storage tank pressure of 6 bar and turn them off at 2 bar. When VTF-2 is inactive the cryogenerators run for approximately 35 minutes every 17 hours. During facility operation the cryogenerators operate nearly continuously. The automatic controls allow the system to operate without operator intervention nearly indefinitely.

The cryogenerator has several integral sensors. Each cryogenerator senses water flow and temperature, helium working gas pressure, oil pressure, and several other parameters critical for operation. If one of the operation-critical parameters is outside the tolerable range, the PLC will shut down the cryogenerator and sound an alarm. Additionally, there are multiple sensors on the storage tank and nitrogen lines. Static and differential pressure sensors are installed in the storage tank. The differential sensor measures pressure at the top and bottom of the LN₂ in the tank, which provides a liquid depth measurement. The nitrogen supply and return lines to the vacuum tank both have pressure and temperature sensors. There is a LN₂ rate flow sensor in the nitrogen supply line. The outputs from the pressure, temperature, and flow sensors are displayed on a touch screen control panel. The control panel also displays pump speed, control valve position, and cryogenerator RPM. The touch screen allows the user to select “Pump” and “Idle” modes. In both modes, the cryogenerators turn on and off at user-set storage tank pressures. In “Pump” mode the PLC also controls the pump and control valve, while in “Idle” mode the pump and control valve are turned off. The cryogenerator speeds are adjusted according to the system pressure; at high pressures the PLC commands the cryogenerators to turn at full speed (1,500 RPM), while at low pressure the PLC will throttle the cryogenerators as low as 900 RPM.

C. Data Acquisition

The data in this work are collected via computer interfaces with the PLC, the pump thermocouples, and the vacuum gauge controller. The cryogenerator system state, the radiation shroud temperatures, and the facility pressure are recorded by a computer. The cryogenerator state is monitored by RS-232 communication directly with the PLC, which provides measurements of nitrogen supply temperature, pressure, and flow rate, nitrogen return pressure and temperature, pump speed, control valve position, and pump head. The cryopump shrouds have manufacturer-installed T-type thermocouples, and hence require no modification. The temperatures are monitored by an Agilent multiplexer and sent to the computer via GPIB. The vacuum facility pressure is measured by a Varian XGC gauge controller, which simultaneously reads and reports the pressures measured by a Varian 571 and a Varian UHF-24 ion gauge. The ion gauge measurements are corrected for xenon during thruster testing.⁵ The facility pressure is sent to the computer by RS-232.

III. Recirculating Liquid Nitrogen System Design

The recirculating LN₂ system has four primary requirements: (1) deliver sufficient cooling to keep the cryopump shrouds at their optimal temperatures, (2) maintain a storage volume of LN₂ to allow immediate delivery of liquid on demand, (3) pump liquid to the vacuum facility, and (4) preferentially collect nitrogen gas from the system.

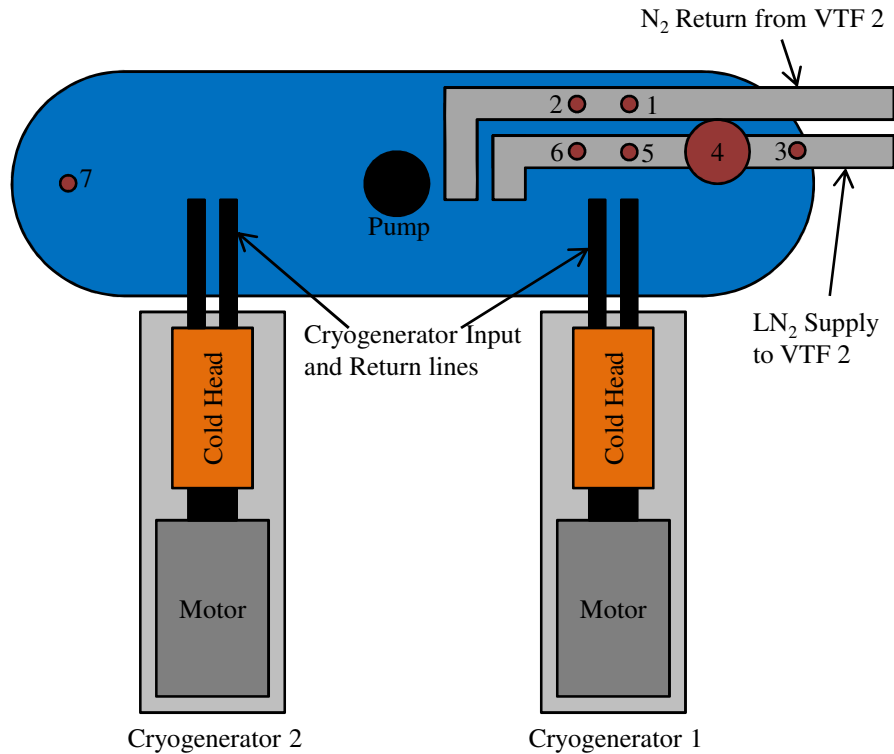


Figure 4: Schematic of the SPC-8 RL Special system. Numbered items are hardware and sensor locations for: (1) return temperature, (2) return pressure, (3) supply temperature, (4) control valve, (5) supply flow rate, (6) supply pressure, and (7) storage tank pressure.

A. Cooling Capacity

The first major requirement of a recirculating LN₂ system is delivered cooling capacity of the system. The ten cryopumps on VTF-2 require a combined LN₂ flow rate of 227 l/hr at steady state in order to cool the radiation shrouds sufficiently to keep the cryosails at their design temperature (13-15 K). The rate of 227 l/hr assumes that the cooling power is from boiling of the LN₂ alone; the pumps remain full of liquid. Thus, the cooling power requirement for the nitrogen shroud is purely from vaporization. A bulk storage tank of LN₂ with a supply pressure of 5 bar will provide saturated LN₂ at 94 K, which has a heat of vaporization of 4.855 kJ/mol and a density of 25.84 mol/l. A flow of 227 l/h, then, will provide 7,911 W of cooling power. Any LN₂ recirculation system, then, must have at least 7.9 kW of cooling power at 94 K and 5 bar.

LN₂ cryogenerators with capacities of several kilowatts are commercially available. The Stirling Cryogenics⁶ SPC-4 cryogenerator is capable of approximately 5.4 kW of cooling at 94 K. The SPC-4 is a four-cylinder cryogenerator which uses compressed helium gas to cool the nitrogen via the Stirling thermodynamic cycle, and requires only electrical power and cooling water. The SPC-4 only requires maintenance every 6,000 hours of operation.

Figure 5 shows that the cooling power delivered by the SPC-4 cryogenerator varies inversely with temperature. A system based on two SPC-4 cryogenerators will be able to provide 7.9 kW of cooling at 84 K; significantly lower than the desired delivery temperature. At 94 K, a two-SPC-4 system will deliver 10.7 kW of cooling; approximately 35% more than required by the cryopumps. The SPC-8 RL Special system integrated into VTF-2 employs two SPC-4 cryogenerators.

B. Liquid Nitrogen Storage

The second requirement of a recirculating LN₂ system is that it maintain a volume of liquid at all times so that it can supply liquid to the cryopump shrouds on demand. The cryogenerators liquefy gas to produce liquid only as needed. The SPC-8 RL Special system at HPEPL has a 3,000 l, vacuum-jacketed LN₂ storage tank which contains approximately 1,500 liters of LN₂.

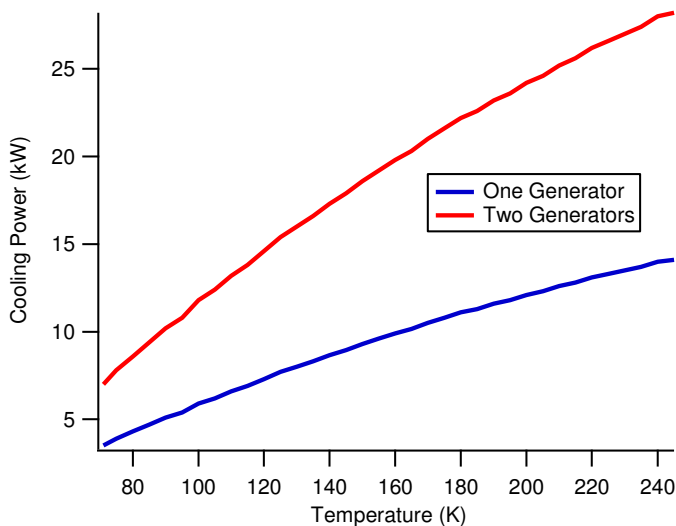


Figure 5: Approximate cooling capacities for one and two SPC-4 cryogenerators as a function of temperature.⁶

C. Liquid Nitrogen Delivery

The third requirement is a method to deliver nitrogen to the vacuum facility. Traditional bulk tank LN₂ systems are pressure fed; the static pressure in the bulk tank forces liquid through the cryopump shrouds. Bulk feed systems use automatic gas vent valves to release evaporated gas, which maintains a constant reservoir of liquid inside the radiation shrouds. Since the evaporated nitrogen gas is vented as it is produced, a bulk tank system will only supply liquid to replace the evaporated and vented gas. The cryogenerator system uses a pump to force liquid into the cryopumps and back to the storage tank and liquefaction system. The pump can drive LN₂ at up to 1,200 l/hr at a pressure head of 3 bar. An automatic control valve downstream of the pump maintains the pressure head at 3 bar. The liquid flow rate is typically 1,100 l/hr during steady-state operation and slightly less, around 900 l/hr, during early pumpdown when rapid boiling increases flow resistance. Automatic gas vent valves cannot be used in a pump-fed system. Since the nitrogen that returns to the cryogenerators during steady-state operation is likely a gas/liquid mixture, an automatic valve will unnecessarily throttle the LN₂ flow. Another method must be used to extract gas from the cryopumps while allowing liquid to enter.

D. Nitrogen Gas Collection

The third requirement of a recirculating LN₂ system is the ability to return gas to the storage tank while allowing liquid to remain in the radiation shrouds as long as possible. Figure 6 shows how this is accomplished through a gravity feed system. LN₂ is first pumped above the vacuum tank, through a main line running down the axis of the tank, and is able to pour into each cryopump shroud. The nitrogen leaving the LN₂ pump is compressed liquid; still at approximately the same temperature as the saturated liquid in the tank, but with the additional pressure from the pump head. This prevents gas bubble formation in the LN₂ supply line. The shroud exhausts are connected to a main return line which is approximately a meter higher than the supply line. This arrangement means that gas will preferentially collect in the return line, and is not present in the supply lines. In this way the shrouds only receive liquid from the supply lines, and the evaporated gas is able to leave the shrouds without interfering with the liquid supply. All of the nitrogen plumbing is vacuum insulated to eliminate unnecessary heat loss to the environment.

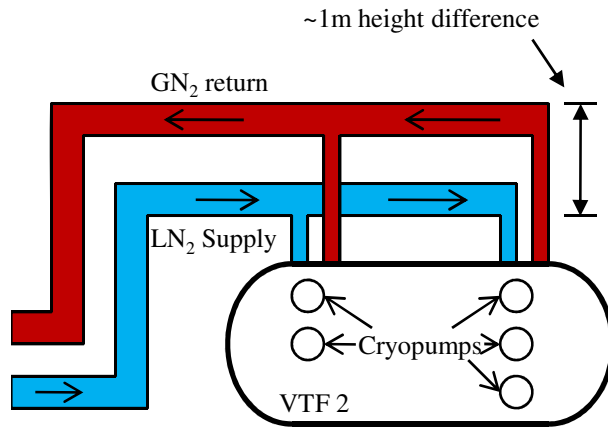


Figure 6: Notional side view of the nitrogen feed system to VTF-2. The cryogenerators, storage tank, and LN₂ pump are to the left of the figure. The height difference ensures the return line fills with gas before the supply line.

IV. Recirculating Liquid Nitrogen Method of Operation

Operation of a recirculating system is very different from a pressure-fed bulk storage system. In traditional bulk-tank-fed systems, activation of the nitrogen cooling is as simple as opening or closing a valve. A pump-fed cryogenerator system is necessarily much more complex to operate: the LN₂ pump, flow control valve, and cryogenerators are constantly monitored to ensure the system does not exceed its cooling capacity or pressure rating. The cryogenerator system has three primary phases of operation: (1) shroud warm-up and idle states, (2) steady-state operation of the radiation shrouds, and (3) initial cooldown of the radiation shrouds.

A. Idle and Warm-Up Modes

The cryogenerator mode of operation is similar when idle and when the radiation shrouds are warming up after a test. In both modes, the PLC turns off the LN₂ pump and control valve, and the cryogenerators turn on only when necessary to reduce the storage tank pressure. In idle mode the cryogenerators turn on approximately once per 17 hours and run for 35-45 minutes. Figure 7 shows pressure in the nitrogen storage tank during an idle mode cycle. The abrupt change in slope of pressure with respect to time as the pressure drops below approximately 3.5 bar is due to cryogenerator throttling; the cryogenerator speed is gradually reduced from 1,500 RPM to 900 RPM when the pressure is below 4 bar. Using the predicted cooling rates of the cryogenerator system in the cooling cycle, the total energy removed from the system during cryogenerator operation is 22 MJ. This is equivalent to the energy released by evaporating 125 liters of LN₂. Thus, the LN₂ system absorbs approximately 362 Watts from the environment, or an effective nitrogen boil rate of 7.4 l/hr.

The facility is shut off by turning off the LN₂ pump and control valve. The cryogenerators continue to run as necessary to control the pressure. When first turned off, the radiation shrouds are full of LN₂, the boiling of which presents a significant additional thermal load on the cryogenerator system. Figure 8 shows the temperature rise of the radiation shrouds after the nitrogen pumping is switched off, as well as the storage tank pressure during the same period. The cryogenerators run twice in approximately 20 hours; a roughly 40% faster cycle time than when the radiation shrouds are at room temperature, which indicates that approximately 175 liters of LN₂ evaporates during the warm-up process; 27 liters more than the 148 liters that evaporate in 20 hours while idle. The radiation shrouds reach 0 °C within 10 hours of pump shutdown. Typically the facility should not be vented until the pumps are above 0 °C, and hence there is minimal risk of significant water condensation on cold pump surfaces. The system requires approximately 20 hours to reach room temperature if left at vacuum.

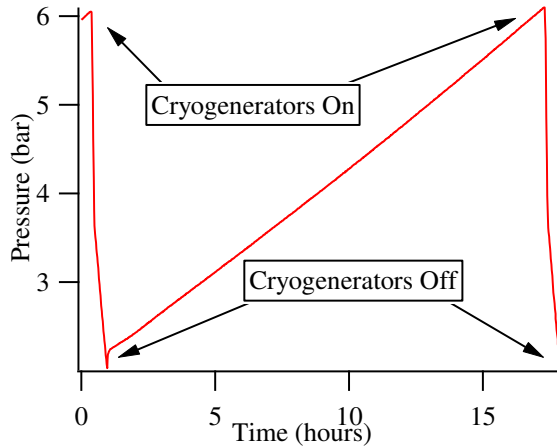


Figure 7: Pressure of the nitrogen storage tank as a function of time during idle mode.

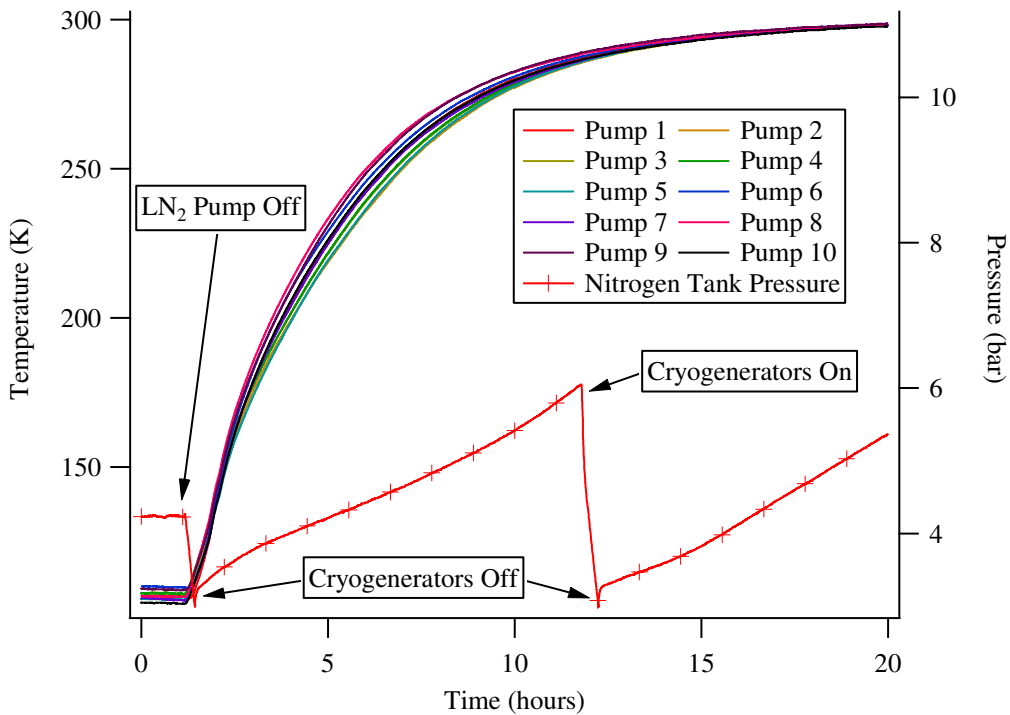


Figure 8: Radiation shroud temperatures and nitrogen storage tank pressure as a function of time during warm-up when turned to idle mode.

A. Radiation Shroud Cooldown

Cryopump radiation shroud cooldown presents the highest possible load to the closed-loop LN₂ system. LN₂ that enters the supply manifold, radiation shrouds, and return manifolds quickly boils and is returned to the storage tank as warm gas. Figure 9 shows the pressure in the storage tank during the cooldown phase, which rises very rapidly during LN₂ pump operation due to the high initial rate of gas production. When the system pressure reaches a user-set maximum pressure (6 bar in Figure 9), the cryogenerators activate. When the tank pressure reaches 10 bar, the PLC controller turns off the LN₂ pump. This stops the flow of nitrogen to the facility to allow the cryogenerators to bring the storage tank pressure back down by condensing gaseous nitrogen. When the tank reaches a user-set pressure (3.25 bar in Figure 9) the cryogenerators turn off and the pump reactivates. The cryogenerators have an additional safety mechanism which prevents them from turning on less than five minutes

after they are deactivated. Early in cooldown this delay means that the cryogenerators may not turn on until the system has already reached 10 bar and the pump has stopped. Later in the cooldown, the cryogenerators turn on well before the LN₂ pump deactivates. Figure 9 shows that the cycle of rising and falling pressure is typically repeated 18 times over 16 hours until gas returning from the radiation shrouds is approximately 110 K, which is cold enough that the cryogenerators can keep up with the cooling demand. The LN₂ pump stays on a little longer each cycle as the radiation shrouds become progressively cooler and thus conduct less energy into the nitrogen. Once the cryogenerators can keep up with the cooling demand (after the 16.5-hour point in Figure 9) the storage tank pressure stabilizes and the LN₂ pump and cryogenerators remain active.

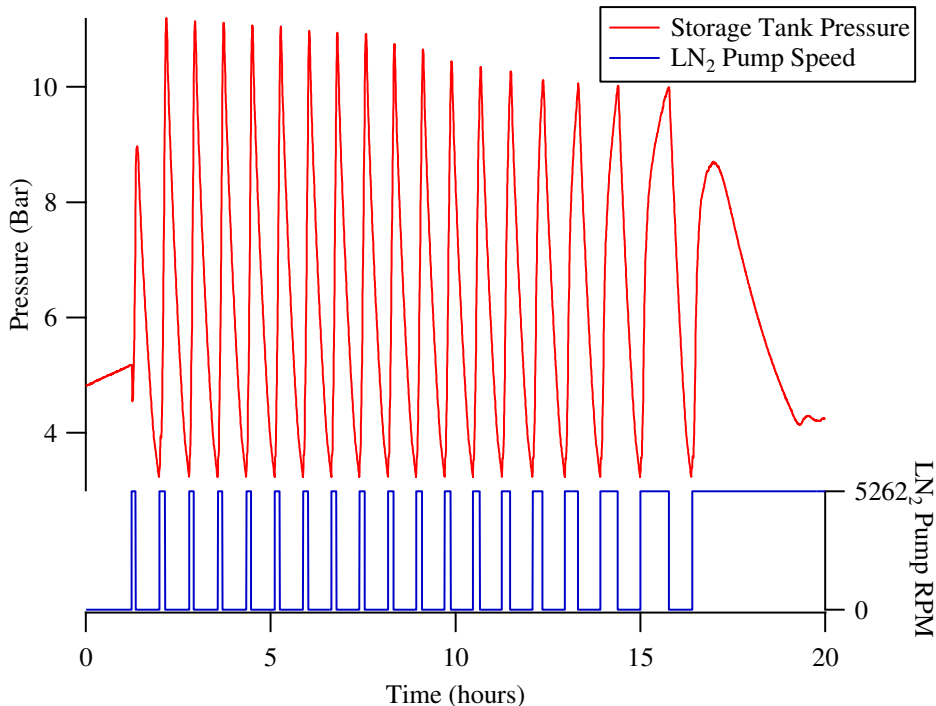


Figure 9: LN₂ storage tank pressure and LN₂ pump speed during the cooldown phase of operation.

B. Steady-State Operation

Steady-state operation is achieved when all ten radiation shrouds have reached their operating temperature. During steady-state operation the cooling load of the pumps is the equal to the cooling capacity of the cryogenerators; hence there is no net flow of energy into the storage tank and the tank pressure remains constant. For many tests, this means a tank pressure of between 4 and 5 bar, and hence a nitrogen temperature between 92 and 95 K. The steady state temperature is determined by the cryogenerator cooling power capacity and the heat loads on the radiation shrouds, and cannot be directly controlled without additional cryogenerator capacity or active reduction of the heat load on the shrouds.

V. Recirculating Liquid Nitrogen System Performance

A recirculating LN₂ system must cool as effectively as a traditional bulk tank feed system. There are two primary measures of performance which determine cooling effectiveness: (1) if radiation shrouds can reach their operating temperature, and (2) time required to cool the radiation shrouds to their operating temperature. Additionally, the rate of liquid consumption is critical to determine the net benefit of a recirculating system; since the recirculating system does not require nitrogen refill. The saved cost in LN₂ is used to determine the break-even point of the system, which is the point after which the saved LN₂ refill costs are greater than the initial cost of the system.

A. Radiation shroud Operating Temperature

Two metrics can determine if the radiation shrouds reach their operating temperature: (1) whether the cryosails reach their operating temperature, and hence the facility reaches its operating pressure, and (2) measurements of the radiation shroud temperatures. The first metric is met since VTF-2 is able to achieve pressures of 2.5×10^{-7} Pa (1.9×10^{-9} Torr), which would be impossible if the radiation shrouds and cryosails could not reach their operating temperatures. The second metric is the temperature of the radiation shrouds: the colder the shrouds get, the better the cryopump will perform as the helium-cooled sails can reach lower temperatures and hence pump faster. Figure 10 shows that, on average, the radiation shrouds maintain a temperature of approximately 106 K, with a maximum and minimum of 111 and 103 K, respectively. The shrouds show a roughly sinusoidal change in temperature which is almost perfectly in phase with the ambient temperature. The ambient temperature changes by more than the radiation shroud temperatures, but this is likely due to the fact that the radiation shrouds are being cooled by a LN₂ system which has a direct relationship between temperature and cooling power. Thus, the temperature increase from a higher room temperature is damped by an increased cooling rate from the cryogenerators. The ambient temperature changes on a roughly 24-hour period, with the high points in the late afternoon and the low points in the early morning, as would be expected in a non-climate-controlled space.

The steady-state radiation shroud temperatures are significantly higher than the expected 84-94 K from the cryogenerator design. This difference is explained by the thermocouple locations and by examination of the LN₂ supply and return temperatures from the cryogenerator system. The shroud thermocouples are measuring temperature of the shroud itself, not the LN₂ lines on the shroud, so they will always read a higher temperature than the LN₂ flowing through the shrouds. Examination of the LN₂ temperatures in Figure 10 shows that the supply and return temperatures are 9-13 degrees lower than the radiation shroud temperatures. Furthermore, the supply temperature remains steady at approximately 95 K. Additionally, the measured supply temperature is of the LN₂ downstream of the pump, where it has been warmed from the conditions inside the storage tank by the energy gained from the pump. The actual storage tank temperature is calculated from the tank pressure by assuming the tank is full of a saturated mixture of liquid and gas. This assumption is justified by the fact that the cryogenerator exhausts and the LN₂ return are deep below the surface of the liquid; there is significant mixing in the tank, which brings it close to thermal equilibrium. The nitrogen tank pressure during the data collection in Figure 10 is approximately 4.25 bar. A saturated liquid at this pressure is only 92 K; two degrees below the design target of 94 K. At 92 K the cryogenerators provide 10.4 kW of cooling, equal to the evaporation of 291 l/hr of LN₂. This power indicates that the radiation shrouds experience a higher-than-expected thermal load from the environment, and justifies the extra cooling capacity designed into the system.

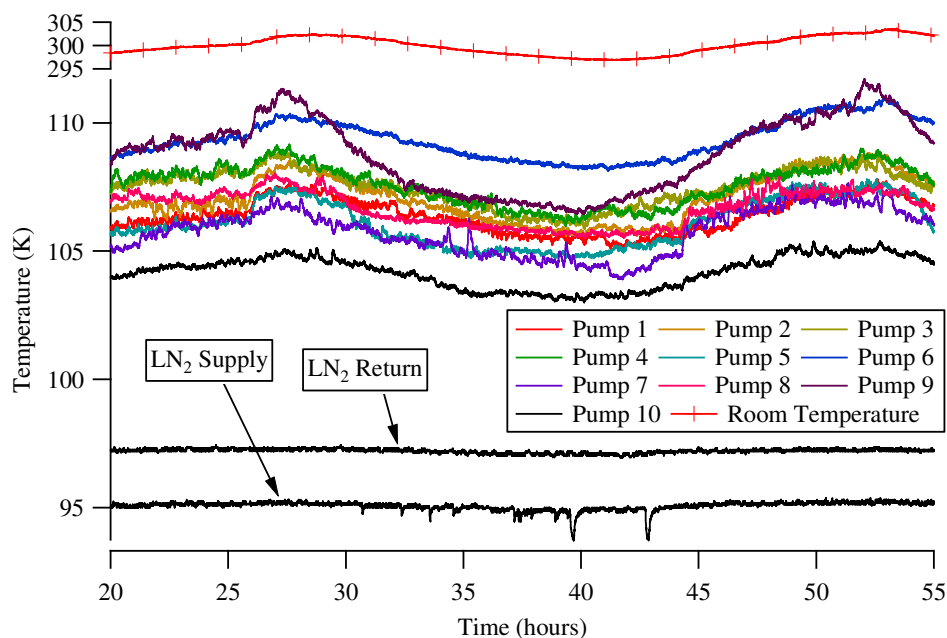


Figure 10: LN₂ supply, LN₂ return, radiation shroud, and room temperatures during steady-state operation.

The cryogenerator system must maintain the radiation shrouds at their operating temperature during active testing when a thruster is exhausting hot gas into the facility. Figure 11 shows the average shroud temperature and vacuum facility pressure over the time range of interest. The testing shown in Figure 11 involved operating a Hall effect thruster at mass flow rates up to 9 mg/s. The facility pressure is never greater than 6×10^{-4} Pa (4.5×10^{-6} Torr-Xe). The average radiation shroud temperature shows no significant change due to the mass flow into the system, and instead only follows the roughly-sinusoidal behavior seen in the ambient temperature. The fact that the radiation shrouds appear immune to the thruster is due in part to shielding inside the facility; graphite shielding has been placed between the radiation shrouds and the thruster. Thus, very little of the thruster jet power is transmitted to the pumps.

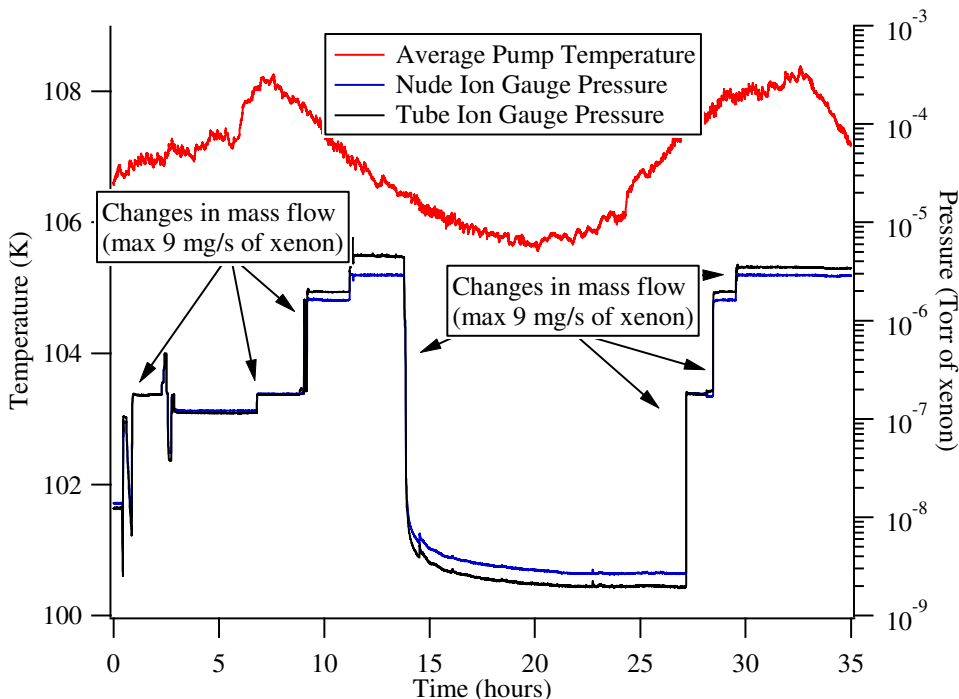


Figure 11: Average radiation shroud temperature and facility pressure as a function of time during steady-state operation with a HET operating at up to 300 V, 9 A, 9 mg/s xenon.

The LN₂ system meets the first criterion: it is able to cool the radiation shrouds to the point where they are effective. The radiation shroud shrouds show small changes over the course of a day of testing, but these changes are explained by the heat load on the system from the ambient air outside the facility. Furthermore, the cryopump shroud temperatures do not change as a function of thruster mass flow or power input. The cryogenerator system holds the radiation shrouds at their operating temperature as long as desired, without any need for LN₂ resupply.

B. Initial Cooling Rate

The time required to bring the radiation shrouds to their operating temperature is of major concern in a facility which experiences short and frequent testing cycles. Figure 12 shows that the radiation shroud temperatures decrease due to the LN₂ flow from the system, then increase when the LN₂ pump shuts off to allow the cryogenerators to lower the system pressure. The first on-off cycle of the LN₂ pump cools the pumps very little because nitrogen at this early stage cools the supply lines. Subsequent cycles have much larger effects on the radiation shroud temperatures.

The radiation shrouds experience very different cooling rates, cooling down in pairs according to their position on the facility as shown in Figure 13. This is a result of the gravity feed system which does not actively regulate the nitrogen flow rate, but rather allows liquid to be pulled by gravity. Pumps 1 and 6, for example, are the lowest pumps in the system and as such cool down the quickest. Pumps 7 and 10 are the next lowest, followed by 2 and 5, 8 and 9, and finally 3 and 4. Since pumps 3 and 4 are highest in the system, they are the last to receive a significant quantity of LN₂ and hence stay within ten degrees of 0 °C (273 K) until approximately 12 hours after cryogenerator system start-up. The on-off cycles on the LN₂ pump continue for approximately 16 hours, after which

the LN₂ return temperature is low enough that the cryogenerators can control the storage tank pressure while the LN₂ pump is active. The shrouds reach their operating temperatures approximately 19 hours after starting the cryogenerator system. The different cooling rates on each radiation shroud are not important to the total time required to cool the system. Since the system has a fixed thermal capacity, the only important result is that all ten shrouds reach the same final temperature at the same time. The coldest radiation shrouds present the smallest load to the cryogenerator system, so as some shrouds cool down they put less energy into the nitrogen, which allows the LN₂ pump to run longer and hence cool the remaining shrouds. This is most evident in the temperatures of pumps 3 and 4 at the end of the cooldown cycle; once pumps 1, 2, and 5-10 have nearly reached their operating temperature, pumps 3 and 4 finally see significant cooling and their temperature drops by almost 150 K in the last three cycles.

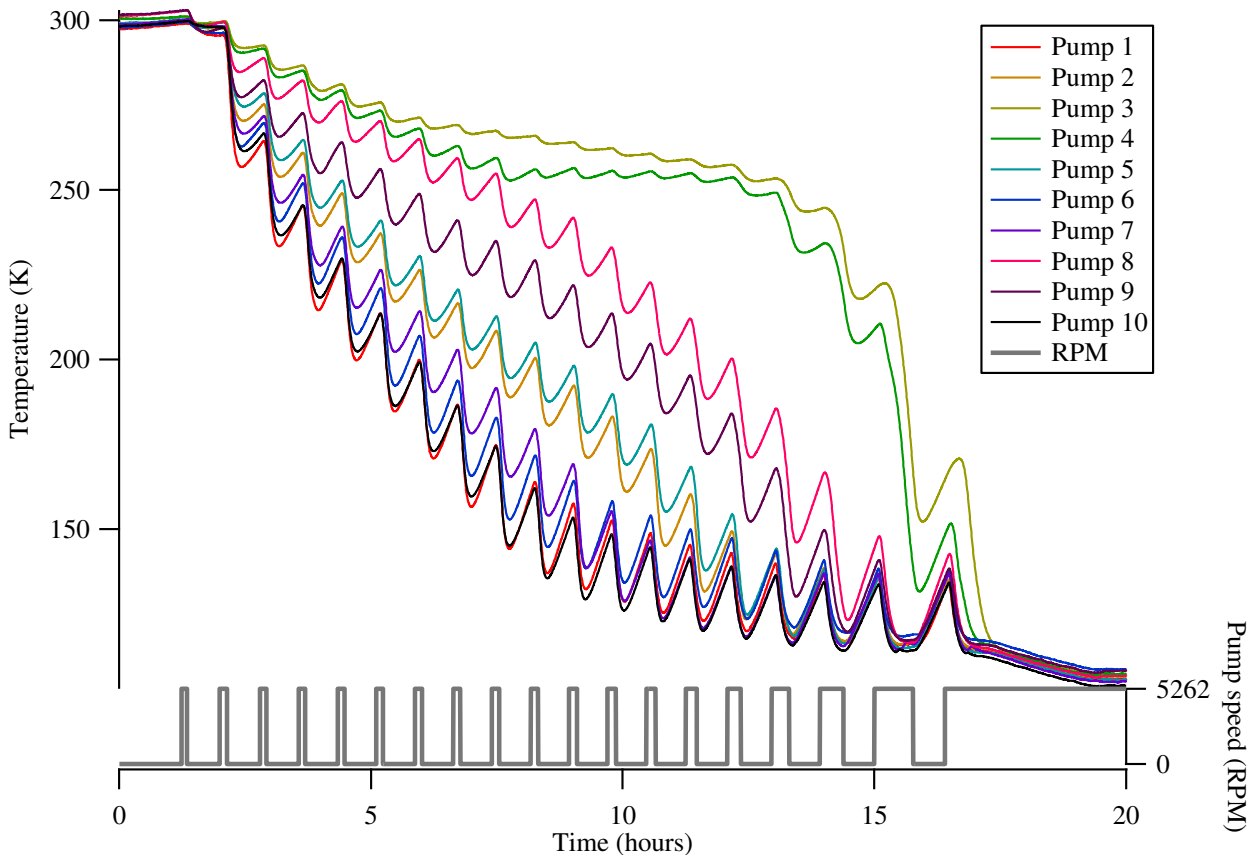


Figure 12: Radiation shroud temperatures and nitrogen pump RPM during initial cooldown.

The equivalent amount of LN₂ necessary to cool the shrouds from room temperature to operating temperature is calculated by assuming the nitrogen in the storage tank contains a saturated liquid. The tank pressure is used to calculate the liquid temperature, from which the cooling rate of the cryogenerators is calculated. Figure 12 shows that the storage tank is between 3.25 bar and 11 bar during cooldown, which translates to cryogenerator cooling rates between 9.5 and 12.5 kW. A piecewise integration of the cryogenerator cooling rates, combined with the heat of vaporization and density of LN₂, gives an estimate of the amount of nitrogen required to cool the radiation shrouds down to their operating points. The time-averaged cooling rate of the cryogenerators is 9.3 kW, including times when the system pressure is low and the cryogenerators are deactivated. Average cooling power while the cryogenerators are active is 11.3 kW, which translates to an 82% duty cycle. This agrees with the data in Figure 12 which shows the times of decreasing pressure (cryogenerators on) is much larger than the time with cryogenerators off. The total cooling energy expended to bring the radiation shrouds to their operating temperature is approximately 586 MJ, or the evaporation of 4970 liters of LN₂. It requires an effective evaporation rate of 290 l/hr to keep the system at steady state, the system will be able to operate for 2.4 days on the volume of nitrogen necessary to cool the system. The calculated nitrogen usage quantifies the vast difference between nitrogen usage during cooldown and nitrogen usage during steady-state operation.

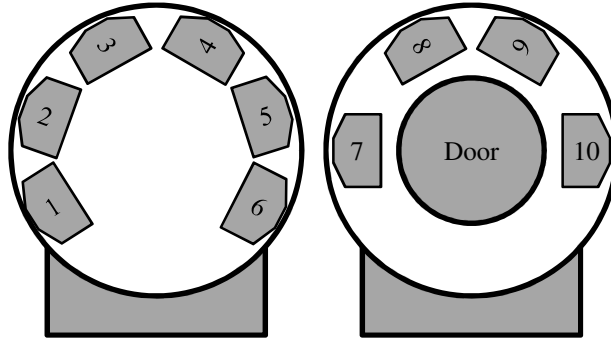


Figure 13: Notional schematic of pump locations at the downstream (left) and door (right) ends of VTF-2.

Figure 14 shows the effect of the reduced load on the nitrogen system due to reduced radiation shroud temperatures, as seen by the nitrogen supply and return temperatures. The nitrogen supply temperature is highest at the very beginning of pumping, at which point the temperature probe and surrounding piping are still being cooled. Nitrogen supply temperatures in the subsequent cycles increase slightly until the 8th cycle, after which they are relatively constant. The return temperature is a major driver in power deposition into the storage tank. Nitrogen returning to the storage tank early in the cooldown process is 150-200 °C warmer than the nitrogen in the supply line, due to the nitrogen lines warming the gas to near room temperature. Since the return lines are almost completely full of gas for much of the cool down process, their temperature rises significantly while the nitrogen flow is off as there is no potential to boil off liquid as a thermal buffer. The cycles in supply and return temperatures are almost exactly in phase with the LN₂ flow rate; every time flow starts the supply and return temperatures quickly drop, and every time the flow stops the temperatures begin to rise. Early in cool down the high temperature of returning gas is as much or more of a heat load than liquid boiling; it takes approximately 34 kW to boil 1,100 liters per hour of LN₂. Heat loads early in cooldown, however, are closer to 80-90 kW as determined by control-volume theory; the energy removed by the cryogenerators during cycle 1 is by definition equal to the energy added by the returning nitrogen during the same time. Since the cryogenerator system is only removing heat at a rate of approximately 11 kW, the cryogenerators will need to run for 8.2 minutes for every minute of LN₂ pump operation early in the cooldown cycle, when the LN₂ flow rate is throttled to between 900 and 1,000 l/hr.

The recirculating nitrogen system brings the radiation shrouds to their operating temperature of approximately 105 K within 20 hours of startup. Figure 15, however, shows that the vacuum facility reaches high vacuum well before the shrouds have reached steady state, indicating that some of the cryosails are at their operating temperature as soon as 10 hours after system startup. The facility pressure reaches 13 mPa (10^{-4} Torr) from the nitrogen system alone, and is below 1.3×10^{-5} Pa (1×10^{-7} Torr) 10 hours after startup. At this point the shrouds and cryosails on pumps 1, 6, 7, and 10 are at or near their operating temperatures, and shrouds and cryosails on pumps 2 and 5 are rapidly approaching steady state. Pumps 3, 4, 8, and 9 are still too warm to be effectively pumping, but six pumps is sufficient to bring the facility pressure below 1.3×10^{-5} Pa (1×10^{-7} Torr). Tasks such as cathode purging and mass flow calibration can be performed at this time; the increase in pressure at the 11-hour mark in Figure 15 is due to a cathode purge, and the spikes at 15 and 16 hours are from mass flow calibrations. The cryopump helium compressors and ionization gauges are usually switched on after the third cryogenerator cycle during cool down. At that point, all of the radiation shrouds except those on pumps 3 and 4 are below 0 °C, and are effectively freezing water out of the facility. The cryosails reach their operating temperature soon after the radiation shrouds reach ~110 K. In the case of pumps 3 and 4, the sails cool to approximately 160 K during the last few cycles of the cryogenerators.

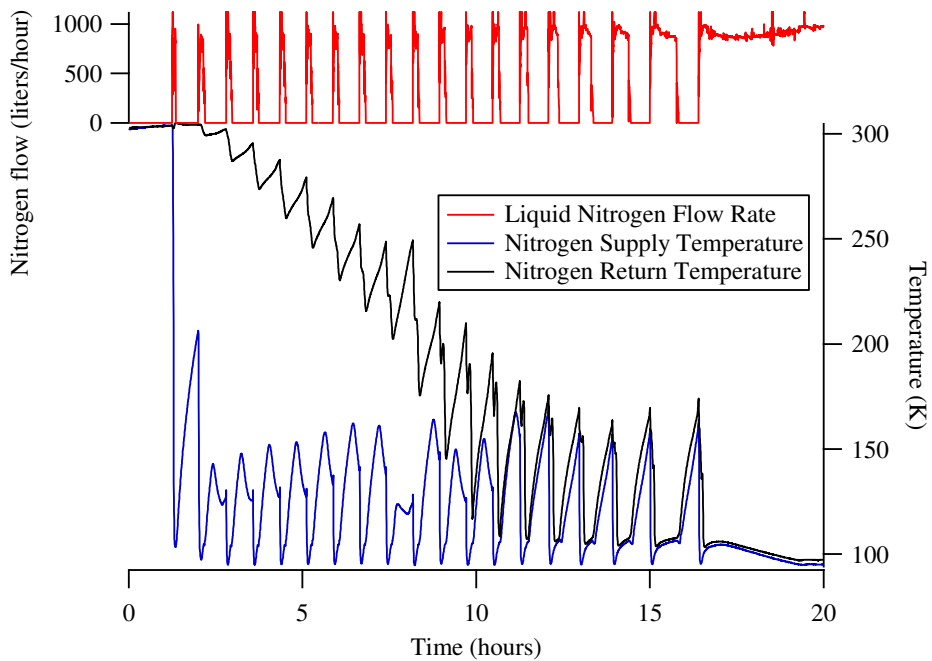


Figure 14: Nitrogen supply and return temperatures and LN₂ flow rate as a function of time during cooldown.

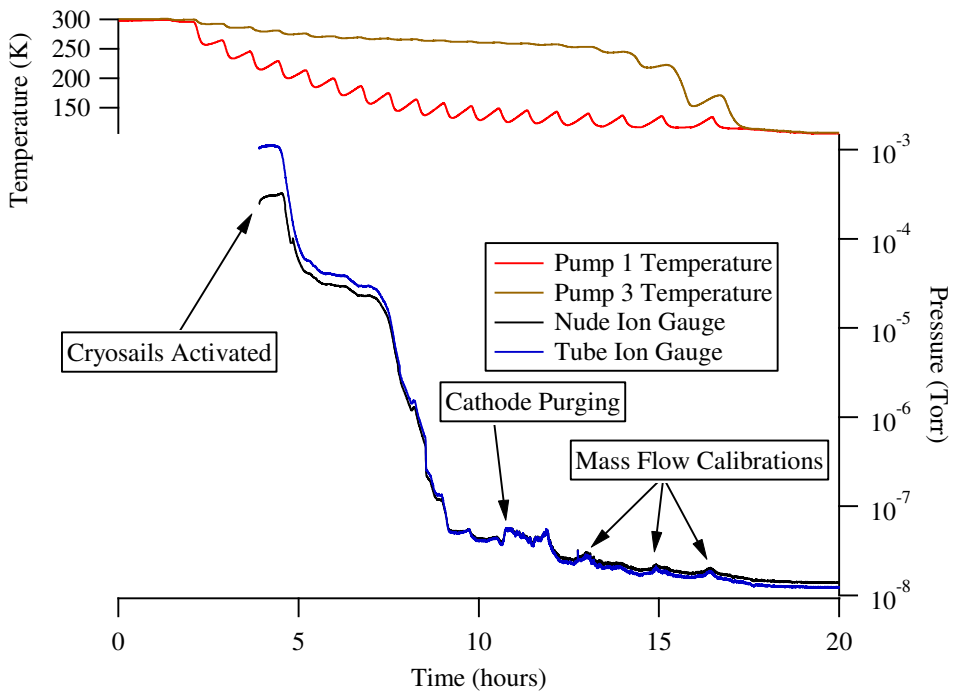


Figure 15: Shroud temperature of pumps 1 and 3, and VTF-2 vacuum pressure as a function of time during cooldown.

VI. Comparison with Bulk Storage

Energy analysis of the LN₂ system has provided the amount of LN₂ that must be evaporated to cool the system (4970 liters), maintain a cold system (290 l/hr), and maintain LN₂ in the storage tank while the system is idle (7.4 l/hr). An effective cost of operation is calculated from these LN₂ usage rates and an approximate bulk price of \$0.35/l of LN₂. Therefore a bulk feed system on VTF-2 will require nitrogen costing approximately \$1,700 to cool down the system, \$100/hour to operate at steady state, and \$2.60/hour to sit idle. A short test with 6 hours of test time will cost \$2,400. A two-week-long wear test will cost \$35,000, and a 5,000-hour life test will cost \$502,000.

The SPC-8 RL Special system cost \$700,000 in 2010. Figure 16 shows a cost comparison between life testing, repeated pumpdowns with 10 hours at high vacuum, and the cryogenerator system. At \$0.35 per liter it will require 6,900 hours of steady-state operation for the saved cost of LN₂ to equal the initial cost of the cryogenerator system. This is not a very long time; lifetime tests of EP thrusters commonly exceed 8,000 hours. Additionally, much of the testing in VTF-2 consists of short tests, typically 10 hours of thruster operation, so a single test will cost approximately \$2,800, thus requiring 250 pumpdown cycles to pay for the system. A thruster test cycle with 10 hours of test time will require approximately 50 hours total to cool the pumps down, run the test, and warm the pumps back up, so 250 tests will use LN₂ equal to 6,900 hours of steady-state operation.

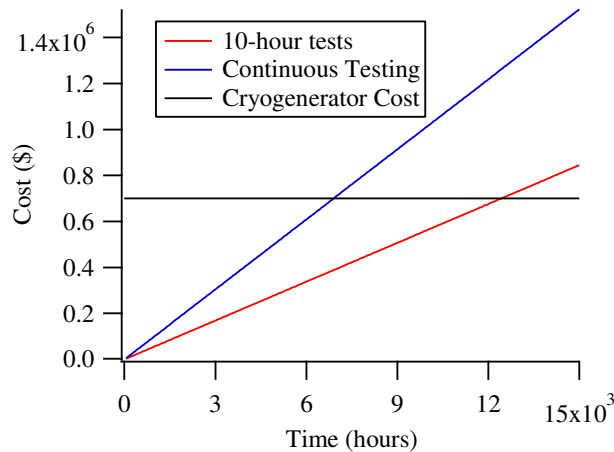


Figure 16: Costs of continuous 10-hour tests, continuous steady-state use, and the cryogenerator system during VTF-2 operation as a function of time.

VII. Conclusions

The addition of the Stirling SPC-8 cryogenerator system to VTF-2 at HPEPL proves that there is a closed-loop LN₂ alternative to costly and inconvenient bulk storage tanks. The SPC-8 system is able to bring the radiation shrouds on all ten TM-1200i cryopumps in VTF-2 to their operating temperature of 105 K in approximately 20 hours at a LN₂ storage tank pressure of 4.25 bar, can autonomously maintain the pump temperatures nearly indefinitely, and can do so without venting any nitrogen. Thermodynamic and system data indicate that VTF-2 requires the equivalent energy of boiling 4,970 liters of LN₂ to cool down to its operating temperature, 290 l/hr for steady-state operation, and 7.4 l/hr to sit idle. The cryogenerator system is fully automated and can be left active for long periods of time with no operator interaction.

The advantages of a closed-loop LN₂ system justify the extra expense of installation and the long cooldown times. The SPC-8 RL Special system on VTF-2 pays for itself after a single 6,900-hour wear test or after 250 short (10 hour) tests, based on an estimated \$0.35/l bulk LN₂ price. A closed-loop system with a nominal storage tank always has LN₂ available for delivery. The cryogenerators act reactively, to re-liquefy evaporated nitrogen, rather than on a constant basis, meaning that no energy is wasted cooling nitrogen that is already a liquid. The cryogenerator system removes the cost and logistical issues associated with LN₂ supply to a cryopump radiation shroud, and replaces them with a nearly unlimited LN₂ supply available at the push of a button.

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