Applicability of ASST-A helium refrigeration system for JLab End Station Refrigerator

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Abstract. The MØLLER experiment at Jefferson Lab (JLab) is a high power (5 kW) liquid hydrogen target scheduled to be operational in the 12 GeV-era. At present, cryogenic loads and targets at three of JLab's four experimental halls are supported by the End Station Refrigerator (ESR) - a CTI/Helix 1.5 kW 4.5 K refrigerator. It is not capable of supporting the high power target load and a capacity upgrade of the ESR cryogenic system is essential. The ASST-A helium refrigeration system is a 4 kW 4.5 K refrigerator. It was designed and used for the Superconducting Super Collider Lab (SSCL) magnet string test and later obtained by JLab after the cancellation of that project. The modified ASST-A refrigeration system, which will be called ESR-II along with a support flow from JLab's Central Helium Liquefier (CHL) is considered as an option for the End Station Refrigerator capacity upgrade. The applicability of this system for ESR-II under varying load conditions is investigated. The present paper outlines the findings of this process study.

1. Introduction

Cryogenic loads and targets at three of Jefferson Lab's four experiment halls (Halls A, B and C) are supported by the End Station Refrigerator (ESR). The experiment hall loads typically include 4.5 K magnet refrigeration, magnet current lead cooling and cryogenic target cooling. The existing cryo-plant is composed of a 1500 W cold box (rated capacity), a 186 kW (250 hp) 1st stage and 746 kW (1000 hp) 2nd stage Sullair compressor, 10,000 liter liquid helium (LHe) dewar and an associated distribution system (*i.e.*, a valve box and three hall distribution cans and transfer lines). This load rating applies to a pure refrigeration load at 4.5 K with no targets at 20 K and no magnet current lead liquefaction load. The cryo-plant's performance as a 4.5 K refrigerator is reduced by 20 K target loads at a cost of approximately 1.0 W at 4.5 K for every 3.0 W at 20 K. Each gram per second of current lead cooling costs an additional 150.0 W (approximately) of 4.5 K refrigeration.

In the recent years, JLab has undergone a major upgrade of its particle accelerator facility, with the goal of doubling the linac energy to 12 GeV [1]. The expected 12 GeV-era load from the three aforementioned experimental halls is significantly larger than the rated capacity of the existing ESR cryo-plant. Presently, an additional 10 g/s of 4.5 K (3.0 bar) liquid helium is required to support the experimental hall loads. This additional support is provided by JLab's Central Helium Liquefier (CHL) and supplied to ESR via a 335 m (1100 ft.) cryogenic transfer-line. The transfer line is designed for a super-critical helium (SCHe) flow of up to 30 g/s. This SCHe from the CHL is supplied to the 10,000 liter dewar, where its refrigeration is utilized by the ESR cold box to support the experimental hall loads and then returned to the helium gas storage tanks located at CHL. The ESR system does not have its own helium gas storage, helium purifier and liquid nitrogen (LN) storage systems and as such must use CHL's by way of inter-connecting helium gas lines and a cryogenic transfer line which supplies both SCHe and LN.

In the past (pre-12 GeV-era), SCHe flow from CHL has been frequently used in conjunction with ESR to provide cooling for high powered end station targets (e.g., HAPPEx, Qweak), some for a long duration [2]. Several modifications (such as using an external refrigeration recovery heat exchanger) have been implemented to efficiently support these high powered targets. The MØLLER experiment, to be conducted in experimental hall A, is a similar high-powered target load that is scheduled to be commissioned by 2020 [3]. This is planned to be a 150 cm liquid hydrogen target with an expected load of 5.0 kW at 20 K. The distribution system from the ESR to hall A is not capable of supporting this and the hall magnet loads. Further, as shown in [2], SCHe support from CHL above 20 g/s is not practical for a significant duration. It must also be considered that the ESR cold box was built in the mid-1970's and has been operational at JLab since the early 1990's, and as such it is not possible to either obtain replacement parts or expect its functionality to remain 'status quo'. Hence, a capacity upgrade of the ESR cryogenic system is essential. In addition to providing the required refrigeration capacity for the three experimental hall loads including anticipated new targets like MØLLER, it can also aid both JLab's Cryogenic Test Facility and the Central Helium Liquefier during their maintenance periods or high demand periods.

The present paper describes a potential implementation of a 4.0 kW 4.5 K cryogenic system (the 'ASST-A' refrigerator) and the applicability of this system to meet the load demands of JLab's experimental halls A, B and C in the 12 GeV-era. A process model has been developed to investigate the capability of this proposed cryogenic system (along with SCHe flow from CHL) at varying load conditions, with or without any high powered targets. Different configurations for supporting the 20 K target load is also evaluated. Finally, the findings are outlined and a planned approach for the ESR upgrade is discussed.

2. Background and motivation

At the pre-12 GeV-era hall loads, and based on the configuration of the cryogenic distribution system at JLab's End Station Refrigerator, it is possible to support up to 3.0 kW of target load (at 20 K) with a 3.0 bar, 4.5 K SCHe flow from the CHL cryogenic transfer line. To support the 5.0 kW MØLLER target, an additional or modified distribution and an additional 2.0 kW, 20 K capacity must be provided by the ESR cryogenic system. This new system would also provide the difference between pre-12 GeV-era and 12 GeV-era hall magnet loads (i.e., 4.5 K refrigeration and liquefaction). In the 12 GeV-era , in addition to a high power target load, the upgraded ESR system must handle up to 1.5 kW of 4.5 K refrigeration load along with up to 9.1 g/s of 4.5 K liquefaction load (magnet lead cooling) from the experimental halls A, B and C. The ESR loads vary substantially based on the experiment and having a refrigerator capable of operating efficiently at varying loads will be ideal. And, it is critical for the upgraded cryogenic system to be able to handle all these loads with a minimum SCHe support flow from CHL to ensure maximum system availability. The main optimization idea is to reduce the capital for the occasional peak loads and provide a system that can efficiently provide for varying capacity needs.

The ASST-A cryogenic system consists of a 4.0 kW 4.5 K cold box (with a tested capacity of 2.0 kW of refrigeration and 20 g/s of liquefaction at 4.5 K), two 186 kW (250 hp) 1st stage and two 522 kW (700 hp) 2nd stage Sullair warm helium compressors [4]. The cold box consists of four turbo-expanders (two in series and two in parallel), eleven heat exchangers grouped into six brazed aluminium cores, two 80 K beds, one 20 K bed and associated valves, piping and instrumentation. There are three process (helium) streams – a high pressure ('*h*') supply and two return streams ('*m*' and '*l*'). There is also a liquid nitrogen (LN) pre-cooler. A simplified flow diagram of the cold box and compressor system is shown in figure 1.

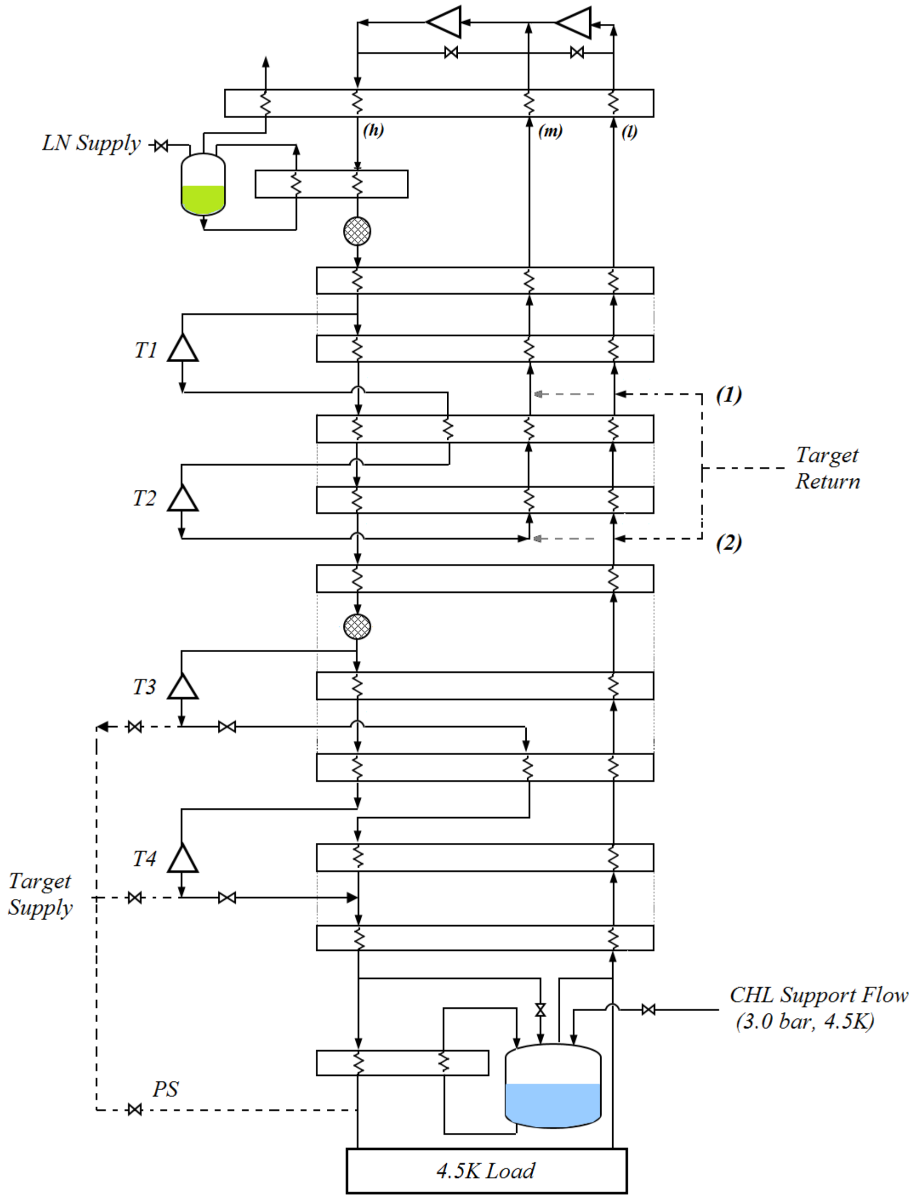

Figure 1. Simplified flow diagram of the ASST-A cold box and warm compressor system.

A majority of the key equipment necessary for this cryogenic system are already present at JLab. The ASST-A cryogenic system was stored at Argonne National Laboratory (ANL) after SSCL cancellation, before being sent to JLab, and was never used at ANL. This system was originally procured in 1992 by the SSCL and used for the accelerator system's magnet string test. During the commissioning period, the ASST-A cold box performance was extensively tested for design verification. The cold box was tested up to 4025 W of 4.5 K refrigeration (100% refrigeration mode), up to 34.3 g/s of 4.5 K liquefaction supplied from makeup gas (100% liquefaction mode) and a mixed mode of up to 2235 W 4.5 K refrigeration with 22.8 g/s 4.5 K liquefaction (50% refrigeration + 50% liquefaction mode). Also, the volumetric and isothermal efficiencies for each compressor stage were measured as a function of the pressure ratio across each stage. Results from these tests are described in [4]. The preliminary concept of the Ganni cycle - floating pressure process was developed and successfully used for the variable capacity operation to recover after the magnet string quench test [5]. Although, there are several provisions in the ASST-A cold box to support a 20 K target flow, this mode of operation has never been evaluated or used and is the primary objective for this study.

3. Model development and verification

A process model for the ASST-A cold box was developed using the characteristics of the sub-components of the cryogenic system supplied by the manufacturer and data from the tests described in [4]. Conservation of mass and energy is applied over several control volumes within the cold box boundary to calculate the unknowns (e.g., mass flow rates, heat exchanger temperature profiles, etc.). The three test modes described in [4] were simulated and matched to the test data, allowing actual component characterizations to be obtained (e.g., turbine flow coefficients, heat exchanger thermal rating and scaling exponent, etc.). Figure 2 shows the calculated performance characteristics of the ASST-A cold box for the tested conditions described in the previous section.

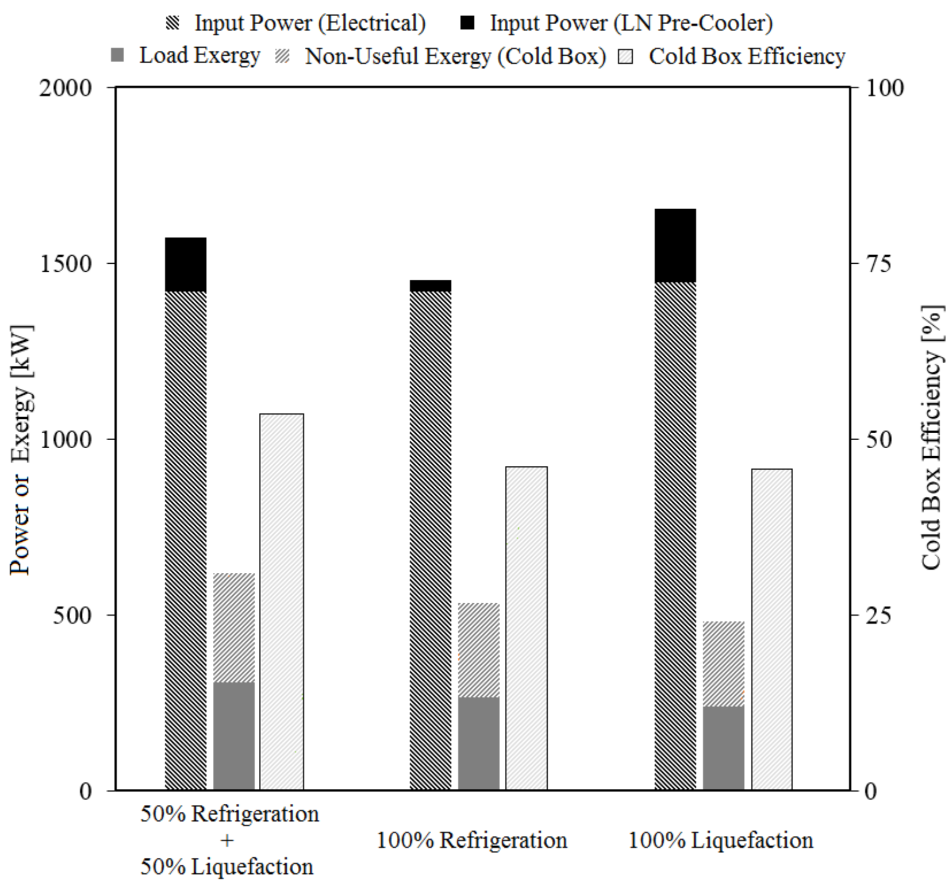

Figure 2. Calculated performance characteristics of the ASST-A cold box under different loading conditions.

4. Process study

The process study for the ASST-A cryogenic system as an upgrade/replacement for the ESR to support the expected 12 GeV-era end station loads was carried out in two steps. For the first step, the performance of this system supporting the baseline 12 GeV-era hall magnet loads of 1.5 kW of 4.5 K refrigeration load and 9.1 g/s of lead cooling (4.5 K liquefaction) was evaluated. Next, a 5.0 kW 20 K target load is added to this (12 GeV-era) baseline load, along with 3.0 bar, 4.5 K SCHe flow from CHL. A detailed description of each of these steps is provided in the following subsections.

4.1. Performance of ASST-A cryogenic system with 4.5 K loads

The baseline 4.5 K refrigeration and liquefaction loads are well within the rated capacity of the proposed cryogenic system without SCHe support from CHL. The T-s diagram from the process study, for this baseline load condition is shown in figure 3. It is observed that a supply pressure to the cold box of 15.0 bar is required to sustain this load. During the commissioning of the ASST-A cryogenic system, the lower limit of the medium pressure (MP) stream (to the compressor system) was recognized as 2.0 bar (due to effectiveness of the 1st stage compressor oil removal system). The same value is used here. It is also observed that, more than one 1st stage and 2nd stage compressors are required to handle the new 4.5 K load. A significant amount of 1st stage compressor bypass (102.1 g/s) is available with this configuration.

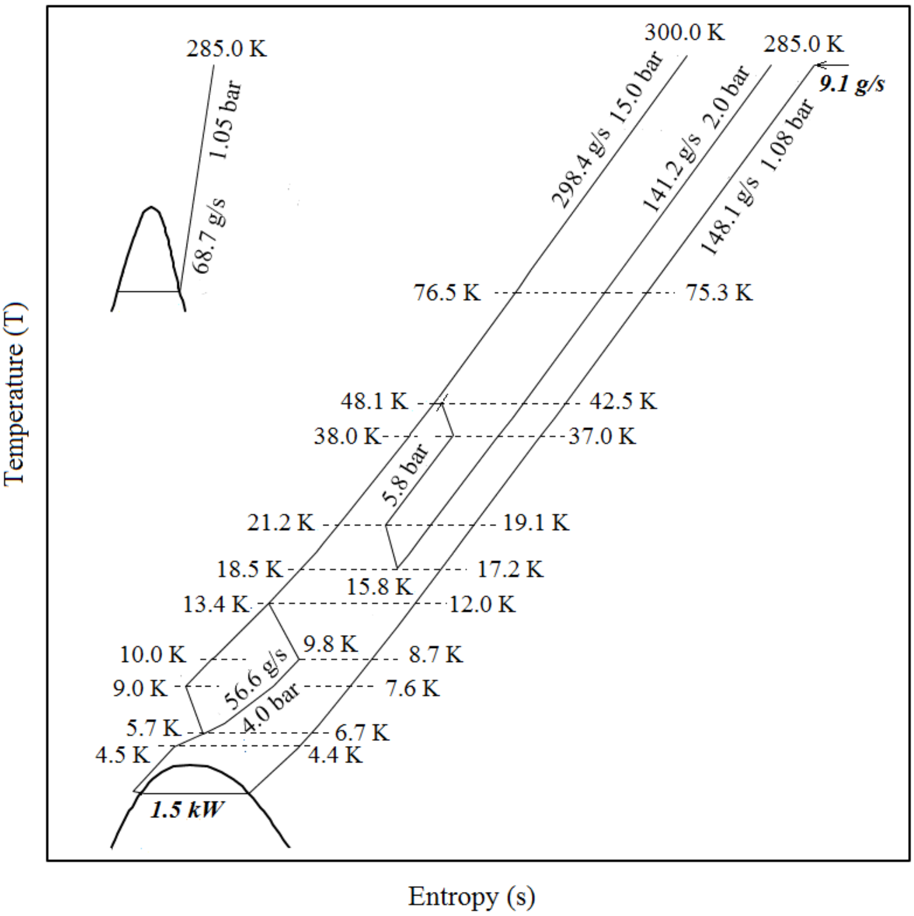

Figure 3. T-s diagram of the proposed refrigerator for the baseline 12 GeV-era 4.5 K loads.

4.2. Performance of ASST-A cryogenic system with 4.5 K and target (20 K) loads

Ten different configurations for handling the 4.5 K loads along with the 5 kW 20 K target load were considered. A detailed description of each of these configurations is provided in table 1. The "Target Supply From" column indicates from where the target is being supplied (per figure 1). "PS" is the 3 bar 4.5 K (SCHe) supply from the refrigerator (not CHL). The "Return To" column refers to the stream designation and the location per figure 1; *e.g.*, (m), (1) means it returns to the medium pressure stream at location (1). The "CHL Support Flow To" column indicates to where the SCHe flow from CHL is being supplied. For supplying flow to the target, three different locations were considered (*i.e.*, T3 outlet, T4 outlet, primary supply) with four different return injection (at 20 K) locations (*i.e.*, '*m*' stream location (1) and (2), and '*l*' stream location (1) and (2)). Two different ways for introducing the 4.5 K

CHL support flow were considered – one into the LHe dewar and the other directly to the target load. '*h*' stream supply pressure to the cold box is maintained at 17.0 bar (and '*l*' stream pressure from the cold box is maintained at 1.08 bar) for all the configurations. A minimum of 2.0 bar at the '*m*' stream pressure from the cold box will be imposed (with the 2nd stage bypass). However, owing to the Floating Pressure Ganni cycle, this pressure will adjust to produce zero 2nd stage bypass. A summary of the results from the process study is given in table 2. The following points are observed from the process study and are discussed from a standpoint of minimizing the CHL support flow.

Table 1. Different configurations examined for supporting the target load.

#	Target Supply From	Target Return To	CHL Support Flow To
1	T3 Outlet	(*m*), (1)	LHe Dewar
2	T3 Outlet	(*m*), (1)	Target
3	T3 Outlet	(*m*), (2)	LHe Dewar
4	T3 Outlet	(*m*), (2)	Target
5	T4 Outlet	(*m*), (1)	LHe Dewar
6	T4 Outlet	(*m*), (1)	Target
7	T4 Outlet	(*m*), (2)	LHe Dewar
8	T4 Outlet	(*m*), (2)	Target
9	PS	(*l*), (1)	LHe Dewar
10	PS	(*l*), (2)	LHe Dewar

Table 2. Summary of process study results.

#	SCHe from CHL	Cold Box LN Use	'*h*' Stream Flow	1st Stage Compressor Bypass	Target Load Supported by CHL Flow
	[g/s]	[g/s]	[g/s]	[g/s]	[kW]
1	22.0	26.4	407.9	89.7	--
2	21.5	28.7	410.8	60.3	2.2
3	22.5	20.8	399.5	86.3	--
4	22.0	23.4	401.4	57.5	2.3
5	24.0	16.6	392.2	78.8	--
6	24.0	17.4	395.5	49.4	2.5
7	26.0	6.8	395.5	71.6	--
8	25.0	11.6	399.3	44.4	2.6
9	27.0	6.1	394.0	23.5	--
10	27.0	5.7	391.4	14.4	--

- As the supply temperature to the target from the cold box is decreased, the required CHL 4.5 K, 3.0 bar support flow increases, and the exergy provided to the target increases for the same heat load. As such, less of the overall target load can be supported by the cold box. So, configurations 1 to 4 require less CHL support flow than configurations 5 to 10.
- For all the configurations, the optimum return injection point for the 20 K target flow is at point 1 (refer to figure 1). When the 20 K return flow is injected at point 2 (which is at a colder temperature), some of the cold box exergy is wasted in mixing with the warmer 20 K return flow.
- Less CHL support flow is required when it is directly sent to the target. Introducing the CHL support flow to the LHe dewar consumes some of the available exergy due to the J-T process and so loses some of its usefulness. However, this also generates additional boil-off flow from the dewar which in turn reduces the LN consumption in the pre-cooler heat exchanger.

Based on the results presented in table 2 and the discussion above, configuration 2 is found to be the optimum configuration for minimizing 4.5 K support flow from CHL. In this configuration, the cold box is able to support 2.8 kW (out of 5.0 kW) of target load with 37.0 g/s of flow from turbo-expander 3 (T3) outlet (at 4.0 bar, 7.6 K). Rest of the target load is supported by directly routing 21.5 g/s (at 3.0 bar, 4.5 K) of flow from CHL. Both the flow streams are returned to the cold box (at 20 K) at point 1 in the '*m*' stream, where the pressure is about 2.7 bar. The cold box uses 28.7 g/s of LN in the pre-cooler heat exchanger, which is only about 40% of the LN consumption of the baseline load case. The compressor system is able to handle the cold flows with a significant amount of available 1st stage bypass (60.3 g/s). The T-s diagram for this configuration is shown in figure 4. Since there is excess 1st stage compressor capacity available, the piping modification to the cold box will be planned to allow injection of the target return flow to either the '*l*' stream (in case the target design dictates the need for additional pressure drop) or to the '*m*' stream.

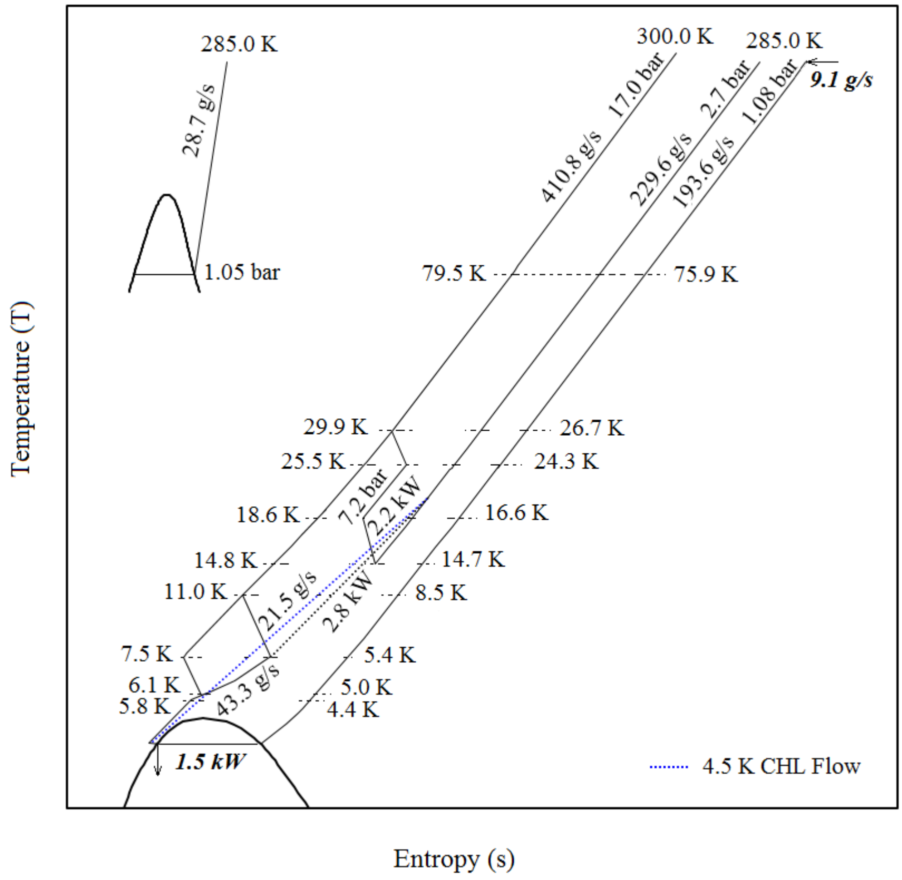

Figure 4. T-s diagram of the proposed refrigerator supporting the 12 GeV baseline 4.5 K loads and target 20 K load in configuration 2.

Figure 5 shows the variation of total target load that can be supported and LN consumption as a function of the 4.5 K flow from CHL for both configurations 2 and 9. It is observed that, Configuration 2 is able to handle up to 5.9 kW of target load (20 K), while configuration 9 is only able to handle up to 5.2 kW (20 K). However, to sustain these loads in the long term both configurations would require a CHL support flow of 30 g/s, which is not recommended. The LN consumption in configuration 2 is about 5% higher than that in configuration 9.

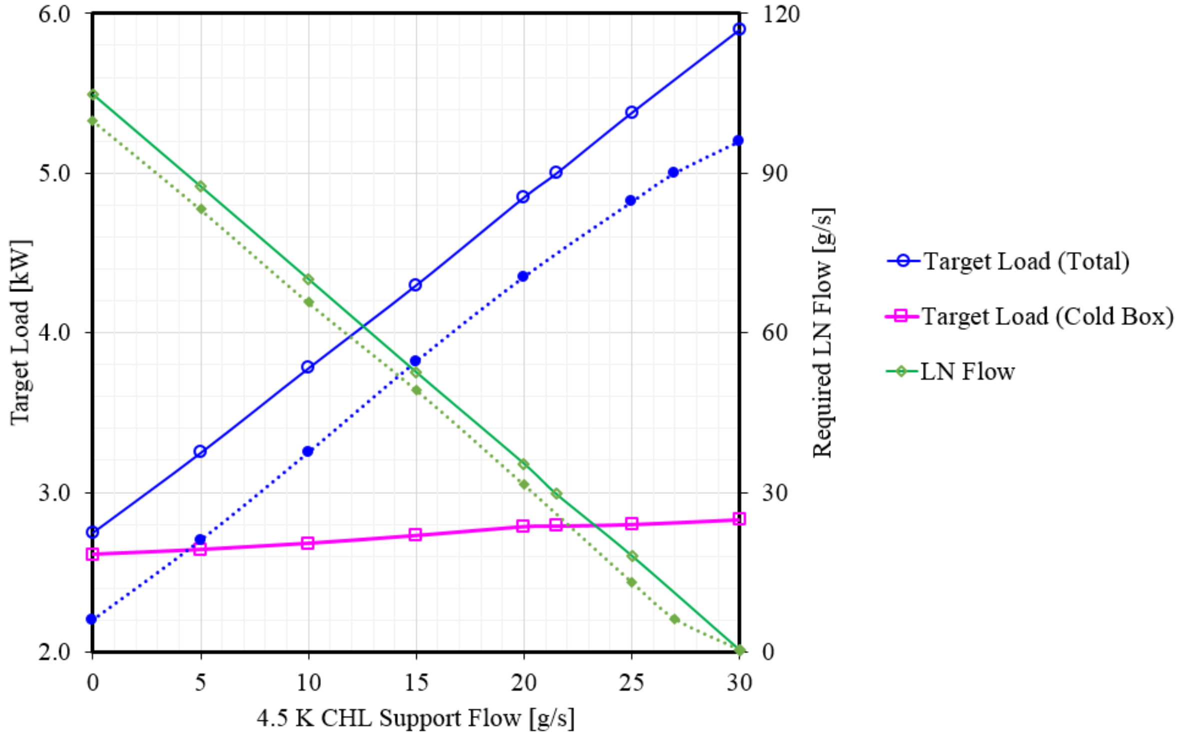

Figure 5. Proposed refrigerator performance for a range of 4.5 K CHL support flow rates - configuration 2 (solid) and configuration 9 (dotted).

5. Conclusion

Performance of the proposed refrigerator, which is the ASST-A cryogenic system, is found to be satisfactory in handling the expected 12 GeV-era ESR loads. It meets the goals to reduce the capital for the occasional peak loads and provide a system that can efficiently handle varying capacity needs. Ten different configurations for supporting a 5.0 kW liquid hydrogen target (at 20 K) have been evaluated, and based on the performance of the cold box, configuration 2 which has a minimum 4.5 K support flow (21.5 g/s) from CHL is planned to be used. If the target pressure drop is high configuration 9 is planned to be used. Based on the results from this process study and the selected configuration, cold box design modifications and the fabrication of a new distribution line to support the high power target is anticipated to started by spring 2018, followed by a load verification performance test using electric heaters.

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