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Development and verification of a transient operating methodology for pump-down operation of 2 K cold compressor system

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Abstract. Multi-stage cryogenic centrifugal compressor trains (cold compressors or CCs) used in 2 K sub-atmospheric refrigeration systems require a transient process operation (or 'pump-down') to establish the target low-pressure steady-state conditions. In sub-atmospheric refrigeration systems for superconducting radio frequency (SRF) cavities, the pump-down process establishes a pressure ratio of approximately 40 (*i.e.* ~ 30 mbar at the load) across the cold compressor train starting from unity. The mass flow rate through compressor train is typically controlled by adjusting the speed of a primary compressor, while the remaining compressors in the train are coupled to the primary through electronic speed ratios. Historically, the transient variation of the electronic speed ratios and the mass flow during the pump-down process has been determined empirically through a tedious trial and error testing process. Often, this empirical approach resulted in a pump-down process path that is either unstable or longer than optimally possible. A 1D transient numerical model for the cold compressor pump-down process has been developed to predict and characterize dynamic behavior of the sub-atmospheric system (cold compressors, loads and associated cryogenic distribution). A transient operating algorithm to select the system parameters, *i.e.* CC speed ratios and overall flow variation, during the pump-down process utilizing the developed model and cold compressor performance maps is proposed. Extensive tests have been performed using the FRIB sub-atmospheric refrigeration system to validate the developed model and to check the applicability of the proposed algorithm. Excellent agreement between the model predictions and the test data provided evidence that improvement in theoretical understanding of the sub-atmospheric system has resulted in simplifications of the pump-down process path. Simplicity of the pump-down process path provides additional benefits of increased reliability and stability of the transient pump-down process.

1. Introduction

1.1 FRIB 2 K System

The Facility for Rare Isotope Beams (FRIB) employs a sub-atmospheric cryogenic system which enables cooling capabilities below the normal boiling point (NBP) of helium (~ 4.2 K). This system is critical for operation of the linear accelerator (linac), which utilizes superconducting radio frequency (SRF) cavities requiring helium bath temperatures near 2 K. The sub-atmospheric

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system lowers the helium bath temperature below the NBP of helium by reducing the cryostat pressure, thereby decreasing the corresponding saturation temperature until reaching the target operational temperature.

Evacuation of the helium vapor (*i.e.* reduction of the cryostat pressure) is achieved at FRIB exclusively using cryogenic centrifugal compressors (cold compressors, or CCs). The FRIB sub-atmospheric system consists of five cold compressors which are operated in series, producing an overall pressure ratio of approximately 40. Helium vapor returning at a pressure of 30 millibar (corresponding to a saturation temperature of ~ 2 K) is compressed by the CC train to above atmospheric pressure, and the flow is subsequently injected back into the main 4 K refrigeration system. A simplified schematic of the FRIB cryogenic system is provided in Figure 1. The benefits of full cold-compression sub-atmospheric systems are discussed in detail within [1, 2].

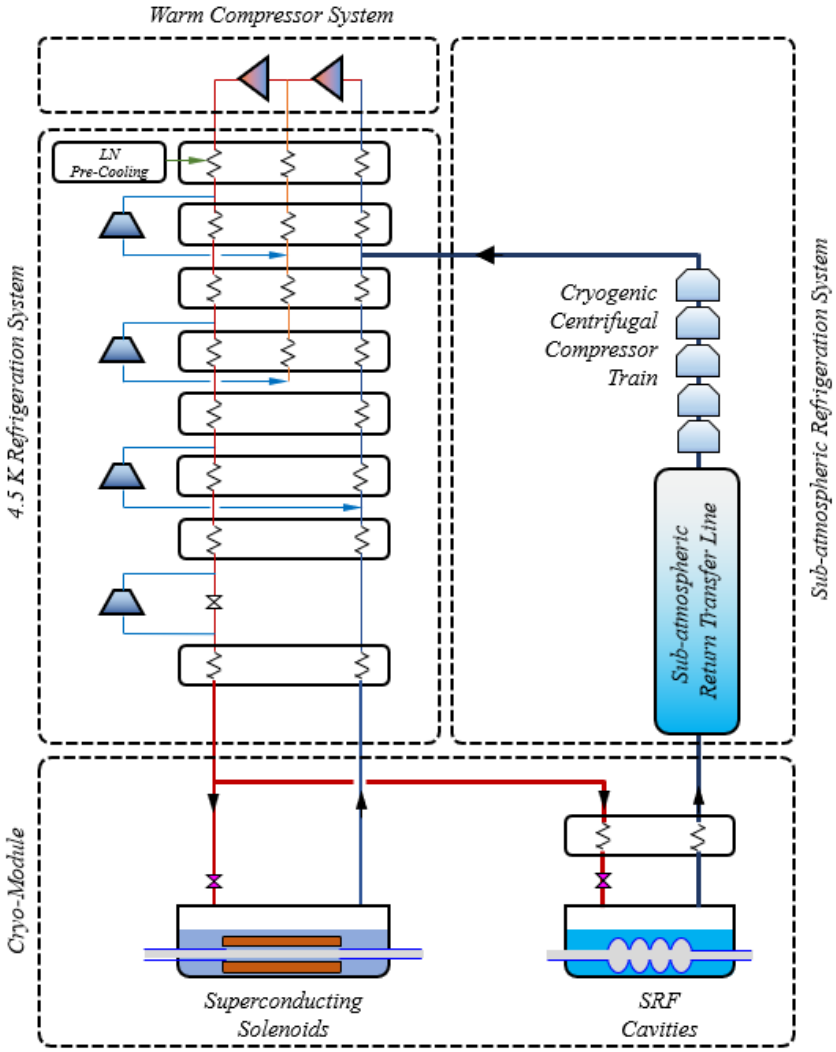

Figure 1. Simplified schematic of the FRIB cryogenic system

1.2 Historical Operation Methodology

The sub-atmospheric system for the Continuous Electron Beam Accelerator Facility (CEBAF, Jefferson National Lab) was the first large-scale system which exclusively used cold-compressors to achieve 2 K operational conditions [3]. The original system consisted of four cold compressors

operated in series, with a fifth compressor stage later being added to improve overall system stability. The operating methodology developed during the commissioning of this system was pioneering, being adopted at future facilities which implemented full cold-compression systems (*i.e.* SNS, FRIB, and additional systems at JLAB) [1, 3, 4].

The operation methodology developed for these systems includes the selection of a "primary" compressor, which is actively controlled to satisfy a target mass flow rate through the compressor train. This primary compressor is typically the final compression stage, as this compressor has the smallest wheel size and subsequently the highest rotational speed, allowing for more precise control. The remaining compressors on the train are "secondary" compressors, which are tied to the primary compressor through electronically implemented speed ratios.

A critical operation of these compressor systems is the transient process present when the system is turned on. This process is colloquially known as "pump-down" and is the procedure that initially evacuates the helium vapor present in the cryostat (starting at pressures above atmospheric conditions and concluding at the operating pressure). The transient process path for each individual compressor during the pump-down sequence is largely dependent upon the secondary compressor speed ratio selection, the target mass flow rate, dynamic and static heat addition, and the system geometry. Traditionally, selection of the process parameters was conducted empirically, based on experimental (*i.e.* trial and error) observations of the system during transient operation. Therefore, attempting to vary the process path also included a requirement for experimental testing to validate the corresponding process parameter selection.

Additionally, it has been observed during transient operation that the stability of the compressor system can be enhanced by preventing compressor deceleration during the pump-down sequence. An operational control methodology was integrated into the system to achieve this criterion, not allowing the individual compressor speeds to decrease while in pump-down mode. This has been found to enable the compressors to operate outside their respective steady-state performance map stability regions while maintaining transient operational stability.

2. Developed Operation Methodology

2.1 System Modeling and Profile Generation

An operating methodology was developed based on system modeling using fundamental thermodynamic relationships rather than control parameters established through extensive experimental testing, removing the necessity for testing when attempting to adjust the transient process path.

A mean-line model was developed to estimate the performance characteristics of the cold compressor train under various operating conditions. This performance model can estimate the stable operational region of each compressor, establishing the surge and choke stability limits. Additionally, the pressure ratio across the compressor stages and for the entire train can be estimated. Input requirements for the developed model include specific geometrical parameters of the individual compression stages, the compressor rotational speeds, and the mass flow rate through the compressor train. Details on the development of the compressor performance estimation model can be found in [2, 5, 6].

In conjunction with the compressor performance model, a system model to estimate pressure variance during transient operation was developed. The system model was developed assuming that there is negligible pressure drop in the 2 K vapor return piping (*i.e.* a single pressure model) which greatly simplified the model and reduced computational time. Mass and energy balances within the two-phase (saturated) cryostat and the single-phase return transfer

line were coupled and allowed for estimating the pressure change as a function of time. These equations are fully derived in [2], with the final form of the system of equations shown below as equations (1) through (3). Change in pressure with respect to time, $\dot{p}$, is calculated as a function of the cryostat mass, m, pressure, p, internal energy, u, enthalpy, h, mass flow rate, $\dot{m}$, and heat addition, $\dot{q}$, and the return transfer line volume, V, compressibility factor, Z, specific gas constant, R, temperature, T, mass flow rate, $\dot{m}$, internal energy, u, enthalpy, h, and heat in-leak, $\dot{q}$. The subscripts utilized include the time step, i, saturated liquid, l, saturated vapor, v, saturation condition, sat, dynamic, dyn, helium gas, g, cold compressor, cc, and return transfer line, RTL.

$$\begin{aligned}\dot{p}_i\left[m_l\left(\frac{du_l}{dp_i}\right)_{sat}+m_v\left(\frac{du_v}{dp_i}\right)_{sat}\right]-\dot{p}_i\left(\frac{m_l}{v_l}\right)\left(\frac{dv_l}{dp_i}\right)_{sat}u_l-\dot{p}_i\left(\frac{m_v}{v_v}\right)\left(\frac{dv_v}{dp_i}\right)_{sat}u_v \\ =h_s\left[\dot{m}_g-\dot{p}_i\left(\frac{m_l}{v_l}\right)\left(\frac{dv_l}{dp_i}\right)_{sat}-\dot{p}_i\left(\frac{m_v}{v_v}\right)\left(\frac{dv_v}{dp_i}\right)_{sat}\right]-\dot{m}_g h_g+\dot{q}_{static}+\dot{q}_{dyn}\end{aligned} \tag{1}$$

$$V\left[\frac{\dot{p}_i}{ZRT}\right]=\dot{m}_g-\dot{m}_{cc} \tag{2}$$

$$V\left[u\frac{\dot{p}_i}{ZRT}\right]=\dot{m}_g h_g-\dot{m}_{cc}h_{cc}+\dot{q}_{RTL} \tag{3}$$

The developed models accurately capture system characteristics observed during FRIB sub-atmospheric operation, and validation of the models is presented in [2]. By utilizing both the compressor performance estimation model and system pressure response model, the process path during transient operation (pump-down) can be established. The process path can easily be manipulated in these models using the compressor speeds (speed ratios), the compressor train mass flow rate, and the dynamic heating in the cryostat. These independent parameters can be adjusted to converge to a desired transient operational path which is stable and reliable.

2.2 Application of Methodology

Proper application of the developed operational methodology requires the selection of a desired transient process path. Selection of the pump-down path is dependent upon the stability region of the compressor, the capabilities of the accompanying 4 K cryogenic system, and the target total pump-down time. For reference, several generic transient process path examples are provided in Figure 2 (left). These process paths are shown between the starting point (SP) of the pump-down process and the operation point (OP) at the conclusion of the pump-down.

The higher the mass flow rate through the compressor train (*path C*) is typically more stable but imposes a larger unbalance on the 4 K cryogenic system (which may require additional 1st stage compressor support). On the other hand, lowering the mass flow rate will shift the transient process path toward the surge line stability limit of the compressor (*path A*), and typically provides more stable 4 K system operation with minimal main compressors. Between these two limits, there can be many intermediate process paths (such as *path B*). Due to the coupling between the sub-atmospheric system and the 4 K cryogenic system, there are multiple ways to select an "optimal" pump-down path depending on the objective of the operator. For the FRIB system, the objective was selected to maximize stability of the cold compressor train while maintaining operation within the normal operating main 4 K compressor capabilities and with minimal transient effect on the 4 K cryogenic system. The FRIB *optimal* pump-down path was like

that depicted as *path A*, with operation of the compressors near the surge stability limit required. Comparison between the objective path selected and the previous operational path at FRIB (specifically for the fifth cold compressor stage) is shown in Figure 2 (right).

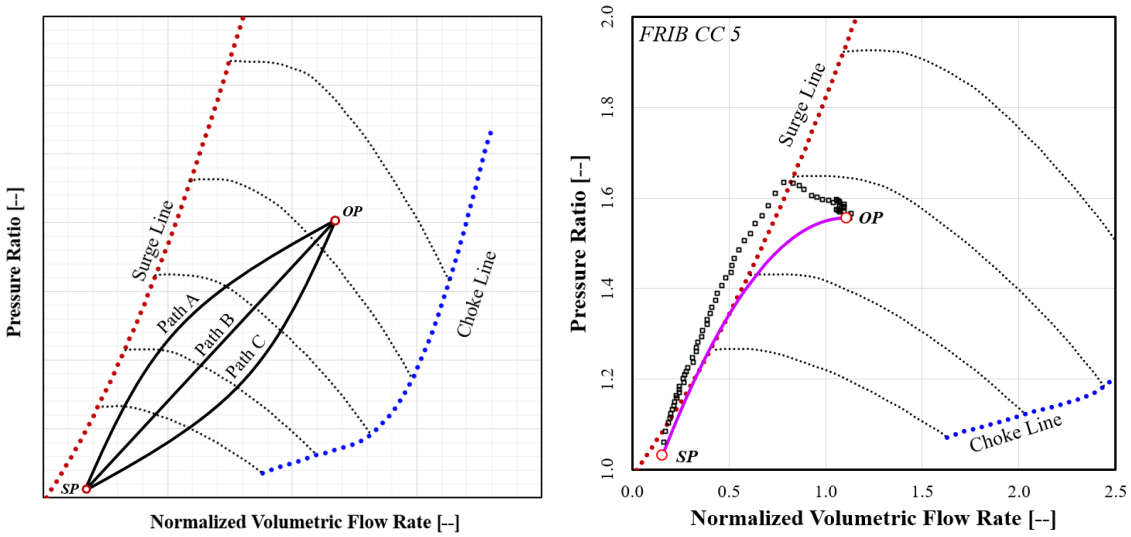

Figure 2. (Left) Generic pump-down process paths on an individual compressor performance map, (right) comparison between target pump-down path (solid line) and previous FRIB pump-down path (symbols) between the starting point (SP) and operating point (OP). Dotted contours represent constant speed lines.

2.3 Speed Ratio Selection

After determination of a general pump-down process path which satisfies both the stability limits of the compressors and the capabilities of the 4 K system, the process path can be used in conjunction with the centrifugal compressor performance model to estimate the speed ratios during pump-down. Analysis of the FRIB system demonstrated that with slight alteration of the pump-down path, the speed ratios of the secondary compressors were found to be *nearly* constant, as depicted in Figure 3.

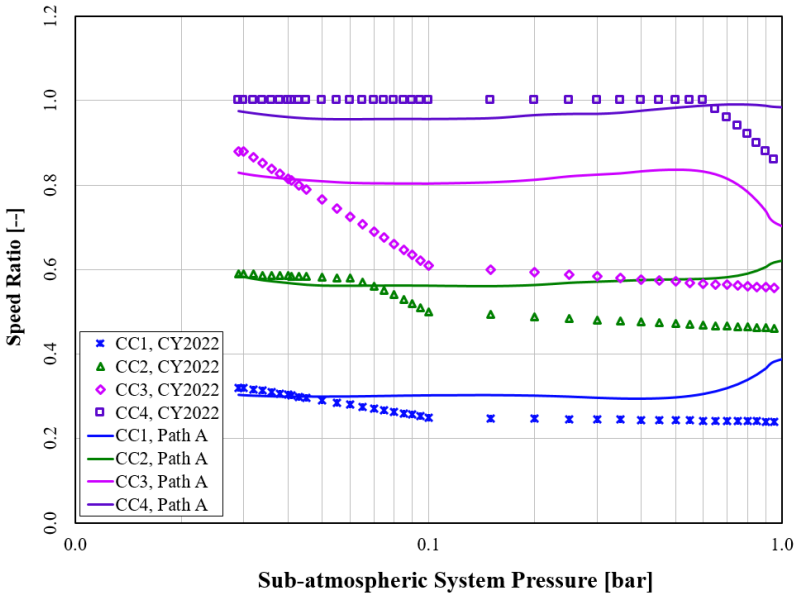

Figure 3. Speed ratio variation vs sub-atmospheric system pressure (previous vs proposed)

2.4 Mass Flow Rate Profile Generation

To simplify the process control scheme during pump-down, constant secondary compressor speed ratios were desired for the pump-down process. Using the assumption of constant speed ratios (as estimated from the predictive model), and assuming the entire compressor train can be considered as a single compressor (due to the fixed speed ratios), an explicit formula was developed to determine the mass flow rate profile for the pump-down process. Although the mass flow rate profile can be generated using the compressor performance estimation model, this would require significant amounts of iteration to converge upon a profile which held the speed ratios precisely constant. Therefore, an alternative method for estimation of the compressor train mass flow profile was developed which conformed to the constant speed ratio assumption.

This alternative method for estimating the mass flow is derived from the volumetric flow characteristics at the compressor train suction, coupling the mass flow rate to the specific volume profile as a function of the pressure (with a constant suction temperature). Additionally, the mass flow profile is generated following the general pump-down path curve of path A (concave). The full derivation of this method can be found in [2], and the final equation is provided as equation (4). Here, the only parameters that are required are the starting (subscript "o") and final (subscript "f") mass flow rates, $\dot{m}$, and the specific volumes, v (starting, final, and present values as functions of the compressor suction pressure and temperature).

$$\dot{m}_{cc}(p) = \frac{(v - v_f)}{(v_o - v_f)}(\dot{m}_o - \dot{m}_f) + \dot{m}_f \tag{4}$$

3. Results and Discussion

3.1 Validation of Methodology

Validation of the pump-down path developed from the proposed methodology included numerous pump-downs with variable starting and final mass flow rates. Figure 4 shows the results of the measured pump-down compared to the estimated compressor paths generated from the described methodology. The pump-down shown had starting and final mass flow rate set points of 190 and 120 g/s, respectively, with a final system pressure of 28.5 mbar. The mass flow rate profile for the pump-down was generated directly using equation (4), inputting the maximum and target mass flow rates along with the final target system pressure.

From Figure 4 (left), it is evident that the pump-down profile is accurately predicted from the proposed methodology, with minimal variance between the measured data and estimated profiles. In conjunction with the compressor performance pump-down paths, the pressure profile was also compared to the estimated profile generated from the system pressure model. Figure 4 (right) compares the estimated pressure profile with the measured pressure profile, showing excellent agreement. The pressure profile was estimated by direct application of the system of equations provided in equations (1) through (3) and accurately captures the transition through the lambda point (where the profile kinks near ~ 50 mbar). Subsequently, this pressure profile can provide an accurate estimation for the total time required to complete the pump-down (in this case, just under two hours).

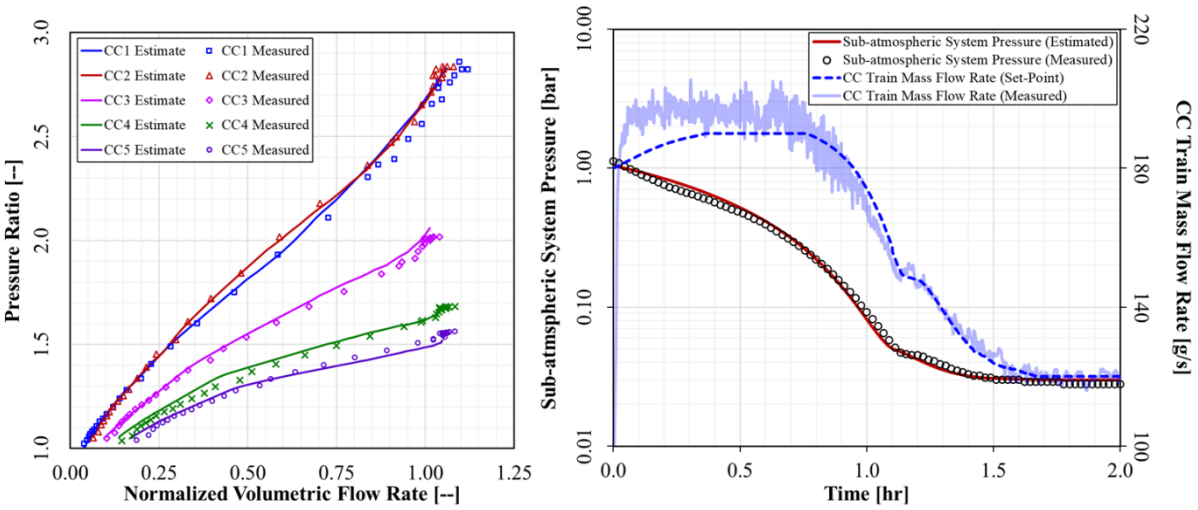

Figure 4. Comparison of compressor pump-down path (left) and sub-atmospheric system pressure (right) estimations versus experimental measurements

3.2 Repeatability of Pump-down

Once the pump-down profile of interest was validated, the settings for the pump-down were utilized in several other pump-downs to examine the repeatability of the pump-down path. As shown in Figure 5, keeping the pump-down settings constant resulted in minimal variance across several transient operations. This conveys the repeatability and reliability of the proposed pump-down path selection methodology.

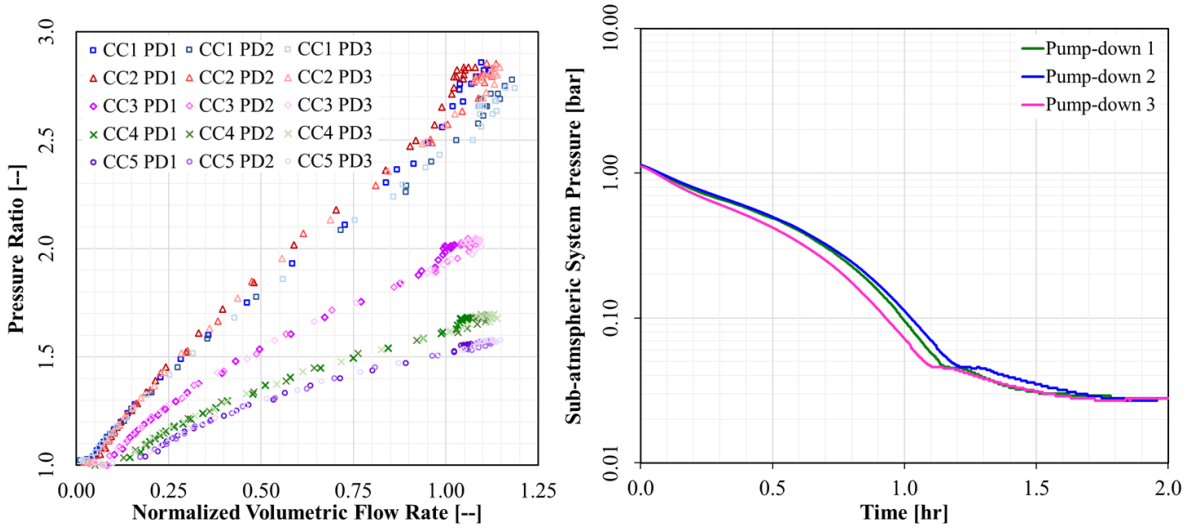

Figure 5. Compressor pump-down paths (left) and system pressure profiles (right) for multiple pump-downs (PD1, PD2, PD3) with constant settings (speed ratios, mass flow profile, and dynamic electric heat)

4. Summary and Conclusion

An operational methodology for the selection of a stable and reliable pump-down path was proposed and validated using the FRIB sub-atmospheric system. This methodology included models to estimate the performance of the cold compressors across the compressor train, and a system pressure model to capture the transient pressure variance during pump-down. With a goal

of a simplified, stable, and repeatable pump-down process, constant speed ratios were implemented during pump-down. This resulted in a smooth process path from the starting point to the operational (final) point. Constraining the speed ratios as constant, an explicit equation for the mass flow profile during the pump-down process was developed and utilized.

Implementation of the developed methodology requires basic geometrical information of the compressors to be known, along with the system geometry, cryogenic plant capabilities and process conditions. All geometrical information required for the compressor and system is presented in [2], and the process conditions (target pressure, liquid volume, vapor volume, *etc.*) should be known to the operational user. If the input parameters for the methodology are known, then the proposed methodology can be utilized to predict the pump-down characteristics of any sub-atmospheric system which operates using cold compressors. This can be beneficial for cold compressor commissioning, operation, and the design of new sub-atmospheric systems.

Presently, the developed methodology requires that the sub-atmospheric system is at steady-state conditions prior to the start of the pump-down sequence (*i.e.* saturated conditions in the cryostats, and constant temperature and pressure in the return transfer line). Ongoing efforts at FRIB are aimed at updating the methodology to include pressure and temperature variability in the return transfer line and capturing the effects of sub-cooled liquid within the cryostat at the onset of the pump-down sequence. This will be particularly beneficial in the case of a "cold" pump-down, when the system has recently "tripped" (*i.e.* turned off) and there is sub-cooled liquid present within the cryostat due to previous operation at sub-atmospheric conditions.

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