Performance Testing of the 4kW ESR 2 Refrigerator at JLab

C. Perry[1*], R. Bhattacharya[1], J. Creel[1], R. Norton[1], B. White[1] and T. Wijeratne[1]

[1] Cryogenics Department, Thomas Jefferson National Accelerator Facility (JLab), Newport News, VA, USA

*E-mail: cperry@jlab.org

Abstract. The End Station Refrigerator 2 (ESR2), a refurbished cryoplant, will replace the ESR1. ESR2 is comprised of the cold box and compressors from the Superconducting Super Collider's 4 kW, 4.5 K ASST-A plant. It also features a new 10 kL liquid helium dewar, a cryogenic distribution system and new control and utility systems. This plant was reconfigured to provide a cold helium supply at 15 K, 12 K, and 8 K for the experimental hall's hydrogen targets. The most significant load will be during the MOLLER experiment, which will see a total hydrogen target load of 5 kW at 15 K. This paper details the commissioning results of the 4.5 K refrigeration system in various modes (maximum refrigeration, maximum liquefaction, and a 50/50 mix) at both 100 % and 50 % capacity. We will also evaluate the performance with an expected MOLLER load. Current performance will be compared with the historical commissioning data from the ASST-A plant.

1. Introduction

The End Station Refrigerator 2 (ESR2) is the replacement for the ESR1, and in addition to handling the 4 K and 15 K loads seen by ESR1, will also support the upcoming MOLLER experiment [1]. The warm compressors and cold box of ESR2 were originally part of the Superconducting Super Collider Lab (SSCL) project in Waxahachie Texas, and was originally designed to support magnet string testing. When the project was canceled, the equipment was decommissioned and brought to Jefferson Lab. The cold box was modified to accommodate cooling of 15 K **h**ydrogen targets, with additional temperatures at 12 K and 8 K [2], [3]. This paper describes commissioning the ESR2 cold box, helium dewar, and cold distribution systems, and compares the performance to previous commissioning efforts [4], [5].

2. Test Plan

ESR2 can be run in either a 100 % or 50 % capacity mode. 100 % capacity utilizes two 2nd stage compressors and two 1st stage compressors and allows maximum mass flow through the turbines, while 50 % capacity will have a reduced mass flow due to only one 1st and 2nd stage compressor running. 50 % capacity mode will handle similar loads seen by ESR1, which will be the case when MOLLER is not running. Testing of both capacity modes will include: 100 % refrigeration, 100 % liquefaction, 50/50, and max 15 K tests, with additional max 12 K and max 8K testing for the 100 % capacity mode. The 12 K and 8 K tests are for the 4000 W MOLLER run and are not needed at 50 % capacity. Refrigeration load will be provided by a 6 kW heater located in the bottom of the 10 kL Helium dewar (Figure 1). The liquefaction rate will be measured by tracking the rate of accumulation of liquid helium in the dewar. This will be done using three methods: a differential

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pressure transducer and a superconducting probe to directly measure the liquid level, and a separate measurement of the warm gas mass flow rate entering the plant. This method is consistent with the one used by Ganni et al. [4]. During this type of measurement, cold vapor from the dewar is pushed back into the refrigerator, which helps with liquefaction. This approach matches the liquefaction load seen during 4 K magnet re-fill, which typically represents the largest liquefaction demand during normal operation.

A 7 kW heater was built to provide the hydrogen target test loads (Figure 2). During the 15 K, 12 K and 8 K target tests the target return temperature is 20 K and an assumed 4 K load of 500 W ref and 5 g/s liq are imposed on the plant.

During target testing, the plant will see a large load at the target temperature and a relatively small load at 4 K causing a mismatch in stream capacities which will result in significant warming of the target supply temperature. To combat this, during the 15 K and 12 K tests only, the return injection header in the cold box will be utilized to shunt some of the 4 K primary return around

Figure 1. 10 kL helium dewar housing the 6 kW heater.

Figure 2. 7 kW heater used to test the hydrogen target loads.

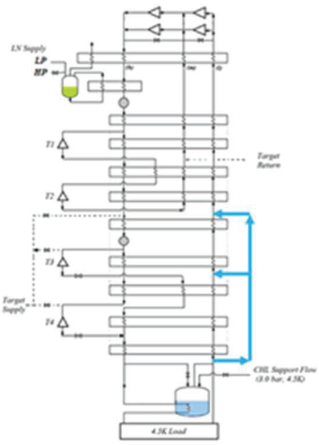

Figure 3. Shunted 4 K Return injection flow shown in blue. A fraction of the total flow bypassed heat exchangers to inject 4 K at the temperature level nearest to the selected hydrogen target supply take-off point.

the heat exchangers and get injected at the target supply temperature level. This will allow turbine T3 and T4 to be utilized to aid in cooling the target supply flow, increasing its capacity.

3. Initial Commissioning

Following stand-alone commissioning of the main compressor system [6], Initial cold box commissioning was performed, which included: LN2 cooldown, turbine startup, filling of dewar with liquid helium and applying a 3 kW refrigeration load at 4.5 K on the plant which satisfied the key performance parameter for the project. During the initial commissioning run several issues were discovered that impacted the ability to complete commissioning. These issues were addressed following shutdown and warm-up of the plant.

Throughout initial commissioning a pressure drop began to develop across the 80 K adsorber bed filter in excess of 1 Atm, as noted by Ganni et al [4], the second adsorber bed was put online in parallel with the first bed, to finish initial commissioning. Both filters were removed and replaced with clean spares. The used filters were clogged with a large amount of carbon dust. The following commissioning run was carried out with both beds online, minimizing the filter pressure drop.

Several cold end diodes stopped working during cooldown, one in particular was the turbine T2 outlet temperature which prevented efficiency and optimum speed calculations from being performed. The main vacuum shell had to be lowered to gain access to the diodes, many were found to have wires that had come loose and simply needed to be re-soldered. Turbine T2 outlet temperature was replaced with a new diode in a new location on the piping due to the inaccessibility of the original diode.

The 4 K return injection header valve did not seal, which impacted the utility of the header. The valve stem was found to be crushed. It was determined that the force from its actuator alone was not sufficient to cause the observed damage and must have occurred during material handling of the cold box and that this issue was missed prior to operation. The valve stem was replaced with a spare.

Prior to cooldown, a helium to vacuum leak was found to exist in the cold box insulating vacuum. Time-of-flight testing was used to locate the leak to a section of the HP header at the 80 K level. It was determined that the diffusion pump on the vacuum shell could maintain proper vacuum during commissioning with a repair to occur following commissioning, however it was during commissioning that the water flow to the diffusion pump became blocked by debris in the cooling water, causing the end of the initial commissioning run. A crack was found along the soldered Al-SS transition joint at the LN2 thermosiphon heat exchanger, causing the observed leak, this joint was replaced by an explosion bonded joint. Following these repairs, the plant was cooled down and commissioning repeated.

4. Results

Commissioning results are tabulated below (Tables 1,2 and 5), comparing results found from previous testing [4], [5]. The process analysis shown in Figure 5 contains data taken during the 100 % capacity max 8 K test which is configured to match the setup expected during the MOLLER experiment run. In all testing modes the recent testing at JLab showed an increased capacity versus SSCL, this is likely, in part due to lowering the exhaust pressure of T3 and T4 to 3.1 Atm at JLab versus the 4 Atm it was operated at SSCL. It is also important to note that the staff at SSCL likely did not have the time JLab staff did to make adjustments and address issues in order to get the most performance from the plant. Turbine performance was similar to SSCL, with the exception of T4 which saw much lower isentropic efficiency at JLab than SSCL. This discrepancy could simply be due to errors in temperature measurements, however this result is still being investigated. JLab implemented an optimum speed control algorithm for turbines, but unfortunately performance improvements were never realized in T3 and T4 because the turbines never achieved optimum speeds, leaving the brake valve fully closed during operation. Turbine T1 and T2 operated at optimum speed in only a few test cases. This issue is still under investigation.

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Table 1. JLab 50 % capacity results

Mode	Ref (W)	Liq (g/s)	LN2 Usage (g/s)	Hydrogen Target Load (W)	Compressor Power Usage (kW)
(1) 100 % Ref	2038	-	11.6	-	654.2
(2) 100 % Liq	-	21	60.6	-	615.1
(3) 50/50	1061	12.5	34.5	-	598.7
(4) Max 15 K	486	4.3	18.5	1496	618.8

Table 2. JLab 100 % capacity results.

Mode	Ref (W)	Liq (g/s)	LN2 Usage (g/s)	Hydrogen Target Load (W)	Compressor Power Usage (kW)
(5) 100 % Ref	4244	-	15.3	-	1258[a]
(6) 100 % Liq	-	47.3	111.6	-	1357
(7) 50/50	2420	31	88.7	-	1366
(8) Max 15 K	509	3.8	25.7	3718	1328[a]
(9) Max 12 K	517	5.5	24.5	4143	1348[a]
(10) Max 8 K	537	5.5	23.5	4930	1327[a]

[a] At least 1 compressor was not at full slide valve position, resulting in lower power consumption.

Table 3. SSCL 50 % capacity results [5]

Mode	Ref (W)	Liq (g/s)	LN2 Usage (g/s)	Compressor Power Usage (kW)
(1) 100 % Ref	1450	-	8.9	664.6
(2) 100 % Liq	-	18	58	693.5
(3) 50/50	795	7.4	24.9	649.1

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Table 4. SSCL 100 % capacity results [4]

Mode	Ref (W)	Liq (g/s)	LN2 Usage (g/s)	Compressor Power Usage (kW)
(4) 100 % Ref	4026	-	17.1	1333.1
(5) 100 % Liq	-	34.3	105.6	1370.1
(6) 50/50	2235	22.8	79.3	1335.6

Table 5. Isentropic turbine efficiencies during JLab testing.

Mode	T1	T2	T3	T4
(1) 100 % Ref	0.748	0.835	0.423	0.125
(2) 100 % Liq	0.760	0.714	0.549	0.530
(3) 50/50	0.760	0.753	0.558	0.418
(4) Max 15 K	0.752	0.776	0.363	0.446
(5) 100 % Ref	0.762	0.872	0.605	0.137
(6) 100 % Liq	0.760	0.828	0.551	0.498
(7) 50/50	0.769	0.873	0.539	0.226
(8) Max 15 K	0.759	0.789	0.549	0.524
(9) Max 12 K	0.759	0.786	0.584	0.301
(10) Max 8 K	0.761	0.826	0.555	0.520

Table 6. Isentropic turbine efficiencies during SSCL testing using data from [4], [5].

Mode	T1	T2	T3	T4
(1) 100 % Ref	0.636	0.736	-	0.635
(2) 100 % Liq	0.738	0.760	-	0.599
(3) 50/50	0.705	0.748	-	0.621
(4) 100 % Ref	0.719	0.753	0.591	0.547
(5) 100 % Liq	0.744	0.766	0.514	0.576
(6) 50/50	0.744	0.767	0.554	0.638

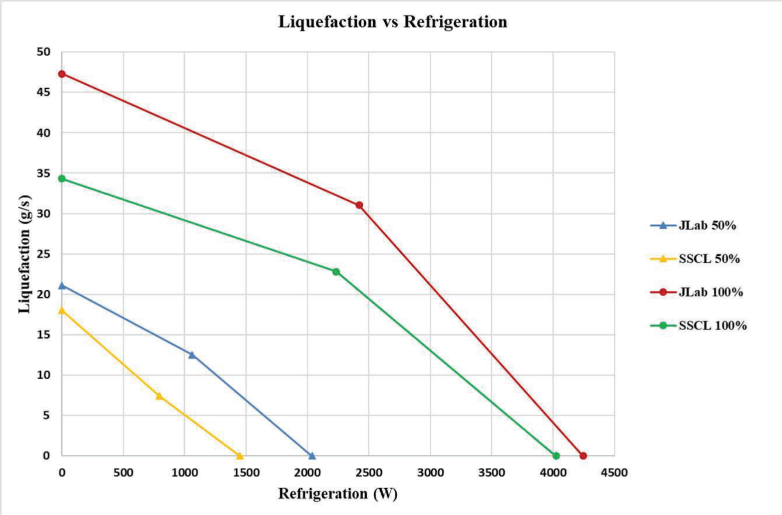

Figure 4. Liquefaction vs. Refrigeration plot

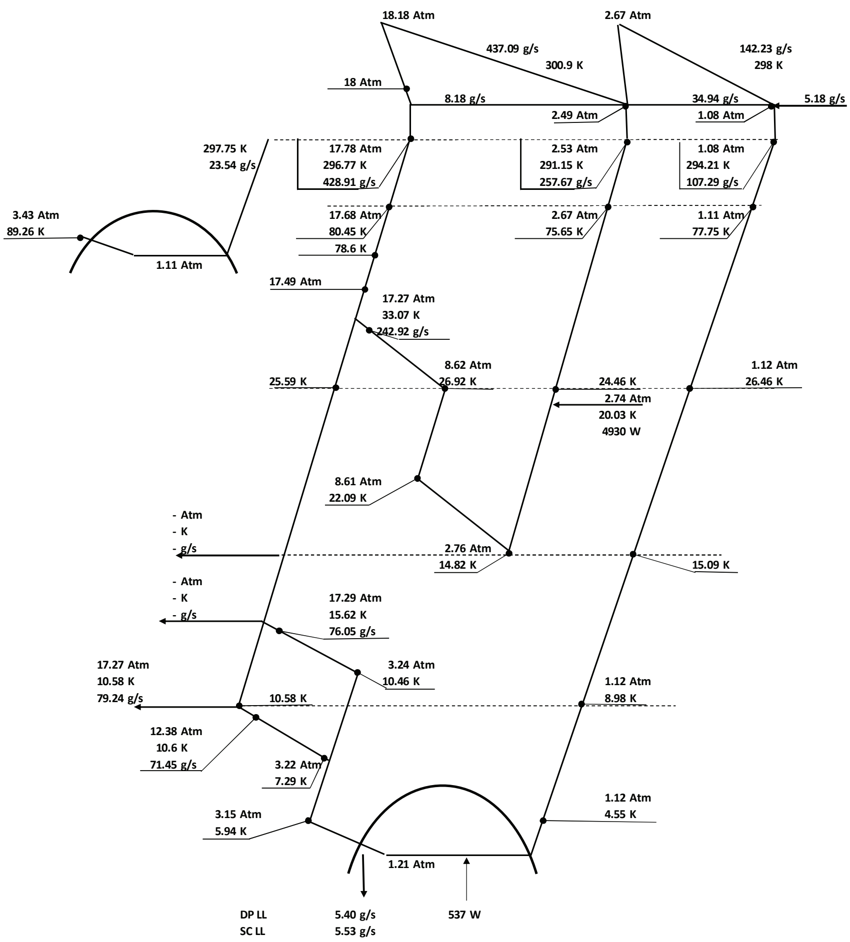

Figure 5. (10) 100% capacity, max 8K test T-S diagram. During this test, the plant is configured to match the setup for the MOLLER experiment, demonstrating the maximum load it can handle.

5.Conclusions

ESR2 commissioning has shown that it can support the upcoming MOLLER experiment, and will have the ability to run in a reduced power mode to handle the smaller loads supported by ESR1 when MOLLER is not running. The re-use of the compressors and cold box resulted in significant reduction to the capital cost of this project, and further demonstrates the effectiveness of equipment refurbishment to achieve project goals despite residing in long-term storage for over 30 years.

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