Commissioning and Operational Results of the Helium Refrigeration System at JLab for the 12 GeV Upgrade

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Milestones

- JLab 12 GeV cold box milestones:
  - Feb. 2006: Project is approved to proceed with engineering; cold box design process studies began
  - Oct. 2008: Approval to begin construction phase; cold box RFP issued
  - Sep. 2009: Based upon competitive bid process, award for given to Linde Process Plants, Inc., to deliver new 18 kW 4.5-K equivalent cold box
  - Mar. 2012: Cold box received at JLab
  - May 2013: Commissioned cold box system
  - Jun - Aug 2013: Investigate high LN usage
  - Aug. 2013: Re-test cold box system
  - Nov. 2013: CHL2 supporting 2-K ops for LINAC commissioning

Configuration

- 12 GeV cold box configuration
  - Three pressure levels (HP, MP and LP)
  - LN pre-cooler (300 to 80 K)
  - Below 80 K, four expansion stages; total of 7 turbines
  - Two physically separate cold box vessels w/ interconnecting transfer-lines
  - Upper cold box (vertical, outside): 300 to 60 K
  - Lower cold box (horizontal, inside): 60 to 4.5 K
  - Dual 80 K beds, single 20 K bed – both with bypass valves
  - Shield load can be supported
    - Using either or both T1-T2 / T3-T4 turbine strings, or,
    - At 80 K
  - 3000 liter helium sub-cooler

Design Capacity

- Specification contained six design ‘modes’
  - Modes 1, 3 and 4 are *guaranteed* by the cold box manufacturer, while
  - Modes 2, 5 and 6 are not; rather they are termed manufacturer ‘*expected*’ performance

Mode #	Mode Designation	2.1-K Load[†] [g/s]	4.5-K Refrigeration [kW]	4.5-K Liquefaction [g/s]	35-55 K Shield Load [kW]	Equivalent 4.5-K Refrigeration [kW][§]
1	Max. Capacity	> 238	0	> 15	> 12	17.6
2	Nominal Capacity	> 200	0	0	> 7.5	13.5
3	Max. 4.5-K Liquefaction	0	0	> 150	> 7.5	14.7
4	Max. 4.5-K Refrigeration	0	> 10.5	0	> 12	11.6
5	Max. Fill	> 200	0	> 35	> 12	17.0
6	Stand-By[‡]	0	> 2.5	0	> 12	3.6

[†] 2.1-K Load means the supply mass flow at 3.25 bar 4.5 K, returning at 1.18 bar 30 K

[‡] Mode-6 requires a minimum amount of rotating equipment while supporting the Linac loads at 4.5-K

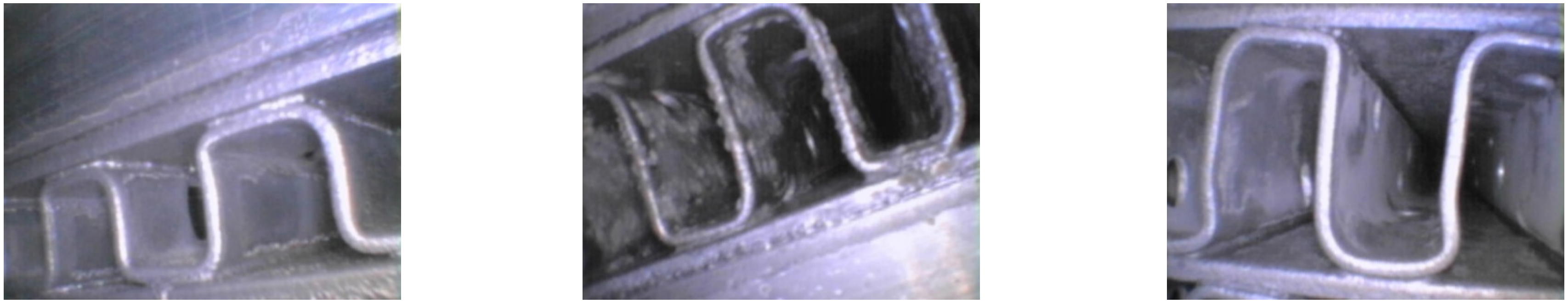
[§] Equal exergy basis: 3.25 bar 4.55 K supply, 1.25 bar saturated vapor return

Liquid Nitrogen Usage

- During spring 2013 commissioning it was found that LN pre-cooler required excessive usage
  - ~2.3 *x* guarantee for Mode-1 (max. capacity)
  - ~2.7 *x* design for Mode-1 (max. capacity)
  - ~3.7 *x* design for Mode-4 (max. refrigeration)
- Although this is results in increased operational costs, <u>*this does not affect the capacity of the refrigerator*</u>
- Subsequent course of actions
  - Warm cold box to ambient temperature
  - Inspect 300 – 80 K HX passes at headers
  - Perform rapid purging of passes
  - Re-cool, verifying cleanliness (to avoid any blockage due to contamination)
  - Re-test

Liquid Nitrogen Usage

- Visual inspection of HX passes at headers
  - Some debris found in HP stream
  - Discoloration of MP passes
    - HP, MP and LP passes shown below:



- Cold box and HX manufacturer, as well as, JLab did not believe this was related to the high LN usage unless this was residual from moisture (which caused blockage of some of the passes)

Liquid Nitrogen Usage

- During the re-test in Aug. 2013, four methods were used to cross-check the LN usage (#1 to #3 were used in the spring)
  - Note: Due to operational constraints, it was not possible to measure the LN storage tank depletion

  #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)
- Results similar to the spring testing were obtained with no improvement in the LN consumption

Liquid Nitrogen Usage

- At this juncture, having eliminated other reasons, improper flow distribution (or 'mal-distribution') was only real alternative to account for the low performance
- HX's with high NTU's (> 30), especially in multi-stream HX's, are extremely vulnerable to improper flow distribution if not carefully considered in the design
- Improper flow distribution in high NTU HX's can be caused by:
  - Hydrostatic differences (if oriented horizontally)
  - Insufficient length for longitudinal conduction
  - Lower flow rates (pressure drop is ~mass flow squared)
  - Improper layering

Liquid Nitrogen Usage

- The following simple calculation illustrates the effect if improper flow distribution on the LN usage

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

Liquid Nitrogen Usage

- So, if ~6% of the passes are blocked, bypassed (flow biased) or have inadequate heat transfer, this can result in an LN usage rate that is ~2.7 times higher
  - If the passes were blocked, this would be only a ~12% increase in pressure drop (which would be difficult to measure)
- Upon analyzing this issue on existing systems further, it appears (perhaps intuitively) that the 'aspect ratio' has a significant influence
  - 'Aspect ratio' – ratio of the effective length to the square root of the total free flow area (all streams)

Liquid Nitrogen Usage

- Aspect ratio for selected systems that use LN pre-cooling

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)

Liquid Nitrogen Usage

- The table below summarizes key HX specifications required by JLab to address proper flow distribution in the RFP

#	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 effective 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

- Items #3 and #4 are often claimed by manufacturers to be an excessive design specification
- The aspect ratio was not part of the original HX specification

Liquid Nitrogen Usage

- The 12 GeV re-design of the sensible heat portion of the LN pre-cooler uses two new cores
  - Core A: HP, MP streams, 5.5 m long with HP & MP stream re-mixing headers
  - Core B: HP, LP streams, 5.5 m long with HP and LP stream re-mixing headers
  - NTU's per meter and aspect ratios for these are in the range of HX's that have performed acceptably
- Existing HP – nitrogen (gas) core is being re-used
- Warm (300 K) flow balancing valves are planned to control the flow split

Liquid Nitrogen Usage

- The following table shows a comparison of the original design and re-design that was selected and is presently being implemented

		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

Liquid Nitrogen Usage

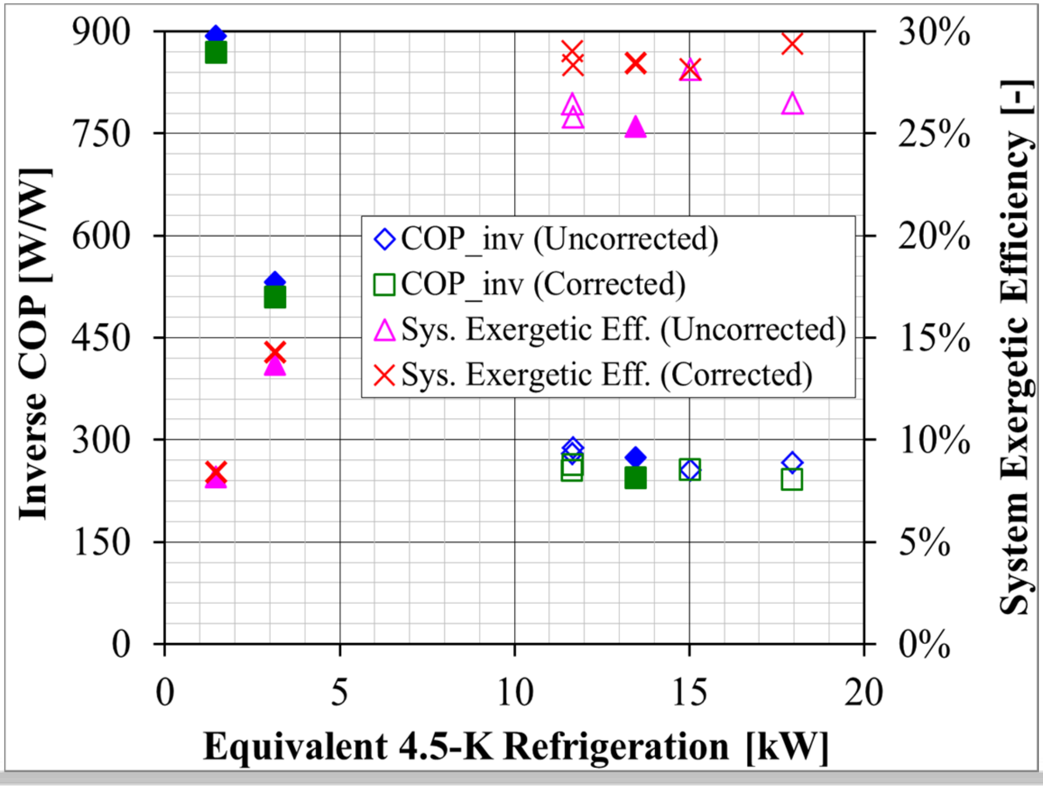
- In systems that use LN pre-cooling, it is quite common to see high LN usage, as compared to the design goal
- Even in systems that do not, it is not unusual in multi-stream HX's for the medium pressure stream exiting the cold box (i.e., 300 K temperature level) to be considerably colder than the design
- 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 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, whether this was planned in the process design or not

Liquid Nitrogen Usage

- MSU-FRIB plans to use two HX's (cores) for the sensible heat portion of the LN pre-cooler
  - Core A: HP, MP and nitrogen streams
  - Core B: HP and LP streams
  - This was same as the option reqested in the JLab 12 GeV cold box RFP
  - Warm (300 K) flow balancing valves are intended to control the flow split
- Due to existing practical limitations, this configuration was not used for the 12 GeV 300 – 80 K HX re-design

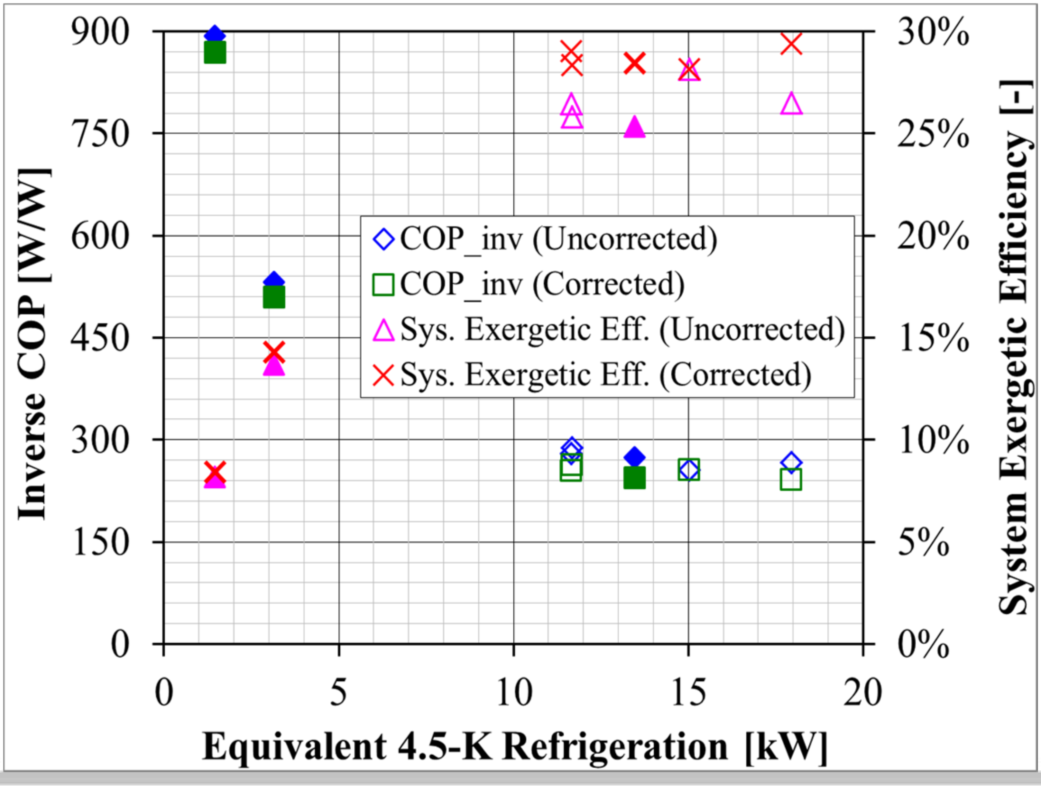
Cold Box Performance

- Below is the 4.5-K cold box inverse coefficient of performance (COP_{inv}) and system exergetic efficiency vs. the equivalent 4.5-K refrigeration load (on an equal exergy basis)
- As can be seen, it has a nearly flat performance down to ~1/3 of the maximum capacity



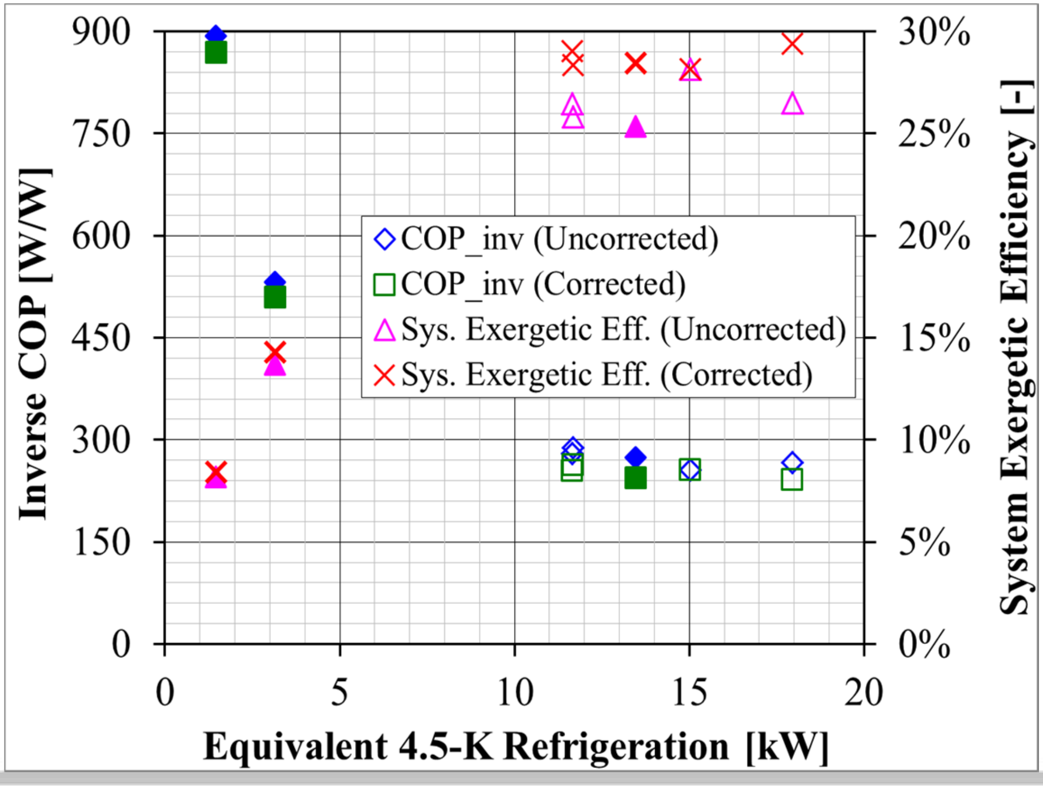
Cold Box Performance

- These extremes reflect different modes
  - Isothermal 4.5-K refrigeration
  - Liquefaction (4.5 to 300 K)
  - Cold compressor load (~30 K 1.15 bar) w/ and w/out some liquefaction



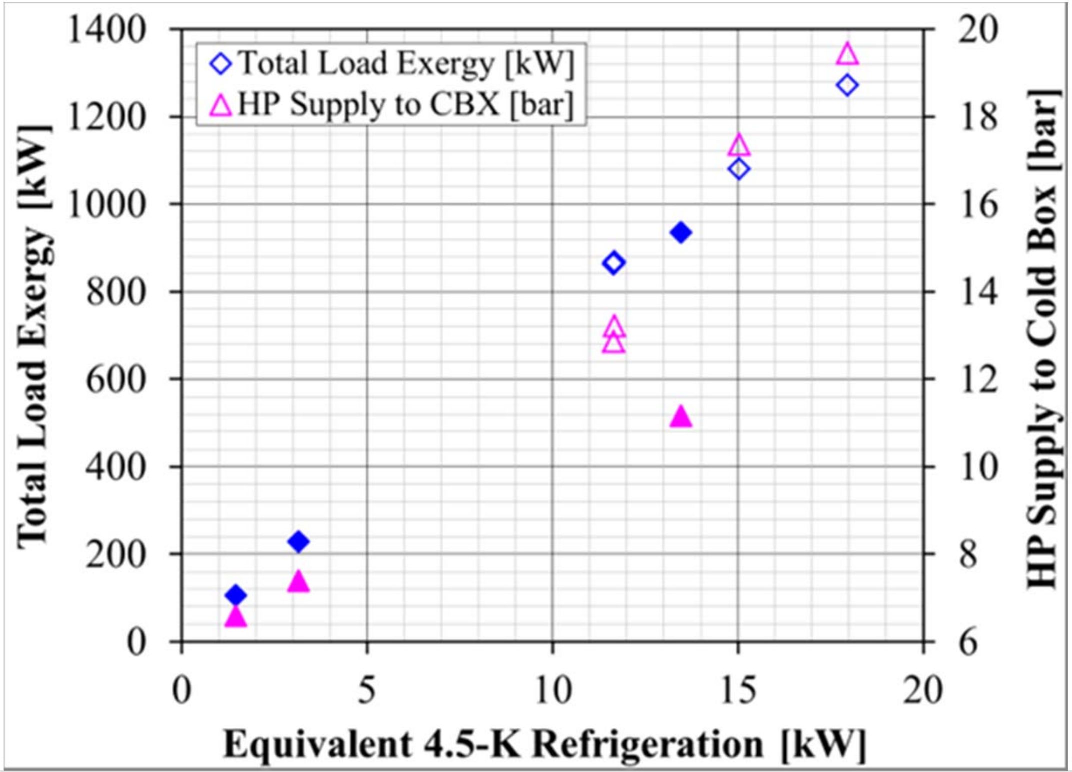
Cold Box Performance

- Uncorrected – reflects present high LN usage
- Corrected – reflects LN usage restored to the (projected) design
- Solid markers indicate pure 4.5-K refrigeration w/ some shield load



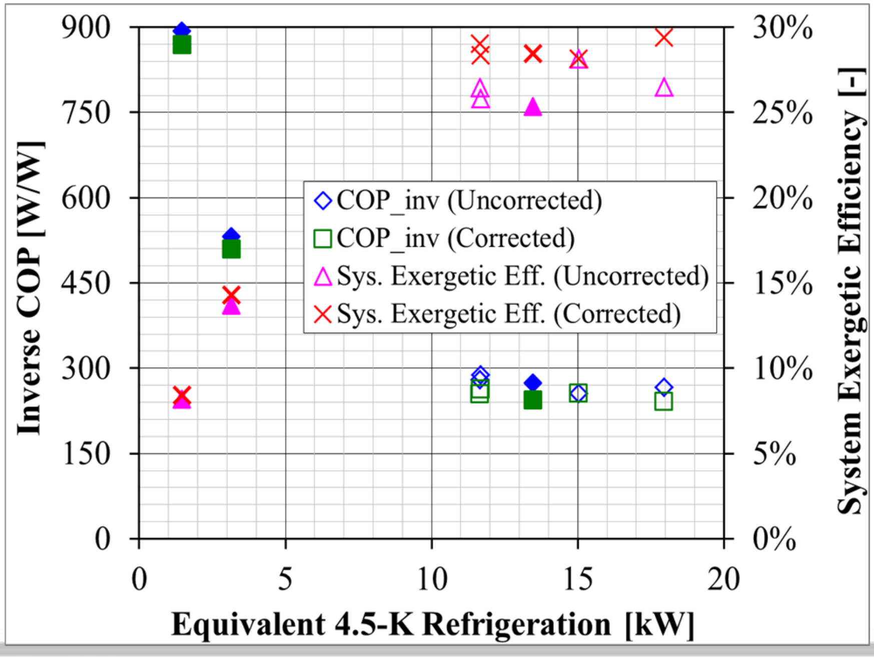
Cold Box Performance

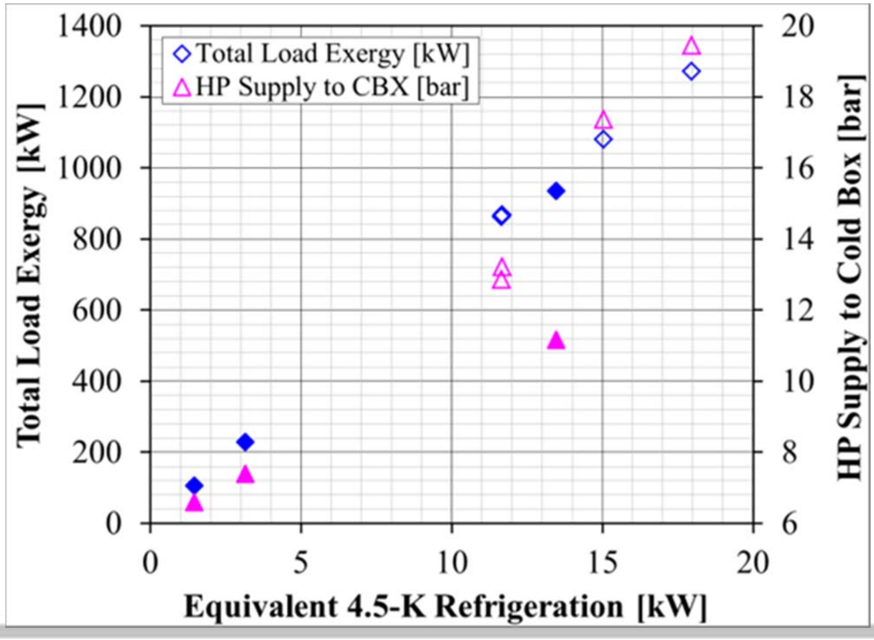
- Turn-down performance ranges from 19.5 to 6.5 bar supply pressure to the cold box
- No turbine shut-down or turbine inlet (pressure) throttling is required, and,
- System can adjust w/ little operator intervention



Cold Box Performance

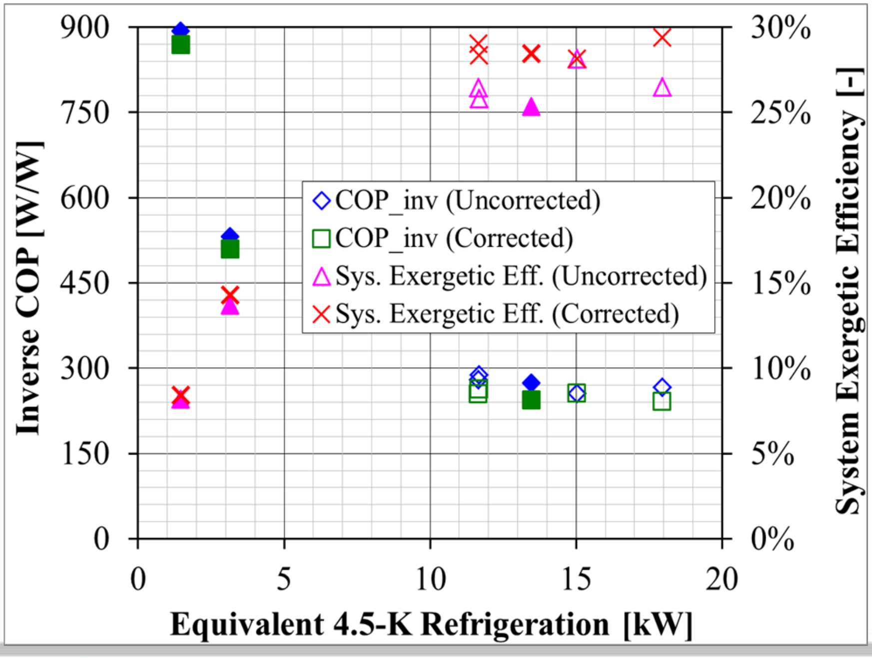
- Below 11 bar supply pressure to the cold box, operator intervention is required to shut down the excess compressor capacity
- Any three of the five compressors can support the minimum turn-down (at 6.5 bar discharge pressure)
- Some improvement in the performance at low capacities may be possible for long term operation at these conditions by making some equipment optimizations
  - This was not done given the limited time for testing and since it is quite far from a normal operating condition and capacity

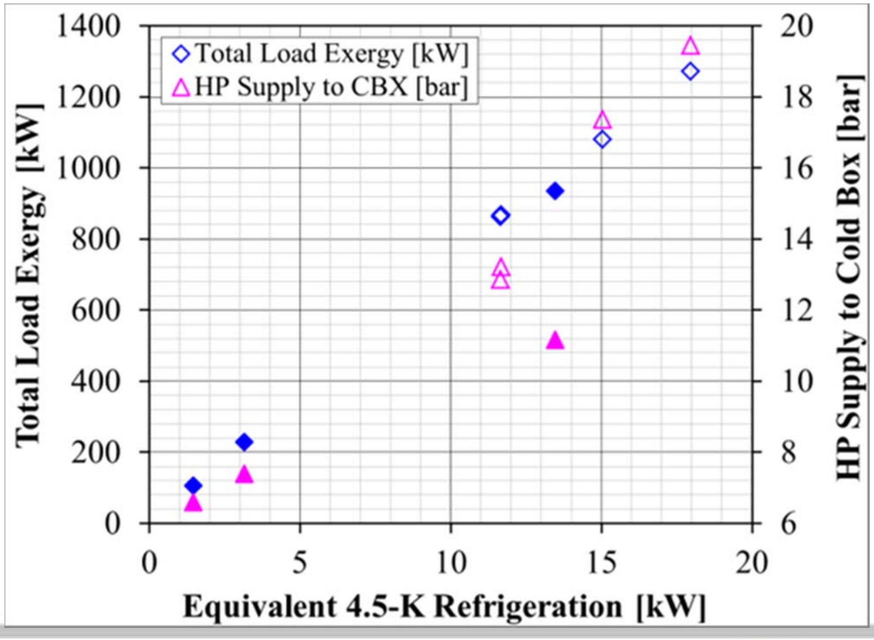




Cold Box Performance

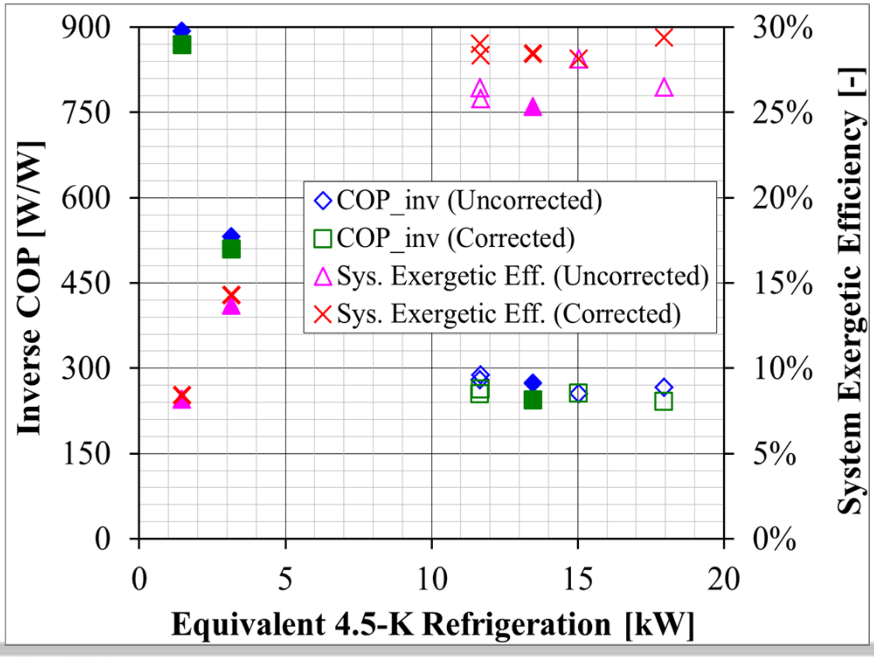
- Cold box design has approximately equal 'Carnot-step' (expansion stage) mass flows, allowing good performance and turn-down capability
- Original JLab CHL (4 GeV system) and SNS cold box designs did not utilize the equal 'Carnot-step' design basis
  - Manifest limited efficient turn-down capability
  - Both have a highly dominate turbine stage mass flows compared to the other turbine stages that require throttling of turbine inlet valves at reduced capacities

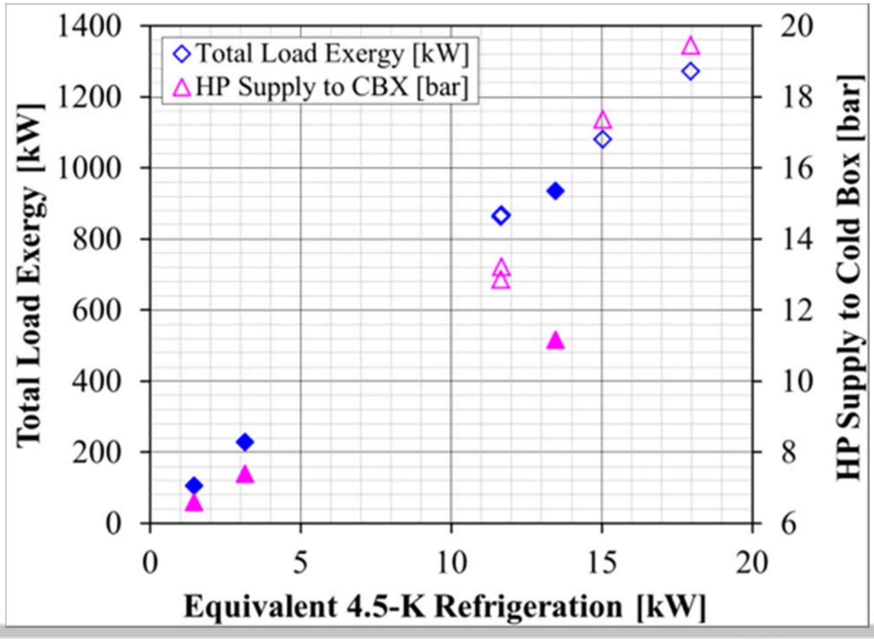




Cold Box Performance

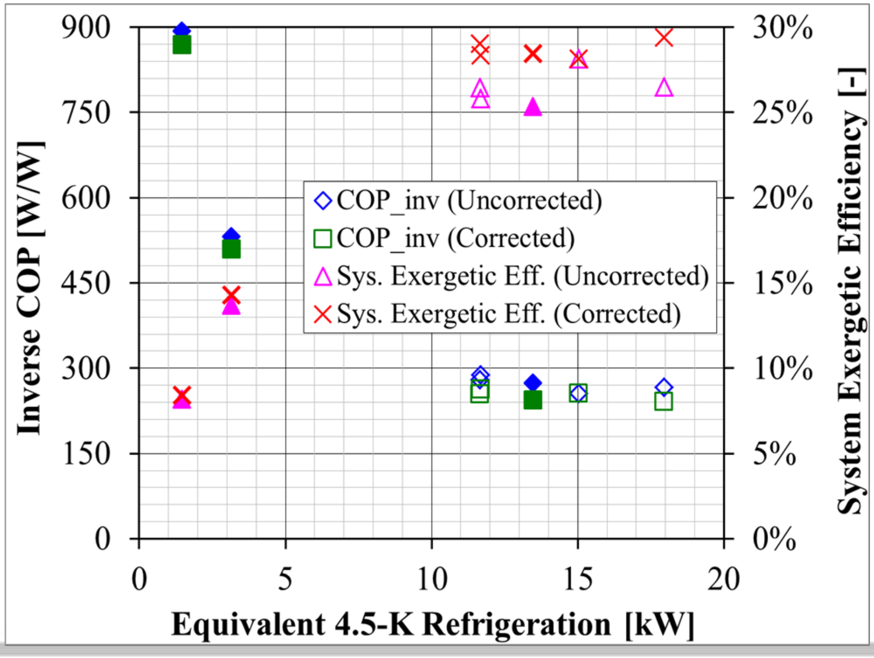
- For the 12 GeV system, in some transient conditions, either or both of the upper turbine strings (exhausting to the MP stream) can trip-off without shutting down (tripping) the cold compressors; unlike the original (4 GeV) CHL
- Also, the full shield load can be supported at nominal (cold compressor) capacity without running the shield turbines (though at an elevated temperature)

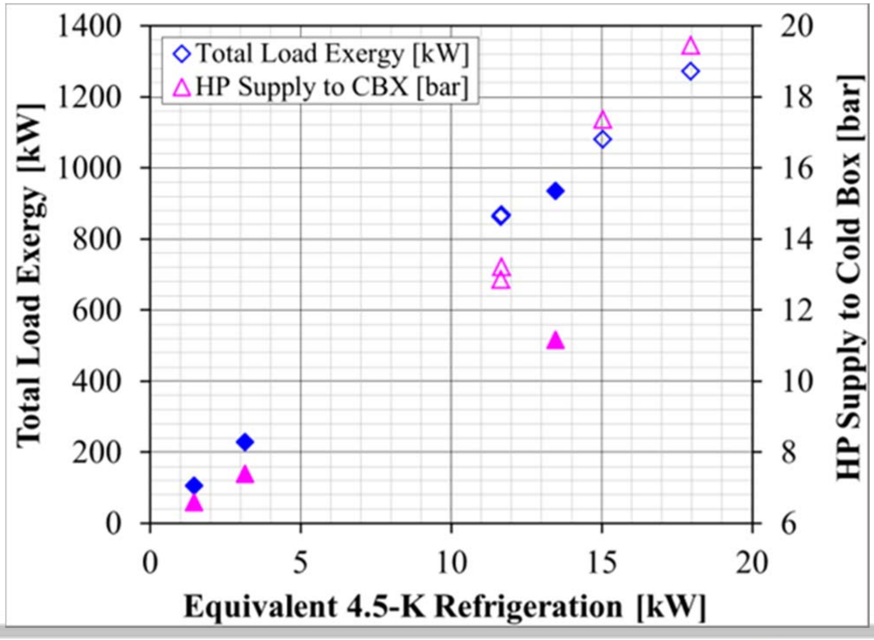




Cold Box Performance

- Refrigeration system is usually operated as a fixed inventory system, with a natural floating pressure operation
  - Automatically monitors for system leakage
    - Apparent by loss in refrigerator’s dewar liquid level
  - Component or load performance issues
    - Apparent by changes in the HP supply pressure to the cold box





Conclusions

- Re-design of LN pre-cooler is being implemented; modification in progress by manufacturer
- Full realization of the Ganni Cycle – Floating Pressure process has been successfully demonstrated in the JLab 12 GeV cold box and compressor system
  - This allows a very wide range of operation (19.5 to 6.5 bar supply to the cold box) with good efficiency (nearly flat down to ~1/3 of max. capacity)
- 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
- Additionally, this process is being used for the MSU-FRIB project and is anticipated to be used in other projects