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Commissioning and operational results of helium refrigeration system at JLab for the 12GeV upgrade

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Abstract. The new 4.5 K refrigerator system at the Jefferson Lab (JLab) Central Helium Liquefier (CHL-2) for the 12 GeV upgrade was commissioned in late spring of 2013, following the commissioning of the new compressor system, and has been supporting 12 GeV LINAC commissioning since that time. Six design modes were tested during commissioning, consisting of a maximum capacity, nominal capacity, maximum liquefaction, maximum refrigeration, maximum fill and a stand-by/reduced load condition. The maximum capacity was designed to support a 238 g/s, 30 K and 1.16 bar cold compressor return flow, a 15 g/s, 4.5 K liquefaction load and a 12.6 kW, 35-55 K shield load. The other modes were selected to ensure proper component sizing and selection to allow the cold box to operate over a wide range of conditions and capacities. The cold box system is comprised of two physically independent cold boxes with interconnecting transfer-lines. The outside (upper) 300-60 K vertical cold box has no turbines and incorporates a liquid nitrogen pre-cooler and 80-K beds. The inside (lower) 60-4.5 K horizontal cold box houses seven turbines that are configured in four expansion stages including one Joule-Thompson expander and a 20-K bed. The helium compression system has five compressors to support three pressure levels in the cold box. This paper will summarize the analysis of the test data obtained over the wide range of operating conditions and capacities which were tested.

1. Introduction

The new 12 GeV helium refrigerator has three pressure levels (high, medium and low pressure; HP, MP and LP, respectively) and uses a liquid nitrogen (LN) pre-cooler and four expansion stages with three turbine strings and one Joule-Thompson (JT) expander. It is separated into two physically separate vacuum vessels for shipping and installation space requirements; an upper and lower cold box (UCBX and LCBX, respectively). The UCBX spans from 300 to 60 K and contains the LN pre-cooler and dual 80-K beds with a bypass valve. The LCBX spans from 60 K to 4.5 K and contains the four expansion stages (seven turbines), 20-K bed with a bypass and a 3000 liter helium sub-cooler. The 12 GeV program at Jefferson Lab (JLab) required a refrigeration system of equal capacity to its original refrigerator design [1, 2] with each refrigerator supporting its own LINAC (i.e., one supporting the 'north' side LINAC and the other the 'south' side LINAC) and any one refrigerator to support a 6 GeV program. The cold box design has been previously presented [3]. The cold box system is well matched to the compressor system which is entirely designed by JLab and built-to-print by industry [4].

The new 12 GeV helium refrigerator was successfully commissioned in the spring of 2013 as described previously [5]. During commissioning, the new refrigerator was tested over a very wide range. After it was brought on-line to support the commissioning of the 12 GeV LINAC in the fall of 2013, it was subsequently operated over a very wide range with good efficiency and minimal operator interaction. It was observed during commissioning that refrigerator required a higher LN consumption than anticipated by the design. This does not affect the capacity of the new refrigerator, but does increase the LN utility cost.

2. Liquid nitrogen pre-cooler

After commissioning in the spring of 2013 was complete, an investigation of the indicated high LN usage was conducted by JLab, in cooperation with the cold box manufacturer and heat exchanger manufacturer. Three methods (#1 to #3) of testing and analysis were performed to verify the LN consumption during the spring 2013 commissioning. These are summarized in table 1. It was not possible to use the depletion rate of the LN supply tank as one of the measurements due to operational and existing equipment constraints. The refrigeration mode, which does not impose a net imbalance on the heat exchangers, was used as a baseline for the LN consumption measurement. All three measurement methods indicated an actual LN consumption rate that was approximately two to three times the predicted-design value, depending on the mode of operation.

Subsequently, the recommended course of action was to warm the cold box to ambient temperature and perform rapid purging of the 300-80 K heat exchanger (HX) passes, visually inspect the HX inlets to verify no obvious blockage was present and then re-cool while verifying cleanliness (to avoid any blockage due to contamination). These actions were taken during the summer of 2013 and the cold box was re-tested in the early fall of 2013. The only anomaly encountered during an internal examination was some debris in the high pressure stream (at the HX HP inlet) and discoloration in the medium pressure passes (at the inlet; see figure 1). The cold box and HX manufacturer, as well as JLab did not believe that this was related to the HX performance issue unless this was residual from moisture causing some of the passes to be blocked. Four methods of testing and analysis were performed to verify the LN consumption during the re-test during the early fall of 2013 (see table 1). Results similar to the spring testing were obtained with no improvement in the LN consumption.

It was agreed at this juncture that the HX was not adequate and a design was pursued which consisted of only two-streams and provided additional length with an intermediate re-mixing headers. A comparison of selected design data for the 300 – 80 K helium-helium HX's is shown in table 2. This re-design is presently being installed by the manufacturer.

Table 1. Methods used to determine LN consumption

#	Method
1	Energy balance using in-stream temperature measurements at 300 and 80-K temperature levels
2	Energy balance using surface mounted temperature measurements at the 300 K temperature level and in-stream measurements at 80-K
3	Energy balance using in-stream temperature measurements at inlet and outlet of helium-nitrogen boiler
4	Cold box LN vessel depletion rate (i.e., supply is closed)

Figure 1. 300-80 K HX HP, MP and LP Stream Discoloration

Table 2. E22410 (300-80K) HX original vs. re-design selected design data

		Existing	Re-Design	
# Cores (# Sections)		1 (1)	2 (2)	
# Streams		3 (HP, MP, LP)	2 (HP, MP)	2 (HP, LP)
Intermediate re-mixing headers		None	Yes (both)	Yes (both)
Core length	[mm]	3900	5500	5500
Heat transfer surface area	[m^2]	1753, 1524, 3294	823, 1600	1455, 2593
Duty (‡)	[kW]	1486	619	845
Net thermal rating (UA) (‡)	[kW/K]	351	138	189
(UA) Margin (§)	[-]	12%	43%	28%
Number transfer units (NTU) (‡)	[-]	54.3	51.2	51.3
Ratio of NTU to core length	[m^{-1}]	13.9	9.3	9.3
Ratio of core to distributor Δp (‡)	[-]	4.6, 4.5, 3.2	3.4, 3.4	3.2, 3.0
Ratio of (core+distributor) to (header+nozzle) Δp (‡)	[-]	11.5, 13.4, 7.6	4.6, 4.6	7.5, 8.5
Aspect ratio (†)	[-]	3.3	4.9	

(‡) Based on required process conditions at maximum capacity (Mode-1)
(§) Ratio of (UA) provided to (UA) required for specified process conditions plus longitudinal conduction
(†) Ratio of effective length to the square root of the total free flow area; see table 5

The issue of flow distribution in high NTU HX's (i.e., NTU ≥ 30), especially in the helium-helium HX used in LN pre-coolers, has been identified as an important design aspect [6, 7]. JLab typically requires four key specifications to address this issue as summarized in table 3. However, manufacturer's do not always adhere to items 3 and 4, claiming it as an excessive design specification. Multi-stream HX's are much more sensitive to flow distribution effects. As an example, referring to table 4, the increased LN consumption (2.7 times greater than the design for mode-1) could be accounted for by losing the cooling to ~6% of the HP stream passes (or an equivalent improper flow distribution), which would only increase the pressure drop in the HP stream by ~12% if they were blocked. The purpose of this example is to emphasize the effect of the flow distribution using a simple calculation. It is apparent from table 5 that the aspect ratio, defined as the square root of the total free-flow area (all streams) to the effective length, is a strong contributor to the actual design performance.

In systems that use LN pre-cooling, it is quite common to see high LN usage, as compared to the design goal. Even in systems that do not, it is not unusual in multi-stream HX's for the medium pressure stream exiting the cold box (i.e., 300 K temperature level) to be considerably colder than the design. Many times this is due to the challenging task of balancing the number of HP stream passes paired to the MP vs. LP streams, while striving to minimize the pressure drop from the load return

Table 3. Typical JLab HX Specification Requirements

#	Requirement
1	Vertically orientation; warm-end on top
2	Net thermal rating (UA) margin (i.e., provided to required, including longitudinal conduction) ≥ 1.1
3	≤ 10 NTU per meter of core (or section) length
4(a)	Ratio of core pressure drop to distributor pressure drop ≥ 3
4(b)	Ratio of the sum of the core and distributor pressure drops to the sum of the header and nozzle pressure drop ≥ 3

Table 4. Example calculation of the effect of improper flow distribution

Liquid nitrogen (LN) usage (test)	$\dot{m}_{LN}$	316.3	[g/s]	
Design LN usage	$\dot{m}_{LN,D}$	119	[g/s]	
Nitrogen cooling enthalpy provided (test)	Δh_N	391	[J/g]	
Additional LN cooling required due to improper distribution	$q_{N,add}$	77144	[W]	$= (\dot{m}_{LN} - \dot{m}_{LN,D})\ \Delta h_N$
High pressure (HP) stream mass flow (test)	$\dot{m}_{HP}$	1216	[g/s]	
HP stream enthalpy difference (300 - 80 K)	Δh_{HP}	1115	[J/g]	
Equivalent HP flow bypassed due to improper flow distribution	$\dot{m}_{HP,byp}$	69	[g/s]	$= q_{N,add} / \Delta h_{HP}$
Fraction of HP flow effectively bypassed (blocked, inadequate heat transfer or equivalent mal-distribution)	ω_{HP}	5.7%	[-]	$= \dot{m}_{HP,byp} / \dot{m}_{HP}$
Number of HP stream HX passes (Helium-Helium HX)	N_{HP}	52	[-]	
Equivalent number of HP stream HX passes bypassed	$N_{HP,byp}$	3.0	[-]	$= N_{HP} \cdot \omega_{HP}$
Fractional increase in HP stream mass flow per passage due to passes being bypassed	ν_{HP}	1.06	[-]	$= N_{HP} / (N_{HP} - N_{HP,byp})$
Fractional pressure drop increase in HP stream (if these passes were blocked)	τ_{HP}	1.12	[-]	$= (\nu_{HP})^2$

Note: Data from mode-1 (maximum capacity) test, 28-Aug-2013 used

through the LP stream. This is especially the case for a system operating over a wide range of modes (e.g., liquefier to refrigerator) and a wide range of capacities [3], whether this was planned in the process design or not.

MSU-FRIB plans to use two HX's (cores) to cover the 300 to 80 K range; one with the HP, MP and nitrogen streams and the second with the HP and LP streams. This was same as the option requested in the JLab 12 GeV cold box request for proposal. Warm (300 K) flow balancing valves are intended

Table 5. Selected 300-80K HX aspect ratio and the tested to design net thermal rating (UA)

HX Designation	*HX Manu-facturer*	*Aspect Ratio* **(§)**	*Streams*	*Scaled test to design (UA)*	*Design NTU per 1 m total length*	*Ratio of test to design LN usage*	*Mode*
MTL-ASST HX-1001	**A**	5.55	*HP-MP*	1.11	13.0	0.7	*(i)*
			HP-LP	1.15	13.0		
JLab CHL1 HX-1	**B**	3.74	*HP-MP*	0.46	13.6	2.7	*(ii)*
			HP-LP	0.44	13.6		
SNS HX310	**C**	2.94	*HP-MP*	0.39	15.4	1.6	*(ii)*
			HP-LP	0.49	15.5		
NASA-JSC E3110/20	**A**	8.38	*HP-LP*	0.90	10.9	1.0	*(i)*
JLab 12GeV E22410	**A**	3.32	*HP-MP*	0.24	13.5	2.7	*(ii)*
			HP-LP	0.73	13.5		
JLab 12GeV Re-design E22410A/B	**A**	4.93	*HP-MP*	N/A	9.3	TBD	*Varies*
			HP-LP	N/A	9.3		
MSU-FRIB E22410A/B	**C**	5.04	*HP-MP*	N/A	12.0	TBD	*Varies*
			HP-LP	N/A	12.0		

Notes:
(§) Aspect ratio is the non-dimensional ratio of effective length to square root of total free flow area
Mode *(i)* - Pure refrigeration at max. or nominal capacity
Mode *(ii)* - 1.2 bar 30 K nominal cold compressor return (~1% of HP stream is for liquefaction in some cases)

to control the flow split. Constrained by existing practical limitations, the re-designed 12 GeV HX's reused the single (small) core for the HP and nitrogen streams and use two new large cores for the HP-MP and HP-LP streams. Warm flow balancing valves are planned to be used to control the HP flow split among these HX's.

3. Cold box performance

The performance of the 12 GeV cold box system during commissioning and in operation for various LINAC load conditions is shown in figures 2 and 3. 'Uncorrected' means the present performance with high LN usage. 'Corrected' means if the LN usage is restored to the (projected) design usage, as is presently being worked. Also, the solid filled markers indicate a pure 4.5-K refrigeration mode (with some amount of shield load). Inverse coefficient of performance (COP_{inv}) is based on an exergetic equivalent 4.5-K refrigeration load. ***As can be seen, the 12 GeV refrigeration has good turn-down performance from 19.5 to 6.5 bar supply pressure to the cold box. No turbine shut down or turbine inlet valve throttling is required over this entire range and the system can adjust between these extremes with little operator intervention***. Below 11 bar supply pressure to the cold box, operator intervention is required to shut down the excess compressor capacity. Any three of the five compressors can support the minimum turn-down (at 6.5 bar discharge pressure). These extremes also reflect different modes; isothermal refrigeration, liquefaction (300 to 4.5 K), cold compressor load (~30 K, 1.15 bar) with some liquefaction, and total cold compressor load. From figure 2 we observe that the performance down to one-third of the maximum capacity does not change much. Some improvement in the performance at low capacities may be possible for long term operation at these conditions by making some equipment optimizations. However, this was not done given the limited time for testing and since it is quite far from a normal operating condition and capacity. The cold box design has approximately equal 'Carnot-step' (expansion stage) mass flows, allowing good performance and turn-down capability [8]. The original JLab CHL (4 GeV system) and SNS cold box designs did not utilize the equal 'Carnot-step' design basis and consequently manifest limited efficient turn-down capability. That is, they both have a highly dominate turbine stage mass flows compared to the other turbine stages and require turbine inlet valve throttling at reduced capacities. For the 12 GeV system, in some transient conditions, either or both of the upper turbine strings (exhausting to the MP stream) can trip-off without shutting down (tripping) the cold compressors; unlike the original (4 GeV)

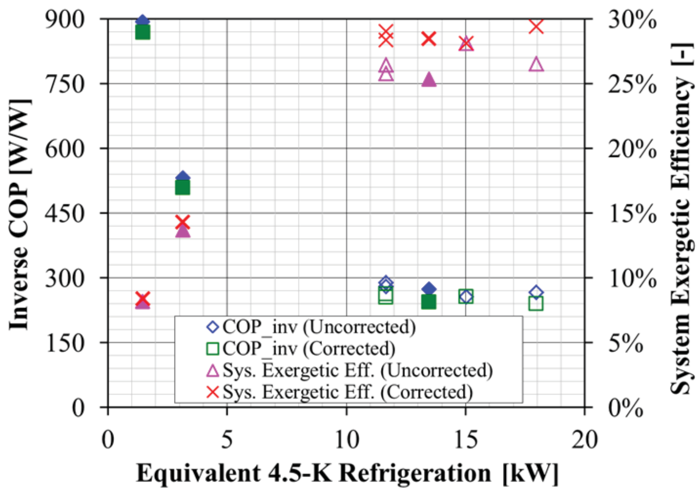

Figure 2. Commissioning and operation performance of the 12 GeV cold box system – inverse COP and system exergetic efficiency

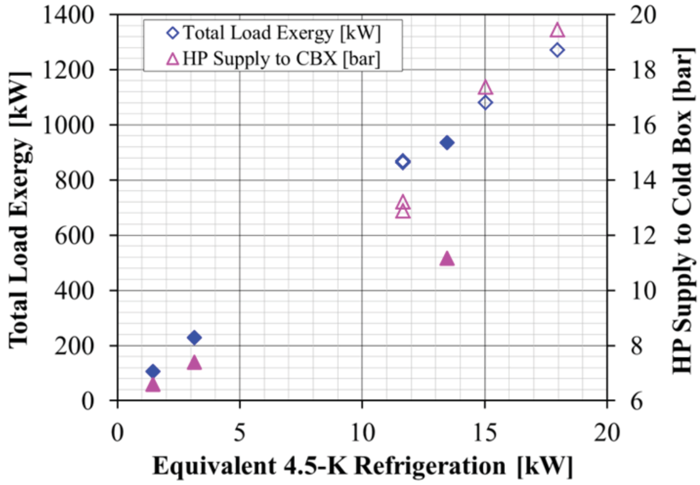

Figure 3. Commissioning and operation performance of the 12 GeV cold box system – total exergy supplied to the load and HP supply pressure to the cold box

CHL. Also, the full shield load can be supported at nominal capacity without running the shield turbines (at an elevated temperature). The refrigeration system is usually operated as a fixed inventory system, with a natural floating pressure operation which automatically monitors for system leakage and component or load performance issues. Leakage is apparent by loss in refrigerator's dewar liquid level and performance issues or changes in load are apparent by changes in the HP supply pressure to the cold box.

4. Conclusion

Full realization of the Ganni Cycle – Floating Pressure process [9] has been successfully demonstrated in the JLab 12 GeV cold box and compressor system, allowing a very wide range of operation with good efficiency. Similar successful results for implementation of this process on the NASA-JSC 20-K refrigeration system used for the James Webb project have been presented [10]. Additionally, this process is being used for the MSU-FRIB project [11, 12] and is anticipated to be used in other projects like LCLS-II.

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