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Evaluation of Helium Loss for a Closed-Loop Cryogenic System

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Abstract. The early detection of significant helium loss is critical for the efficient operation of cryogenic plants, particularly during periods of helium supply shortages. This study introduces a novel indicator that quantifies the remaining helium gas within a cryogenic plant and its associated cryostats under normal operating conditions by simplifying the calculations for components operating in stable states. The proposed indicator accounts for the standard operational status of the cryogenic system while incorporating the effects of external temperature variations at different locations of the helium gas buffer tanks, as well as the geometry of liquid helium vessels in horizontally positioned cryostats. A retrospective analysis of archived operational data from an active cryogenic system demonstrates that the indicator captures daily helium variations of up to 1.09 % of the total helium inventory. The peak variations are primarily caused by sudden environmental temperature changes and sharp fluctuations in level readings during liquid helium filling of superconducting magnet cryostats. When smoothed using daily averages, the indicator shows an uncertainty of ±0.13 % of the total helium inventory over a 13-day period, during which the system exhibited negligible helium loss. These findings suggest that the indicator is an effective tool for monitoring helium loss in closed-loop cryogenic systems under normal operating conditions.

1. Introduction

Helium supply shortages have occurred periodically in the past, posing significant challenges for facilities that rely on helium imports. Cryogenic plants supporting light sources must provide a continuous supply of liquid helium to maintain the temperature of superconducting devices in accelerators. Given the scarcity of helium and the substantial consumption required for superconducting operations, these plants typically operate as closed-loop systems, recovering helium gas from vaporized liquid helium. While scheduled maintenance and statutory safety checks inevitably lead to some helium loss—manageable through experience-based inventory planning—unpredictable losses due to component leakage, cryogenic plant trip events, or superconducting device quenches necessitate a reliable monitoring mechanism. To address this, an indicator capable of quantifying the remaining helium gas in the cryogenic plant and associated cryostats is essential for early leakage detection and timely corrective actions. Previous studies have explored helium loss monitoring in cryogenic systems. For instance, a study at CERN [1] reported a helium inventory evaluation with 1 % accuracy, setting a 10 % annual loss threshold

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for its 130-ton helium inventory as an abnormal leakage alert. Another study [2] introduced an online helium inventory monitoring program that analyzes data over multiple 10-day periods to determine the average daily loss rate.

2. Approach

For early system leakage detection, lowering the abnormal helium loss threshold and increasing monitoring frequency are beneficial. In a small-scale cryogenic system targeted with a 2 % helium inventory threshold and weekly inspections, a reliable indicator must have an uncertainty below 1 % to detect leakage confidently.

Based on mass conservation, the total helium mass in a closed cryogenic system—comprising the cryogenic plant and downstream cryostats—should remain constant without loss. Accurate evaluation requires accounting for helium in the plant, cryostats, and interconnecting piping. The cryogenic system includes process components (compressor, oil removal module, cold box) and storage components (buffer tank, dewar, cryostat), linked by warm piping and vacuum-insulated transfer lines for helium distribution, as illustrated in Figure 1 [3].

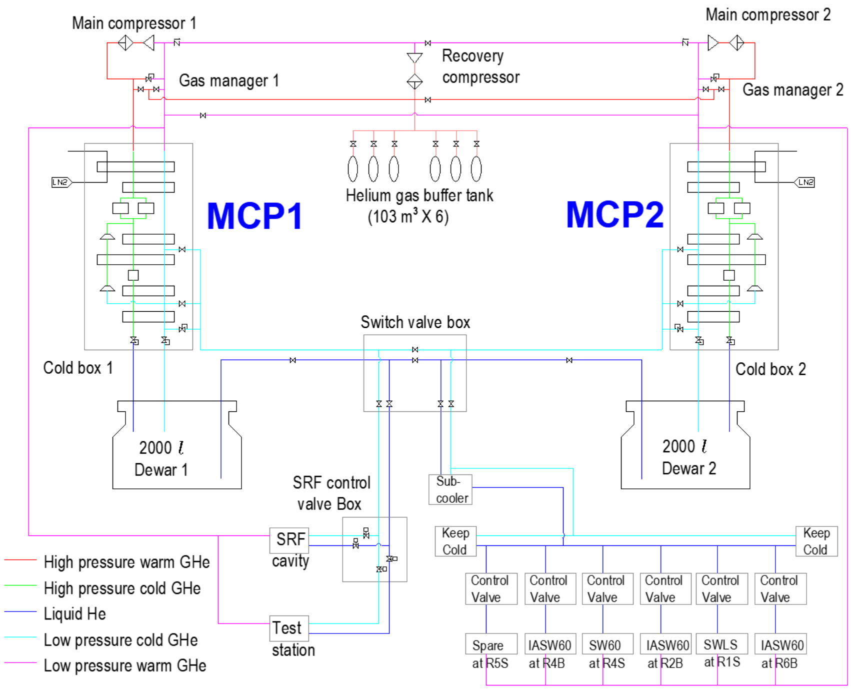

Figure 1. The closed-loop helium cryogenic system.

Since precisely calculating total helium mass is complex, this study focuses on daily normal operation, using helium mass variations as an indicator of loss. Under steady conditions, gaseous helium in process components and cryogen helium in transfer lines are considered quasi-stable and are excluded from the indicator. Thus, the helium status (HS) indicator represents the helium mass stored in the buffer tank, warm piping, cryostats, and dewar, formulated by Equation 1:

$$\mathrm{HS} = \sum_i (\rho_i \times V_i)\,,\, i \in \{\text{buffer tank, warm piping, cryostat, dewar}\} \quad (1)$$

3. Calculation equation

Helium gas is typically replenished in the cryogenic system when a shortage in helium inventory occurs. To maintain consistency with the standard units used in helium market assessments, we adopt a reference state of 300 K temperature and 1 atm pressure. The helium mass is then converted into volume units based on this reference state for uniform evaluation. Thus the indicator HS is reformulated by Equation 2:

$$\mathrm{HS} = \sum_i \left(V_{s,i}\right), i \in \{\text{buffer tank, warm piping, cryostat, dewar}\} \quad (2)$$

3.1 Buffer tank

The buffer tank is typically located outdoors, making the stored helium highly susceptible to environmental conditions. The available data for estimating the stored helium mass are obtained from temperature and pressure sensors. The helium weight W, given temperature T, pressure P, and volume V, follows the ideal gas Equation 3:

$$P \times V = \frac{W}{M} \times R \times T \quad (3)$$

where M is the molar mass and R is the gas constant. Using Equation 3, we convert the helium weight to the volume V_s at the reference state (T_s, P_s) by Equation 4:

$$V_s = \frac{T_s}{T} \times \frac{P}{P_s} \times V_{tank} \quad (4)$$

where V_{tank} is volume of the buffer tank.

3.2 Warm piping

The process components of the cryogenic plant, located at different points, are interconnected by piping. To simplify the calculation, short piping sections with small volumes can be identified and their helium content neglected. The remaining long pipelines primarily consist of the high-pressure supply line and low-pressure return line, which connect the compressor station to the cold box, as well as the make-up line that links to the buffer tank. Adopting temperature T_s and assuming negligible temperature variation—since helium gas passes through the piping in a short time—the helium volume can be determined by Equation 5:

$$V_s = \frac{P}{P_s} \times L_{pipe} \times A_{pipe} \quad (5)$$

where L_{pipe} and A_{pipe} are respectively the length and the cross-sectional area of the warm piping.

3.3 Cryostat and dewar

A cryogenic plant for an accelerator-based light source supplies liquid helium to maintain the superconducting radio frequency cavity (SRF) or superconducting magnet (SM) at cryogenic temperatures. The SM, with a low heat load, operates in liquefaction mode, where vaporized helium returns to the compressor to reduce operating pressure, enabling higher magnetic fields. The SRF, with a high heat load, operates in refrigeration mode, where cold gas from vaporized liquid helium cools warm helium gas via heat exchangers to enhance cooling capacity of cold box.

To ensure reliable operation, the SM and SRF are fully immersed in a liquid helium bath, eliminating the need to account for their complex geometries when evaluating helium inventory. The available signals in the cryostat and dewar include liquid helium level, temperature, and pressure. Since helium exists in both liquid and gas phases, the total inventory is obtained by summing their respective masses. Neglecting the SM cell geometry, the helium stored in the cryostat is expressed by Equation 6:

$$V_s = V_{SM} \times \left\{H \times \rho^l_{T,SM} + (1 - H) \times \rho^g_{T,SM}\right\} / \rho_s \quad (6)$$

where V_{SM} is volume of SM cryostat; $\rho^l_{T,SM}$ and $\rho^g_{T,SM}$ is respectively the density of liquid helium and gas helium in the SM cryostat; ρ_s is the density of helium gas at reference state; H is the percentage level of liquid helium.

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Similarly without considering the geometry of the SRF cell, the helium stored in the SRF cryostat is expressed by Equation 7:

$$V_s = V_{SRF} \times \{H \times \rho^l_{T,SRF} + (1 - H) \times \rho^g_{T,SRF}\} / \rho_s \tag{7}$$

where V_{SRF} is volume of SRF cryostat; $\rho^l_{T,SRF}$ and $\rho^g_{T,SRF}$ is respectively the density of liquid helium and gas helium in the SRF cryostat.

The helium stored in the dewar is expressed by Equation 8:

$$V_s = V_{dewar} \times \{H \times \rho^l_{T,dewar} + (1 - H) \times \rho^g_{T,dewar}\} / \rho_s \tag{8}$$

where V_{dewar} is volume of dewar; $\rho^l_{T,dewar}$ and $\rho^g_{T,dewar}$ is respectively the density of liquid helium and gas helium in the dewar.

4. Application and discussion

The cryogenic system of Taiwan light source (TLS) at National Synchrotron Radiation Research Center (NSRRC) supplies liquid helium to maintain the operating temperature of one SRF, housed in a 500-liter cryostat, and five SMs with cryostat volumes of 40, 250, 121, 121, and 121 liters, respectively. The system includes two cryogenic plants, each with a 450 W cooling capacity at 4.5 K, and a 2000-liter dewar. Helium gas inventory is stored in six horizontally positioned buffer tanks, each with a 103-cubic-meter volume [3].

Applying the parameters in Table 1 and Equations 4–8 to five-week archived data of TLS cryogenic system, using the software Wolfram Mathematica for calculation, the helium inventory trend (HS) was analyzed, as shown in Figure 2. HS is calculated every 30 seconds, displayed with a one-day moving average window. The results indicate that HS is significantly influenced by environmental temperature, with daily variations ranging from 60 to 72 m^3 (1.23 % to 1.49 % of the daily average) on days with substantial temperature fluctuations.

Table 1. Parameters used for evaluation of total helium in TLS cryogenic system.

Item	Quantity	Volume (m^3)	Density (kg/m^3)	Pressure (bar)	Temperature (K)	Level (%)
Reference state	–	–	0.16252	1.01325 (1.0 atm)	300	–
Buffer tank	6	(horizontal) 103.0	–	measured	environment	–
Dewar	2	(vertical) 2.0	liquid: 116.646 gas: 24.176	1.40	4.587	measured
SM	5	(vertical) 0.04 (horizontal) 0.25, 0.121, 0.121, 0.121	liquid: 123.728 gas: 17.977	1.07558 (15.6 psi)	4.288	measured
SRF	1	(horizontal) 0.5	liquid: 119.687 gas: 21.448	1.26312 (18.32 psi)	4.467	measured
Warm piping	6	0.313, 0.563, 5.761, 0.8, 0.563, 5.761	–	measured	300	–

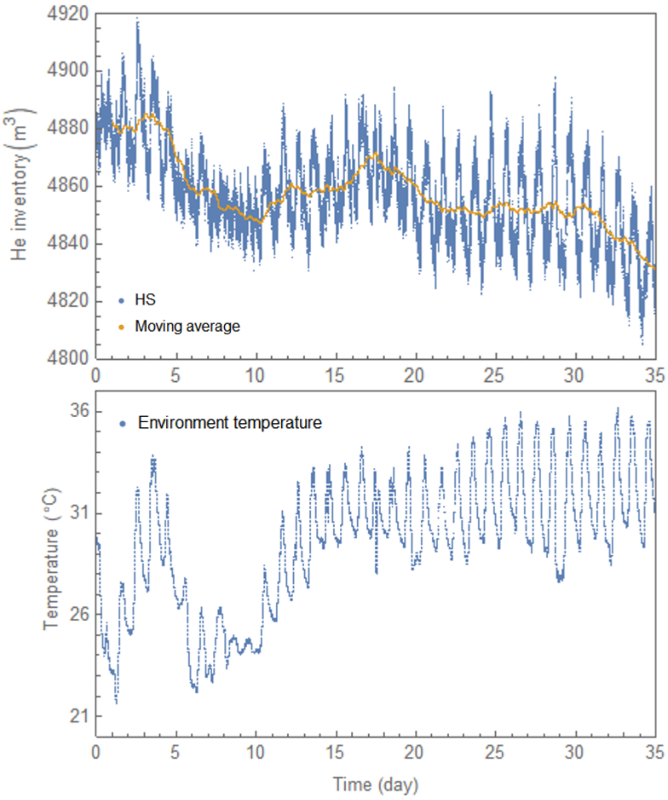

Figure 2. Total helium in TLS cryogenic system and environment temperature.

This variation of HS could be further reduced if considering the temperature difference for the buffer tanks, the geometry effect for the cryostat with horizontal position, and the non-uniform temperature for the cold helium gas in cryostat and dewar.

4.1 Temperature difference for the buffer tanks

The buffer tanks are located in varying conditions, with some exposed to direct sunlight and others shaded. Consequently, their temperatures differ due to the effects of sunlight and positioning. Each buffer tank, with a 3-meter diameter and 14-meter length, is horizontally positioned and connects to the cryogenic plant at the inlet end. A small, thermally insulated sampling chamber is attached to the non-inlet side of each tank. Sensors inside the chamber monitor the temperature and pressure of the helium gas within the buffer tank.

Figure 3 shows the temperature and pressure variations over two days during the summer for a buffer tank exposed to sunlight and isolated from the cryogenic system. Temperature sensors are located in the shaded air and inside the sampling chamber, while pressure sensors are positioned at the inlet end and inside the chamber. The results reveal temperature differences at various locations and a time lag between pressure and temperature changes.

4.2 Geometry effect for the horizontally positioned cryostat

To improve the accuracy of the helium inventory indicator, the geometry of the cryostat should be considered. The cryostat's liquid helium vessel is cylindrical and can be positioned either horizontally or vertically [4, 5]. For a vertically positioned cryostat, a level sensor is sufficient to evaluate helium inventory, as the sensor reading is proportional to the liquid helium volume.

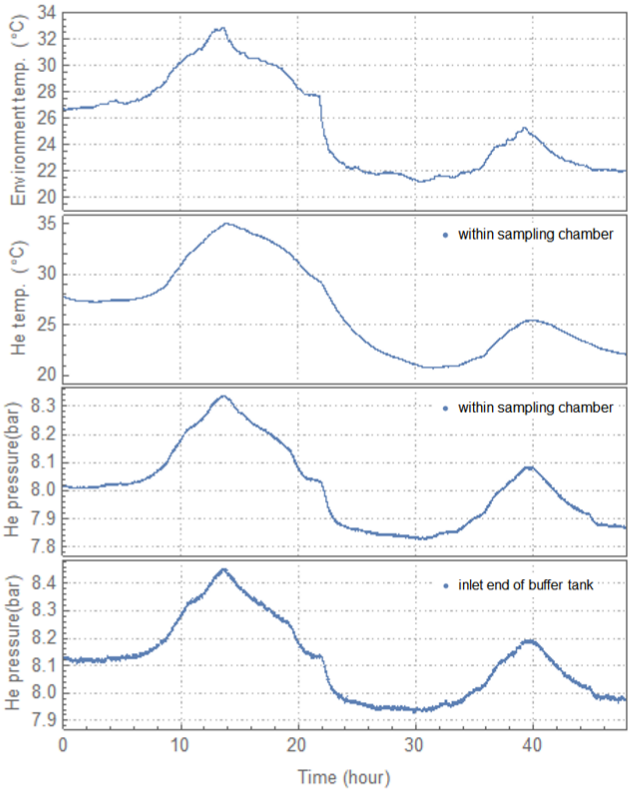

Figure 3. Temperature and pressure variations for an isolated buffer tank.

However, for a horizontally positioned cryostat with a liquid helium level above 50 %, neglecting the vessel's geometry will lead to an underestimation of the helium inventory.

In the horizontally positioned SRF cryostat, liquid helium is continuously filled, maintaining a fixed level for precise pressure control within 1 mbar variation, allowing the geometry effect to be ignored for simplicity. In contrast, the SM cryostat does not have continuous liquid helium flow, and its level fluctuates between maximum and minimum values. The transfer consumption due to the high heat loss flexible transfer line, connecting the SM cryostat to the main line, is minimized by limiting its usage time.

For a horizontally positioned cylinder vessel as shown in Figure 4, a volume factor V_f is introduced to account for both geometry and liquid helium level, expressed by Equations 9-10:

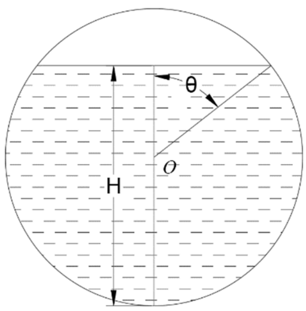

Figure 4. Cross section of a cylinder vessel positioned horizontally.

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$$V_f = 1 - \{\theta - (2H - 1) \times \sin(\theta)\} / \pi \tag{9}$$
$$\theta = \cos^{-1}(2H - 1)\ and\ H \geq 50\ \% \tag{10}$$

The helium stored in the SM cryostat with horizontally positioned vessel is obtained from modifying Equation 6 and expressed by Equation 11:

$$V_s = V_{SM} \times \left\{V_f \times \rho^{l}_{T,SM} + \left(1 - V_f\right) \times \rho^{g}_{T,SM}\right\} / \rho_s \tag{11}$$

4.3 Non-uniform temperature for the cold helium gas in cryostat and dewar

For a cryostat partially filled with liquid helium, the space above the liquid level contains cold helium gas with a temperature gradient. Using the saturation temperature density to calculate the gas weight tends to overestimate the inventory. Calculating the average density of the cold helium gas at varying levels is complex. Instead, we use the gas density at saturation temperature, adjusted by a gas factor (less than one), in Equations 6-8 and 11 to estimate the helium inventory. A gas factor of 0.5 is chosen for this calculation.

4.4 Total helium in TLS cryogenic system after refined evaluation

Figure 5 presents the helium inventory trend of the TLS cryogenic system, using the same archived data and calculation interval as in Figure 2, but accounting for the cryostat's horizontal position, varying helium temperatures in the buffer tanks, and a gas factor to adjust for non-uniform helium gas temperatures in cryostat and dewar. In Figure 5(a), the deviation between the envelopes of maximum and minimum peaks is smaller compared to Figure 2. The moving average in Figure 5(a) more effectively identifies helium inventory loss.

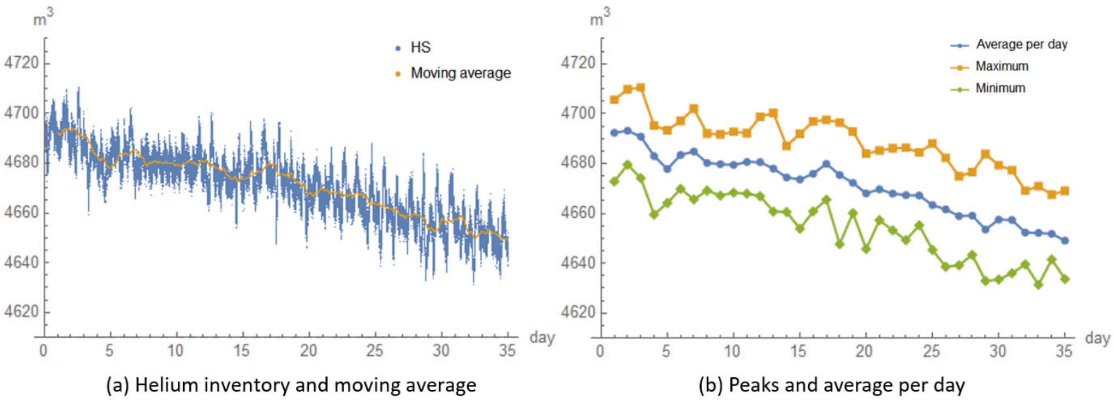

Figure 5. Total helium in TLS cryogenic system with reduced variation.

In Figure 5(b), the daily average, maximum, and minimum values without time window overlap provide clearer identification of the helium loss trend. The daily variation ranges from 36 to 51 m^3 (0.76 % to 1.09 % of the daily average) on days with significant environmental temperature fluctuations. From days 4 to 17, the daily average shows negligible helium loss, with an uncertainty of ±6 m^3 (±0.13 % of total helium). From days 17 to 35, the average helium loss is 1.7 m^3 (0.28 kg) per day. These results suggest that helium loss can be reliably monitored on a weekly basis.

A detailed comparison of the calculated HS and archived data, as is shown in Figure 6, for days 29 to 35, reveals that the peak values are primarily caused by sudden environmental temperature changes and sharp fluctuations in level readings during the filling of liquid helium into the SWLS and SW60 superconducting magnet cryostats. Figure 6 shows that the

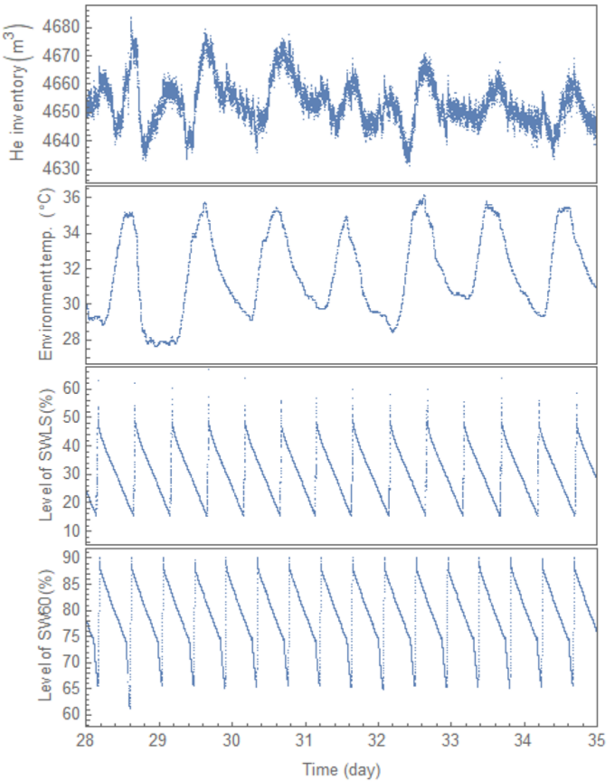

Figure 6. Peak values due to abrupt change of environment temperature and liquid helium level.

environmental temperature change dominates the variation in HS, despite the calculation equation accounting for the temperature of helium gas in the buffer tanks.

5. Conclusion

An indicator for monitoring the variation in total helium inventory within the cryogenic system under normal operating conditions has been developed. It accounts for temperature differences in the buffer tanks, the geometric effects of horizontally positioned cryostats, and the non-uniform temperature of cold helium gas in the cryostat and dewar. Verification using five weeks of archived data shows that this indicator exhibits a peak-to-peak daily variation of up to 1.09 % of the total helium inventory, with a daily average uncertainty of ±0.13 %. This indicator is suitable for real-time monitoring of helium inventory, allowing for weekly identification of helium loss and early detection of system leakage.

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