Cryogenic Plants for SRF Linacs

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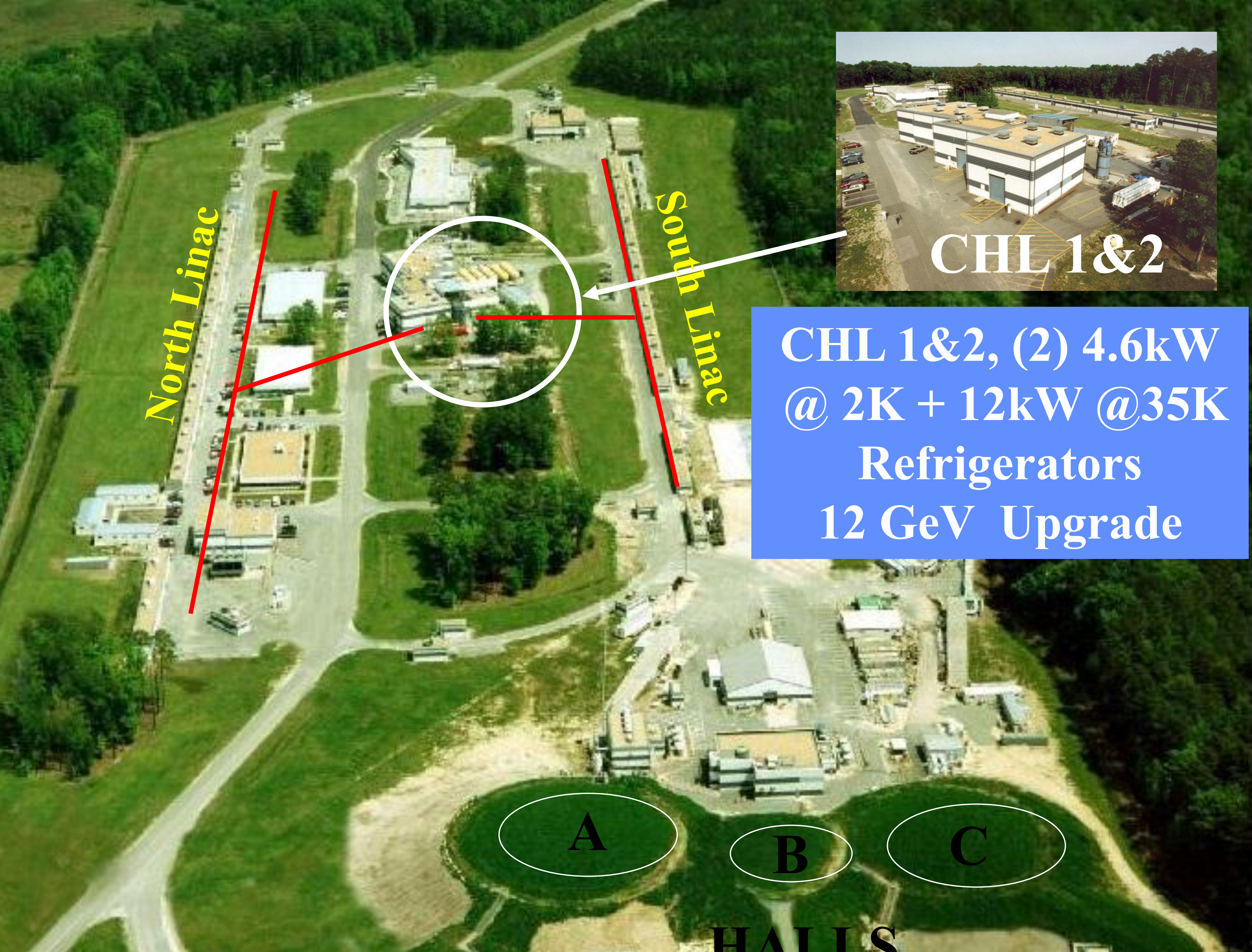
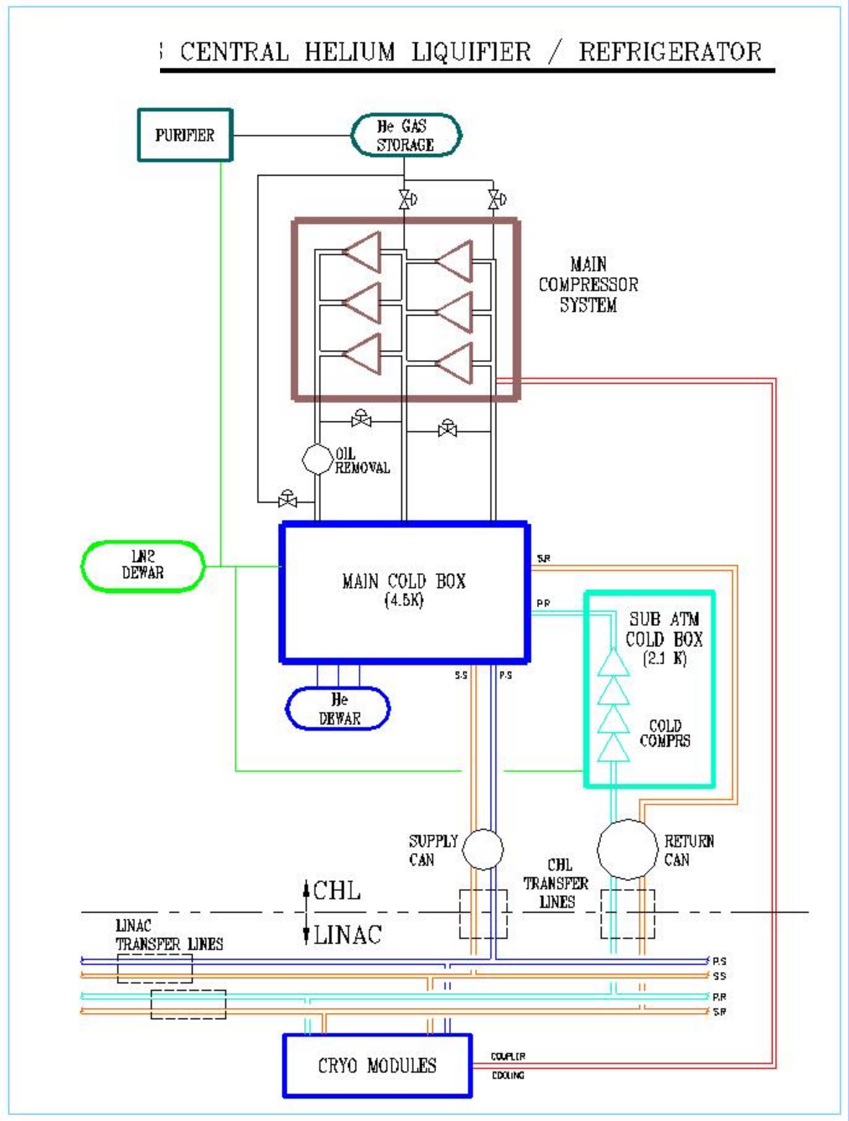

CHL 1&2
North Linac
South Linac
CHL 1&2, (2) 4.6kW
@ 2K + 12kW @35K
Refrigerators
12 GeV Upgrade
A
B
C
HALLS

Central Helium Liquefier System



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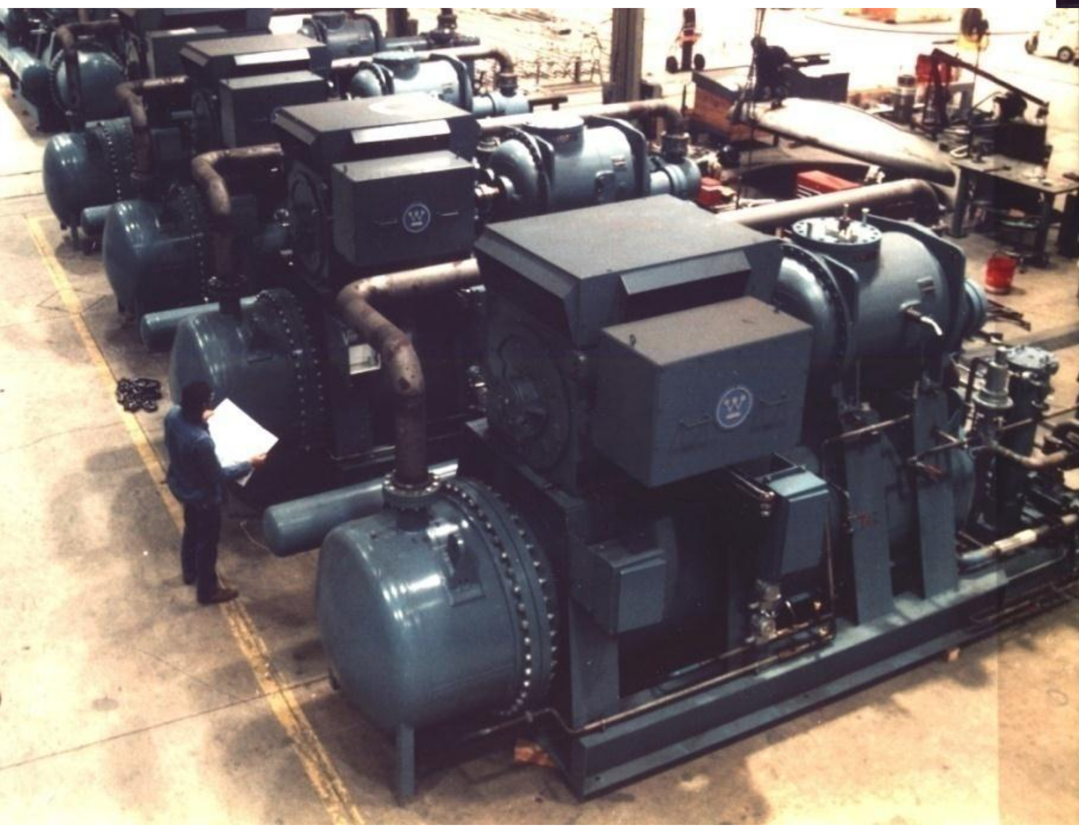
CHL-1 Warm He Compressors and Cold Boxes

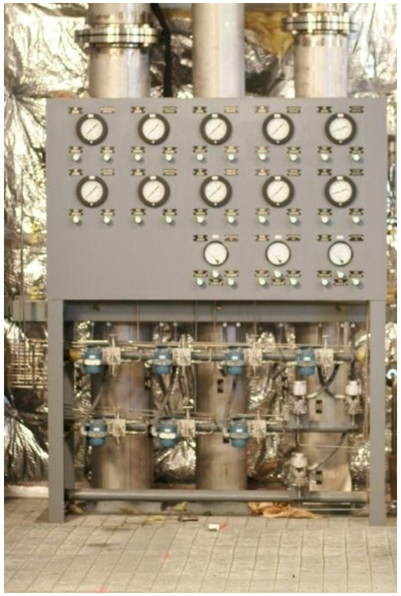


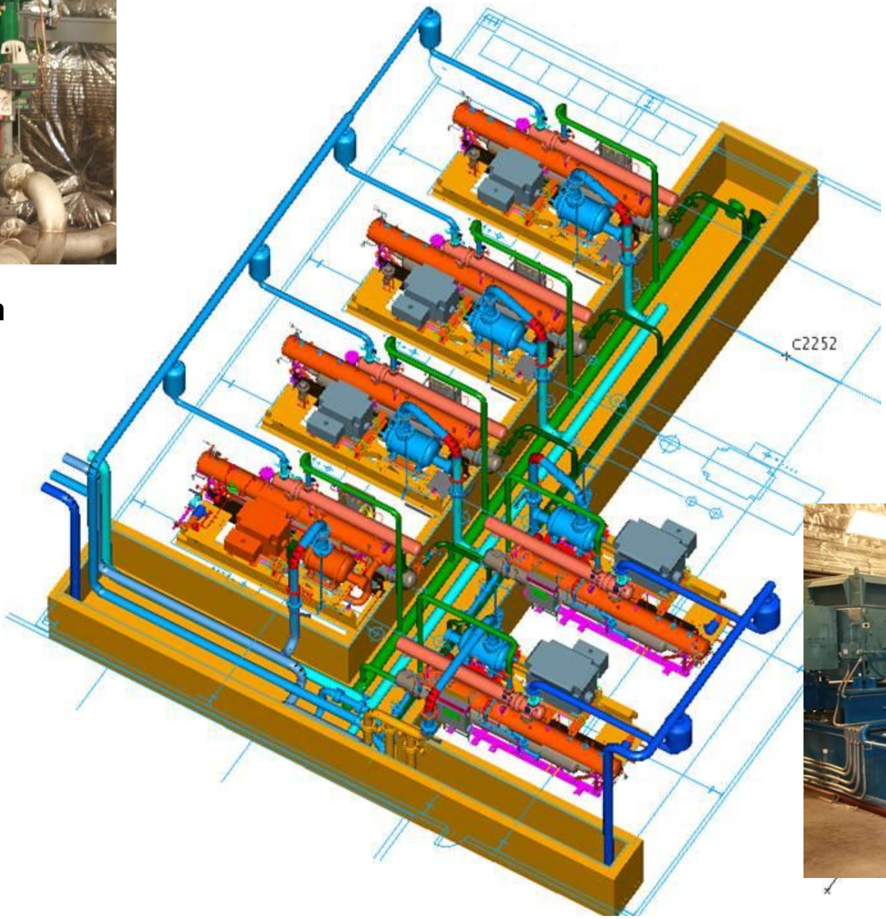
4K Cold Box and Original 4 Stage 2K Cold Box

Current CHL-1 4K & New 5 Stage 2K Cold Boxes

CHL-2 Warm Helium Compressors

Gas Management System





Motor Control Center

Warm Helium Compressors

Upper CHL-2 4.5K Cold Box Shipping/Installation

300-60K Section

CHL Lower 4.5K Cold Box Installation

60-4.5K Section

Purifier, LN_2 Dewar, Gas Storage, Guard Vacuum

He Purifier, 1PPMv

Guard Vacuum

He Gas Storage

LN_2 Storage

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JLab CEBAF Central Helium Liquefiers

- Operating at 6 GeV (CHL #1), 1993-2013
  - —Load: 4.25 kW @ 2K, 11.65 kW @ 35-55K
  - —Capacity: 4.6 kW @2K, 12 kW @ 35-55K
  - —10 g/s liquefaction
- New 12 GeV (CHL #1 + new CHL#2), 2013-?
  - —Load: 7.4 kW @ 2K, 14.65 kW @ 35-55K
  - —Capacity: 9.2 kW @ 2K, 24 kW @ 35-55K
  - —25 g/s liquefaction

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JLab SRF Cryoplant Design Partnerships

- **SNS, Spallation Neutron Source, Oak Ridge TN, USA**
  2.3kW @ 2.1K , 8kW @ 35-55K, 10 g/s liquefaction
  Status: Operational 2007

- **FRIB, Michigan State University, Lansing, MI, USA**
  3.6kW @ 2.1K, 20 kW @ 35K-55K, 4.5kW @ 4.5K
  Status: Construction Stage

- **LCLS-II, SLAC, Stanford University, Palo Alto, CA USA**
  4kW @ 2.0K, 13.4 kW @ 35K-55K, 1.2kW @ 5K-8K
  Status: Design Stage

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As Plant Operators Ourselves

We want…..and work to achieve (using new technology and lessons learned from project to project)

- — Low cost capital plant equipment cost
- — High reliability
- — High efficiency regardless of % of plant load
- — High plant availability
- — Low helium gas loss
- — Low utility and manpower cost

When we add design margin to our loads and cryoplant calculated performance, we are saying we will most likely be operating at some partial load
<u>So our operation needs to be efficient at some unknown turn down load</u>

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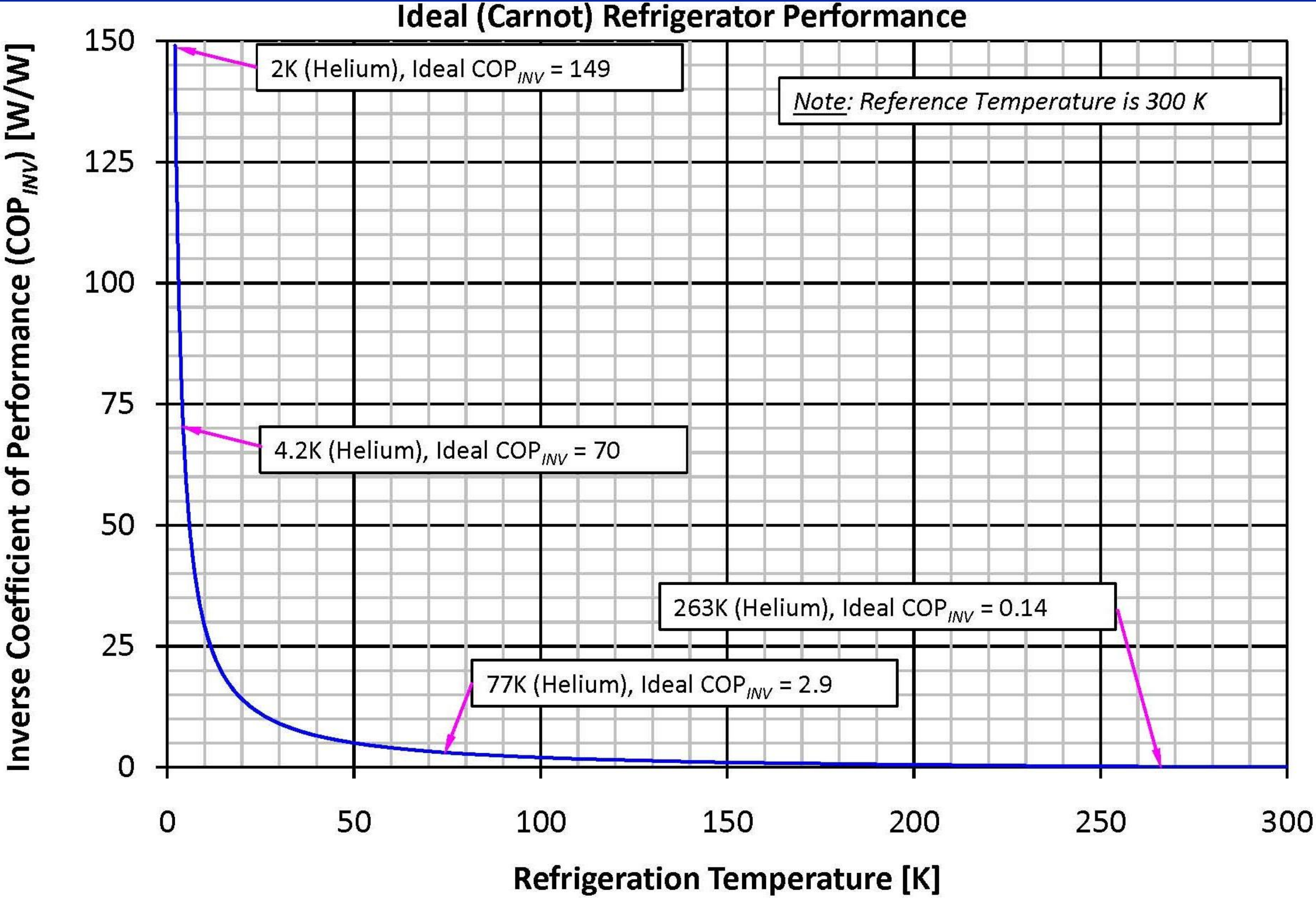
Quality of Energy, Ideal



KEY ITEMS ACCOMPLISHED SINCE 1993 (1)

- **5-6 years of continuous plant operation before major plant maintenance shutdown periods**
- **99%+ plant availability even after 20+ years**
- **+/- 100 microbar 2K pressure regulation with slow frequency response via modification of cold compressor control & 2K cold box assembly design**
- **Plant control unattended automation**
- **Contamination elimination by re-purifying helium before putting into system**
- **Easy older plant "floating pressure" modification for 20% power reduction and improved availability (**

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KEY ITEMS ACCOMPLISHED SINCE 1993 (2)

- Low helium gas loss by plant design (Ex: SNS ~$15K US/yr, NASA JSC ~undetectable)
- Ganni Cycle design for new plants, constant high plant efficiency for >3 to 1 load turn down
- 40% reduction of LN_2 use for new plants
- Extended major warm helium compressor maintenance periods from 35,000 to 74,000 hrs
- Best cryoplant design outcome when extended into the load cryostat (more on this later)

Warm Oil Flooded Screw Compressor Efficiencies

Regardless of pressure, peak compressor efficiencies occurs with pressure ratios of 2.5-3.5

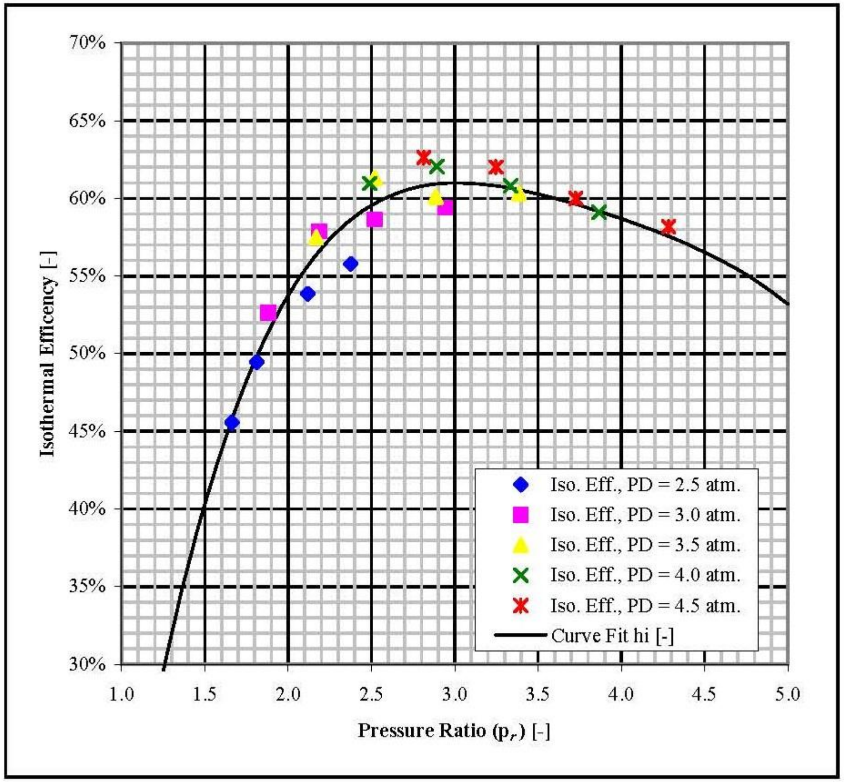

FIGURE 1.3 BRV=2.2 1st Stage

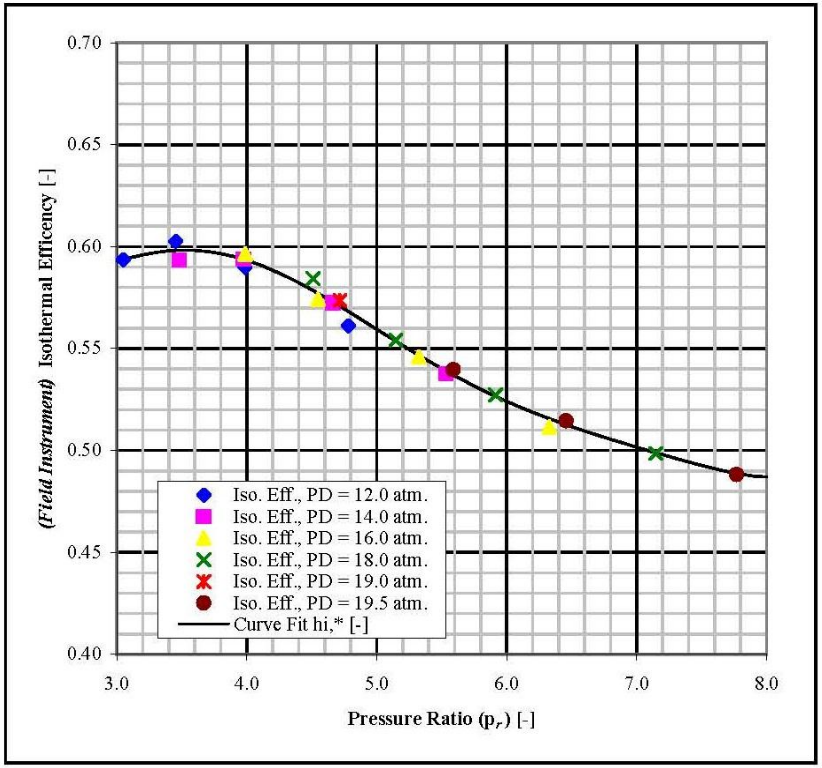

FIGURE 1.4 BRV=2.6 2nd Stage

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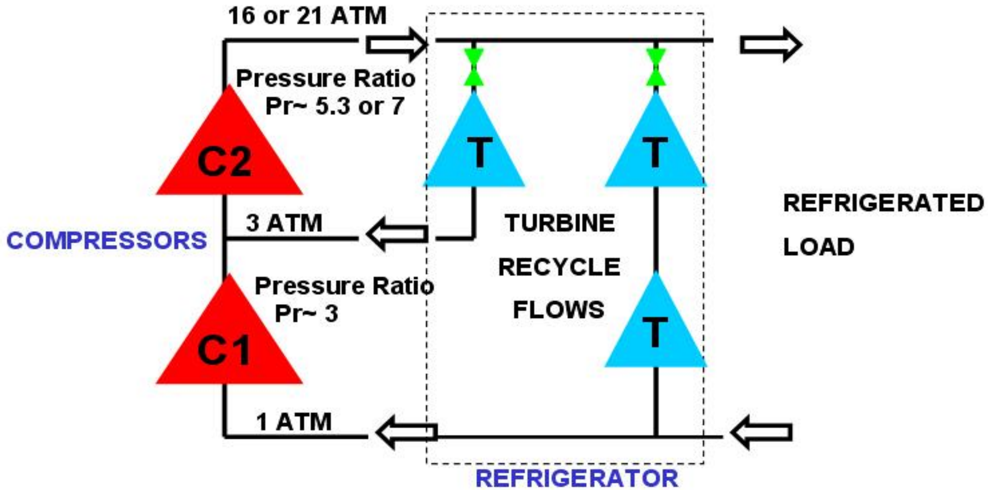
THE GANNI PROCESS CYCLE



STANDARD INDUSTRIAL
HELIUM REFRIGERATOR SYSTEM

Traditional Helium Cycles

Poor pressure ratio matching.

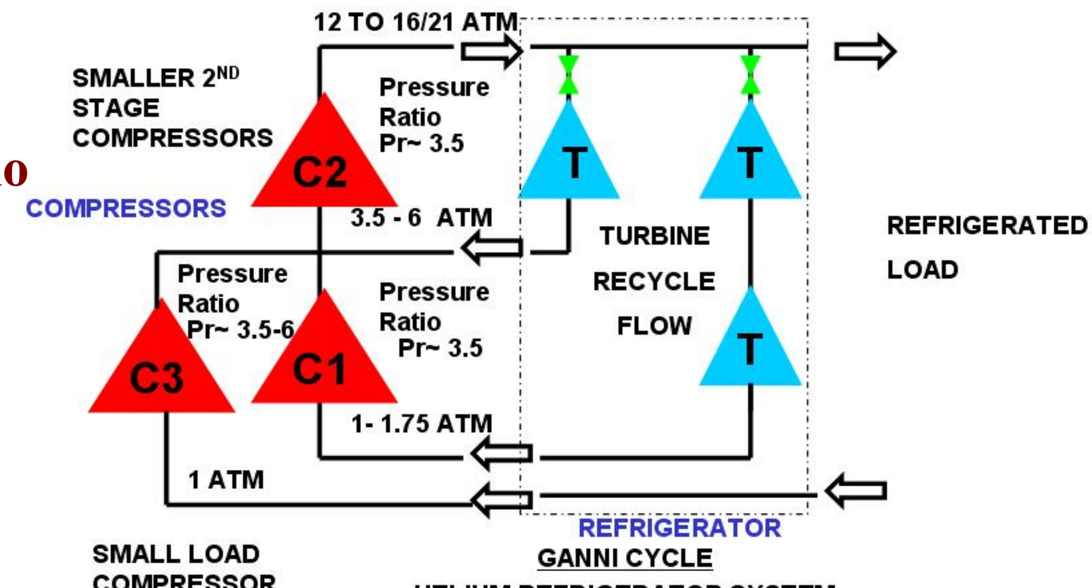
Resulting in large losses in 2nd stage compressors (which require the largest fraction of the electrical input power).

Ganni Cycle

Good (even optimum) pressure ratio matching.

Resulting in low losses for both stages.

Flow from load is separated from turbine flow (since it is a smaller fraction of the total flow).



GANNI CYCLE
HELIUM REFRIGERATOR SYSTEM

GANNI CYCLE COMPRESSOR CONFIGURATION

- **MP and HP compressors compress 4.5K cold box turbine bypass flows**

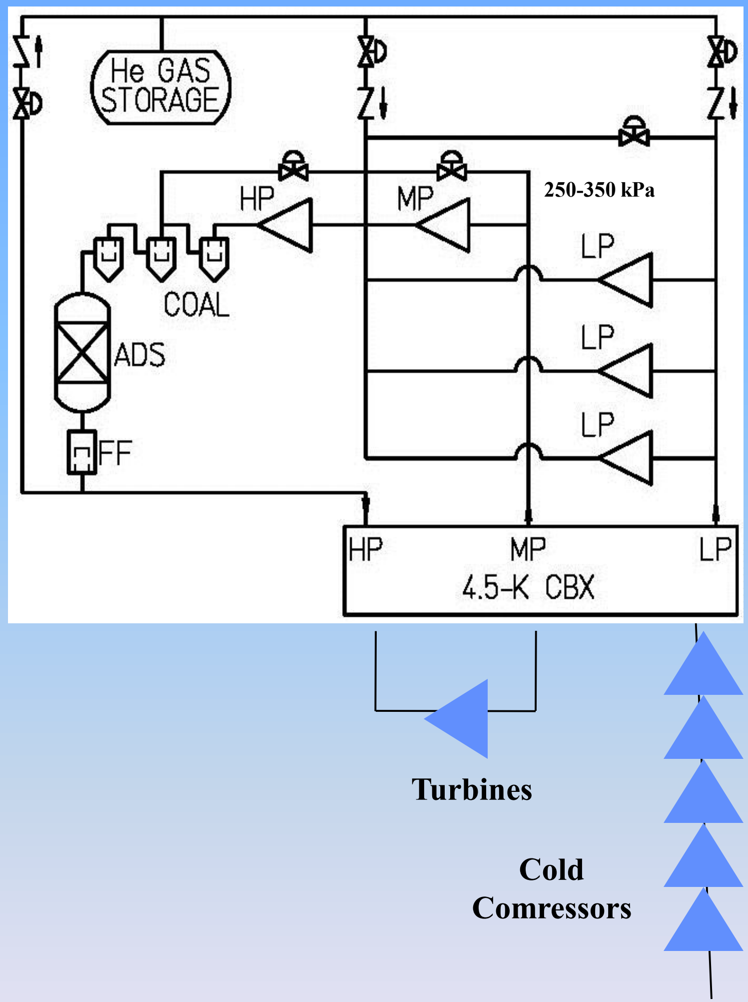
- **LP compressor stage compress loads that must operate at 100 kPa (i.e. cold compressor discharge, etc.)**

- **There is no attempt to normally control suction, inter stage, or discharge pressures of the MP and HP stages with bypass valves. Pressures are allowed to occur naturally 2.5-3.5 pressure ratio with pressures based on system gas charge into or out of the system.**

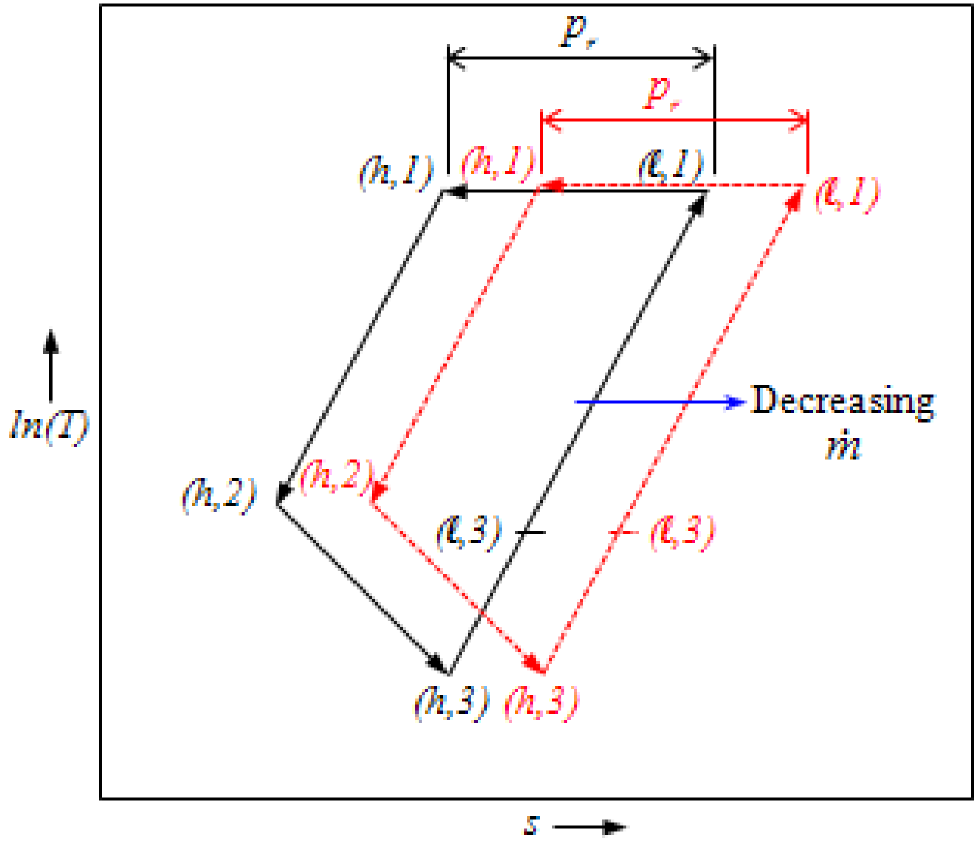
- **System charge pressure is controlled by liquid level within a dewar used to subcool the supercritical 4.5K leaving the 4.5K cold box. Decreasing level (increase charge)/Increasing level (decrease charge)**

- **4.5K cold box turbine inlet valves are allowed to remain fully open, refrigeration is controlled by varying HP and MP differential pressure, variable turbine brake control keeps turbine specific speed efficiency at design**

- **With small variations of refrigeration load, system is self regulating based on amount of refrigeration return flow**

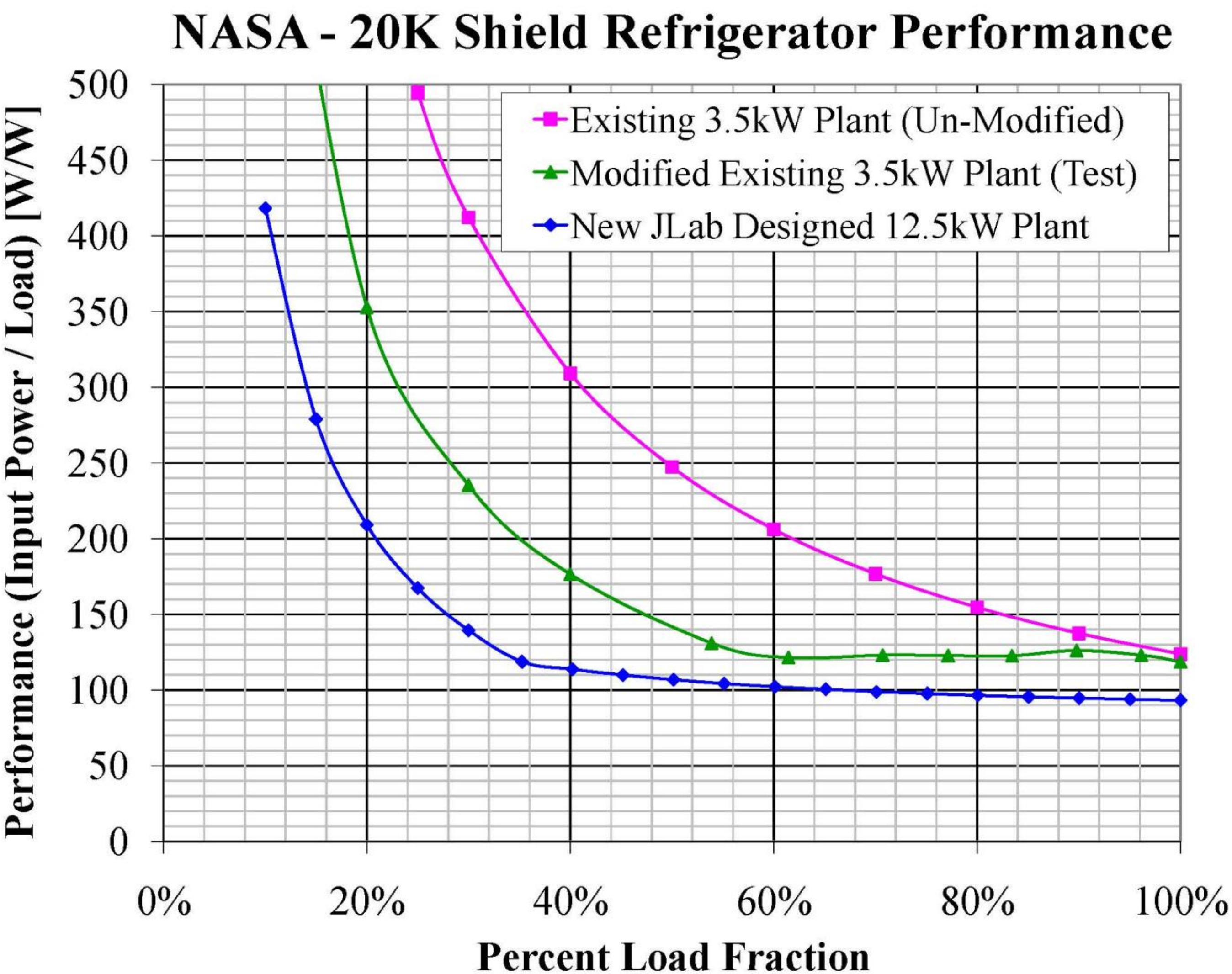


Floating Pressure T-S Diagram



In the floating pressure process, the compressor suction and discharge vary, but at a constant pressure ratio (p_r). ***This is opposed to traditional cycles that attempt to force the controls to the design T-s condition by adding heat, bypassing expander flow, bypassing compressor flow or the throttle expander inlet valve.***

NASA JSC Test Results



A Floating Pressure System is……….

(this is not in a text book)

A constant pressure ratio system that maintains a constant efficiency and constant volume flow *for a variable load*

Symbols:

$\dot{m}$	[g/s]	Mass flow rate
Q	[ℓ/s]	Volumetric flow rate
p	[atm]	Pressure
p_r	[non-dim.]	Pressure ratio
T	[K]	Temperature
ρ	[g/ℓ]	Density
C_p	[J/g-K]	Specific heat at const. pressure
γ	[non-dim.]	Ratio of specific heats
ϕ	[non-dim.]	$=(\gamma-1)/\gamma$
Φ_x		Expander flow coefficient
$\dot{W}_C$	[W]	Compressor input power
E_L	[W]	Load Carnot power
η	[non-dim.]	Efficiency
N_0	[kPa/atm]	Unit conversion constant

Subscripts:

h	High pressure
l	Low pressure
L	(Shield) load
C	Compressor
r	Ratio
x	Expander
v	Volumetric

Compressor mass flow, $\dot{m}_C = \eta_v \cdot Q_C \cdot \rho_{l,1}$

With, $\rho_{l,1} = \dfrac{N_0 \cdot p_{l,1}}{\phi \cdot C_p \cdot T_{l,1}}$

Expander mass flow, $\dot{m}_x = \Phi_x \cdot \dfrac{p_{h,2}}{\sqrt{T_{h,2}}}$ if, $p_{r,x} \geq 2$

Since, $\dot{m} = \dot{m}_C = \dot{m}_x$

This results in a constant pressure ratio,

$$p_r = \frac{p_{h,2}}{p_{l,1}} = \left(\frac{\eta_v \cdot Q_C}{\Phi_x}\right) \cdot \left(\frac{1}{\phi \cdot C_p}\right) \cdot \frac{\sqrt{T_{h,2}}}{T_{l,1}} \cong \text{Constant}$$

Compressor power input, $\dot{W}_C \sim \dot{m}_c \cdot \ell n(p_r)$

Load exergy, $E_L \sim \dot{m}_x \cdot f(p_r)$

This results in a constant efficiency,

$$\eta_{carnot} = \frac{E_L}{\dot{W}_C} \cong \text{Constant}$$

And, a constant volume flow, since,

$p_l \sim \dot{m}$ and, $p_h = p_r \cdot p_l$,

So, $p_h \sim \dot{m}$ and, $Q = \dot{m} / \rho \sim \dot{m} / p = \text{Constant}$

Also, since $p_r = \text{constant}$, $\boxed{q_L \sim p_h}$

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5 Stage CC Design Development & Performance

- Tested 250 g/s CC train with sample flow reductions at each pressure
- Time prevented lower testing
- Upper flow rate limited by 4.5K cold box max capacity

Reference:
CEC 2001, Madison ,Wi
Advances in Cryogenic Engineering
Volume 47A, Pages 288-304
"Design, Fabrication, Commissioning, and Testing of a 250 g/s, 2-K Helium Cold Compressor System"
V. Ganni, D.M.Arenius,B.S. Bevins, W.C. Chronis, J.D.Creel, J.D.Wilson Jr.

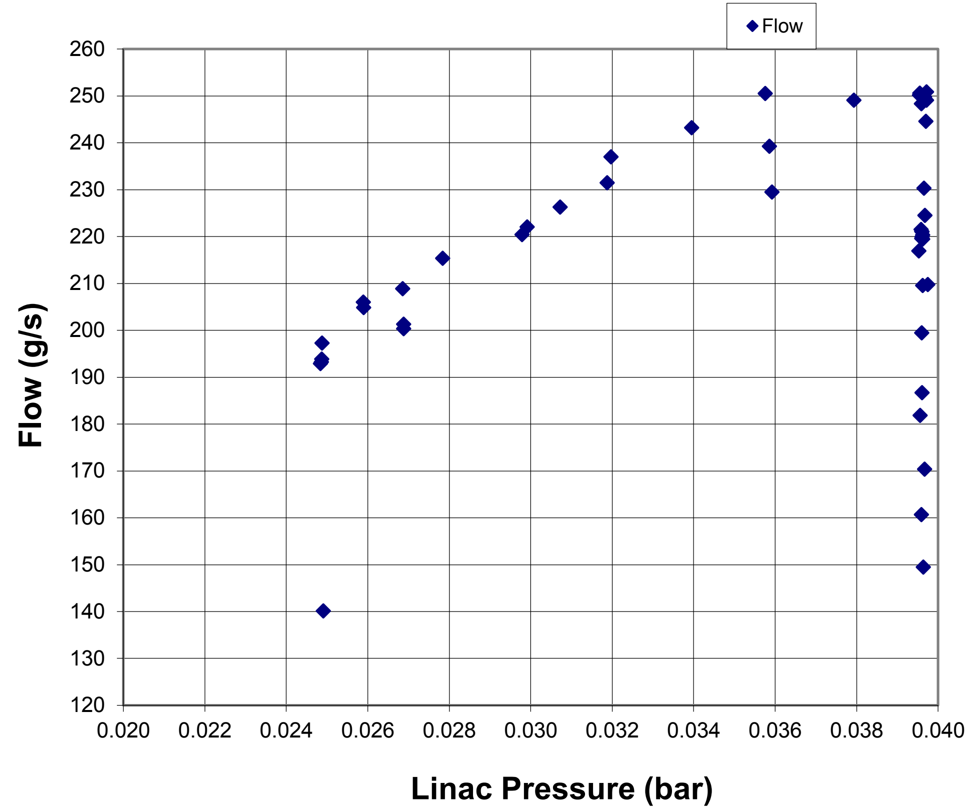


Figure-5.2.0b

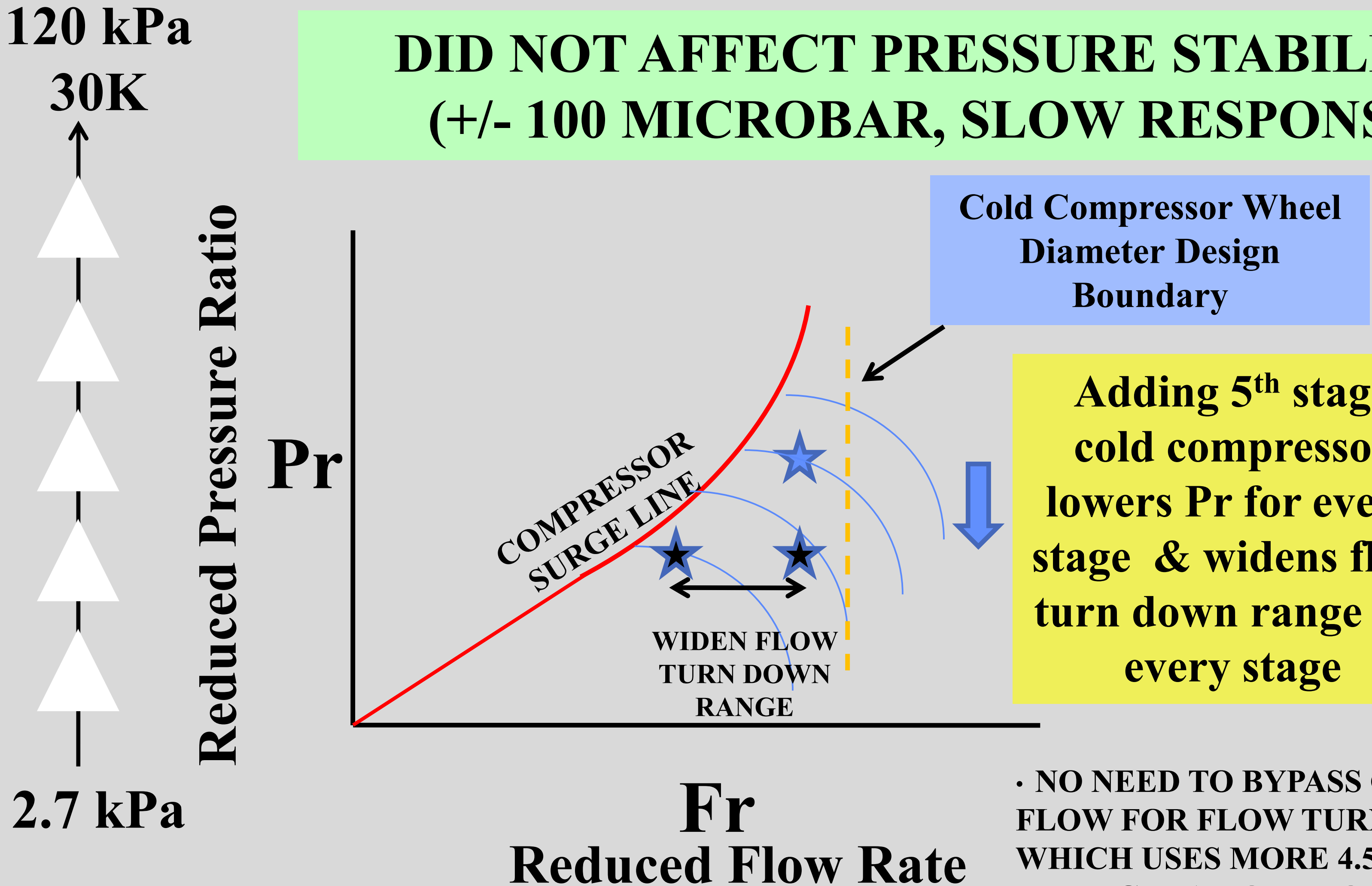
MOVED FROM 4 TO 5 STAGES FOR COLD COMPRESSORS

- **Early CHL-1 Design Internals Before, 4 stages**

- **Latter Internals After, 5 stages**

WHY 5 VS. 4 STAGES OF COLD COMPRESSORS?

DID NOT AFFECT PRESSURE STABILITY (+/- 100 MICROBAR, SLOW RESPONSE)



Adding 5th stage cold compressor lowers Pr for every stage & widens flow turn down range for every stage

- NO NEED TO BYPASS CC TRAIN FLOW FOR FLOW TURN DOWN WHICH USES MORE 4.5K REFRIGERATION FROM PLANT

Remember the earlier COP Power Graph

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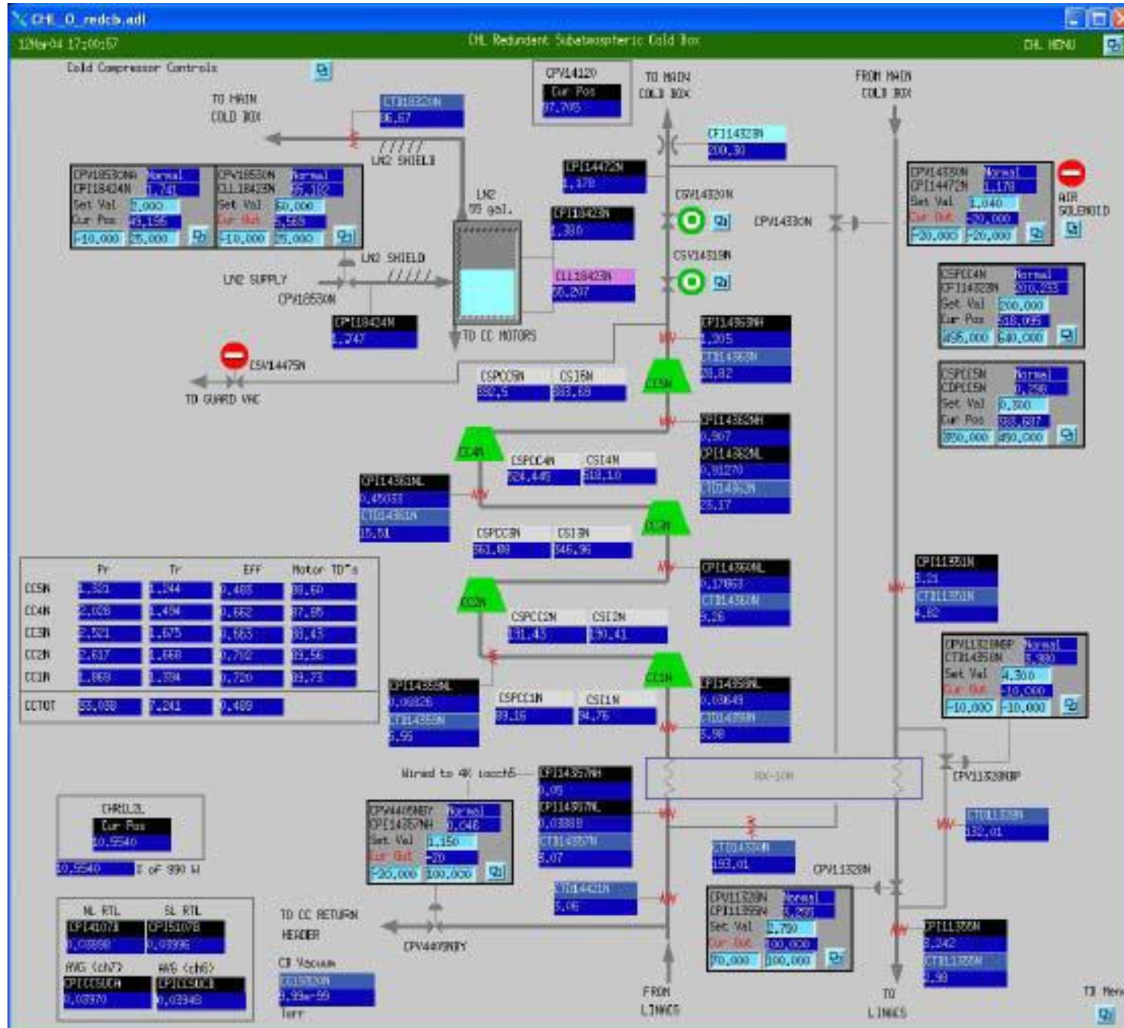
1993 Cold Compressor Control Changes

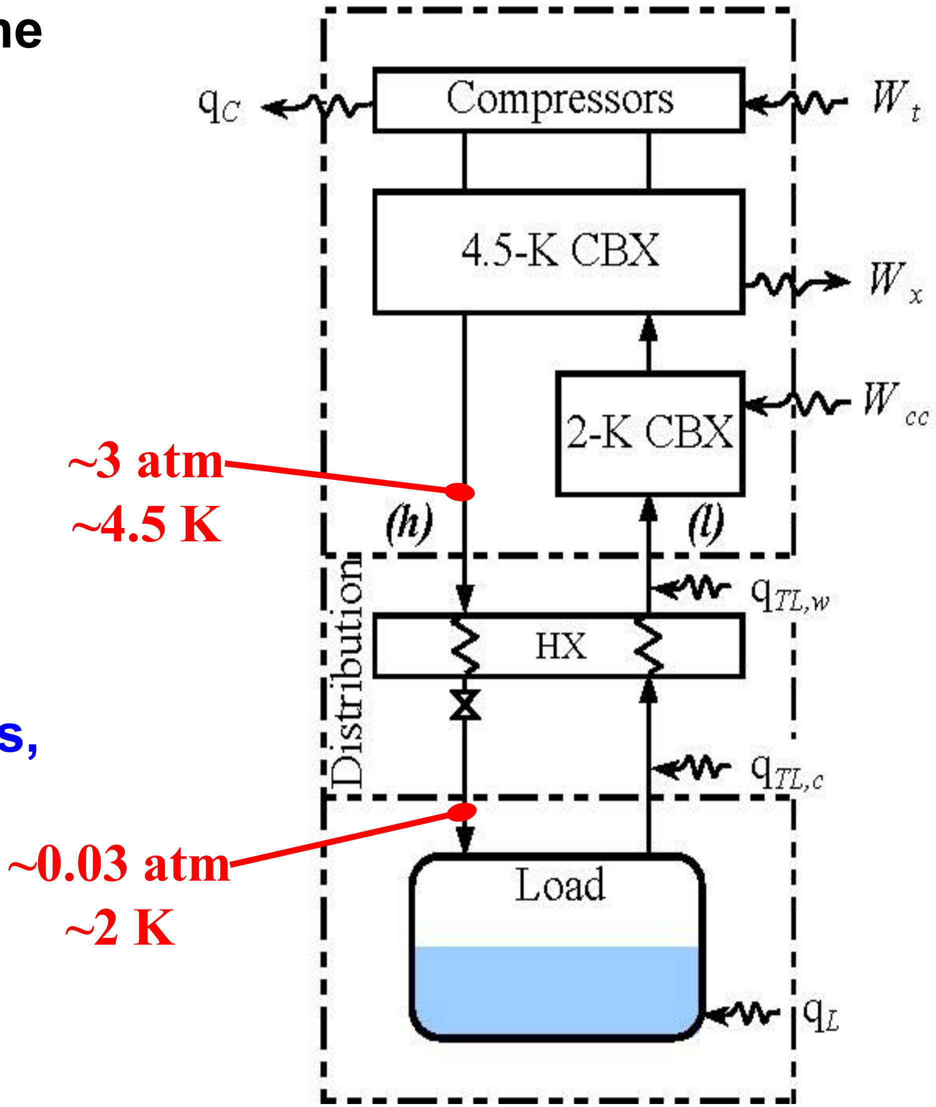
- 5 Stage design, 1999
- Elimination of previous CC inter-stage P&T /Speed control
- Venturi discharge flow measurement
- Locked speed ratios after pump down of CC1-CC3 to CC4 speed
- CC4 controlled to maintain discharge flow
- CC5 speed is fixed pressure delta P control
- CM heat control under tunnel return pressure
- Menu based auto data base pump down



2-K Process Improvements (1)

- **For thermo-hydraulic reasons, the supply pressure to the load is usually**
  - **~3 atm (super-critical) for large systems and,**
  - **~1.2 atm (saturated liquid) for small systems**

- **But the load is sub-atmospheric**
- **(what about the availability lost between these pressures…that is, *throttling from the supply pressure to 0.03 atm ?***



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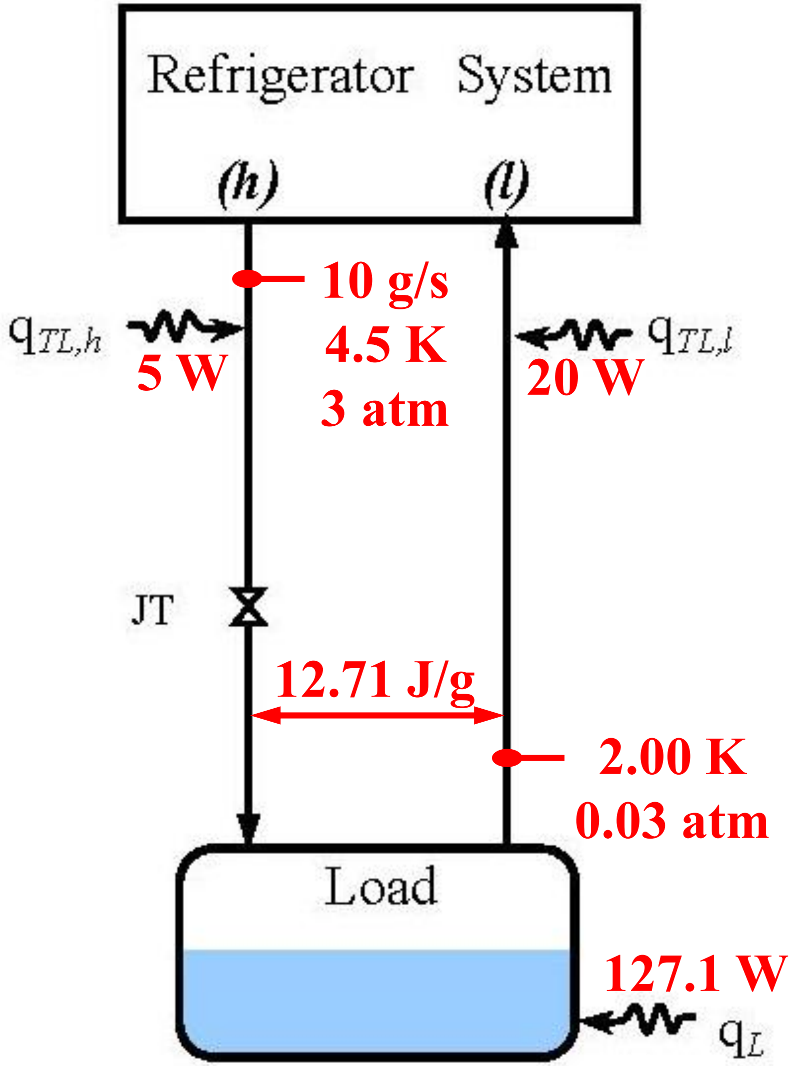
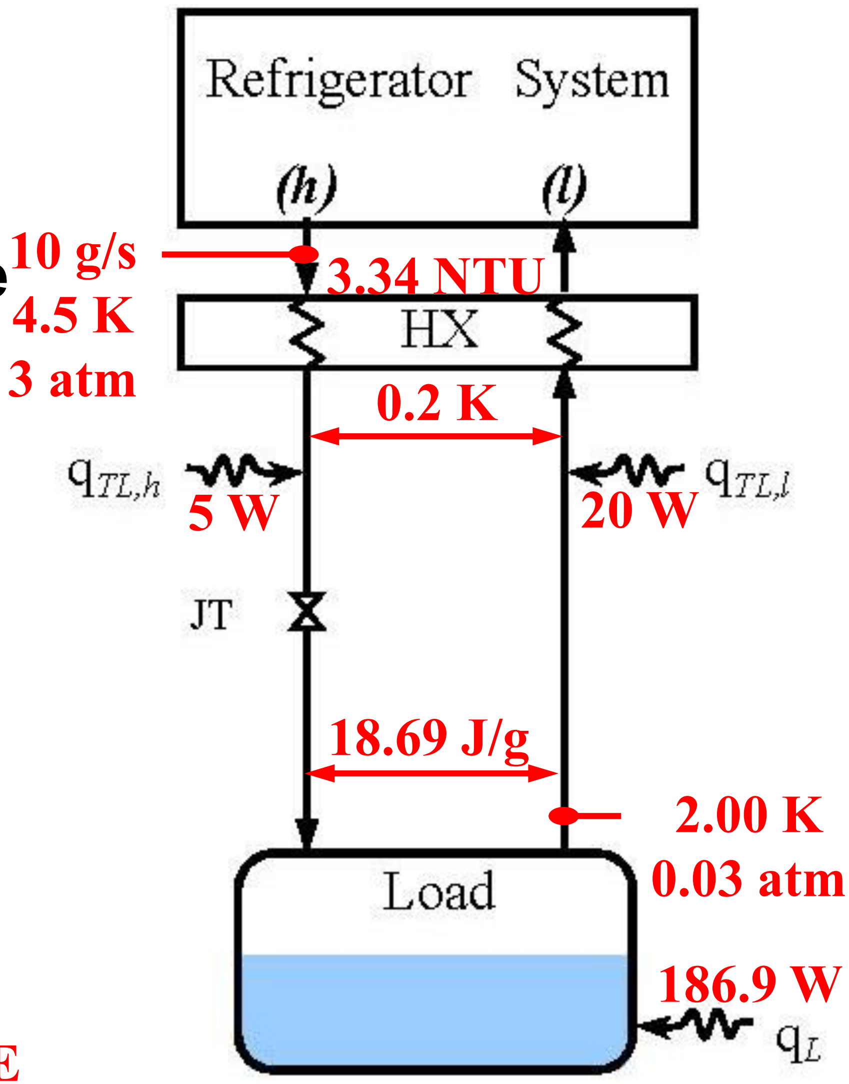
2-K Process Improvements (2)

- Why is heat exchange necessary?
  - —Latent heat at 0.03 atm is 23.41 J/g
  - —Without any HX, only ~12.71 J/g is supplied to the load
  - —For 10 g/s, 4.5 K and 3 atm supply from the refrigerator system, this is a load of 127.1 W



2-K Process Improvements (3)

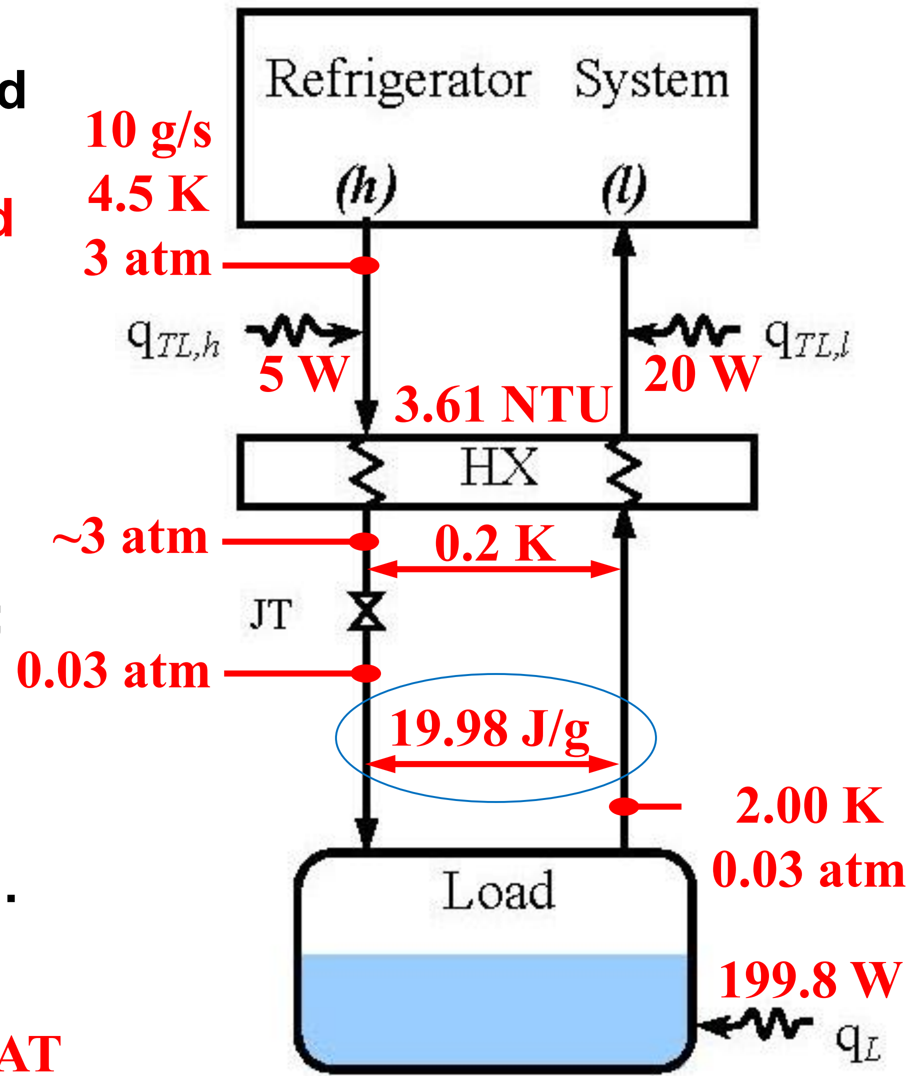
- JLab CEBAF design (1980's)
  - —By adding a HX, the load can be increase (by a factor of ~1.5) for the same refrigerator supply
  - —Typical HX cold-end (CE) stream temperature difference is 0.2 K; chosen for practical reasons:
    - Keep *(h)* stream leaving HX above lambda
    - Realistic HX design



NOTE: HX IS AT THE CCS
i.e. 2K RETURN TRANSFER LINE

2-K Process Improvements (4)…TODAY

- **SNS design (~2002)**
  - —By distributing the HX to the load (rather than centralizing it near the refrigerator system), the load can be increase above the early 'JLab design' by ~7% for the same refrigerator supply
    - Due to the transfer-line heat load (20 W in this example) being adsorbed at ~4 K level; instead of the 2 K level ,as is the case for the JLab design
  - —But, we are still throttling from 3 to 0.03 atm across the JT valve…

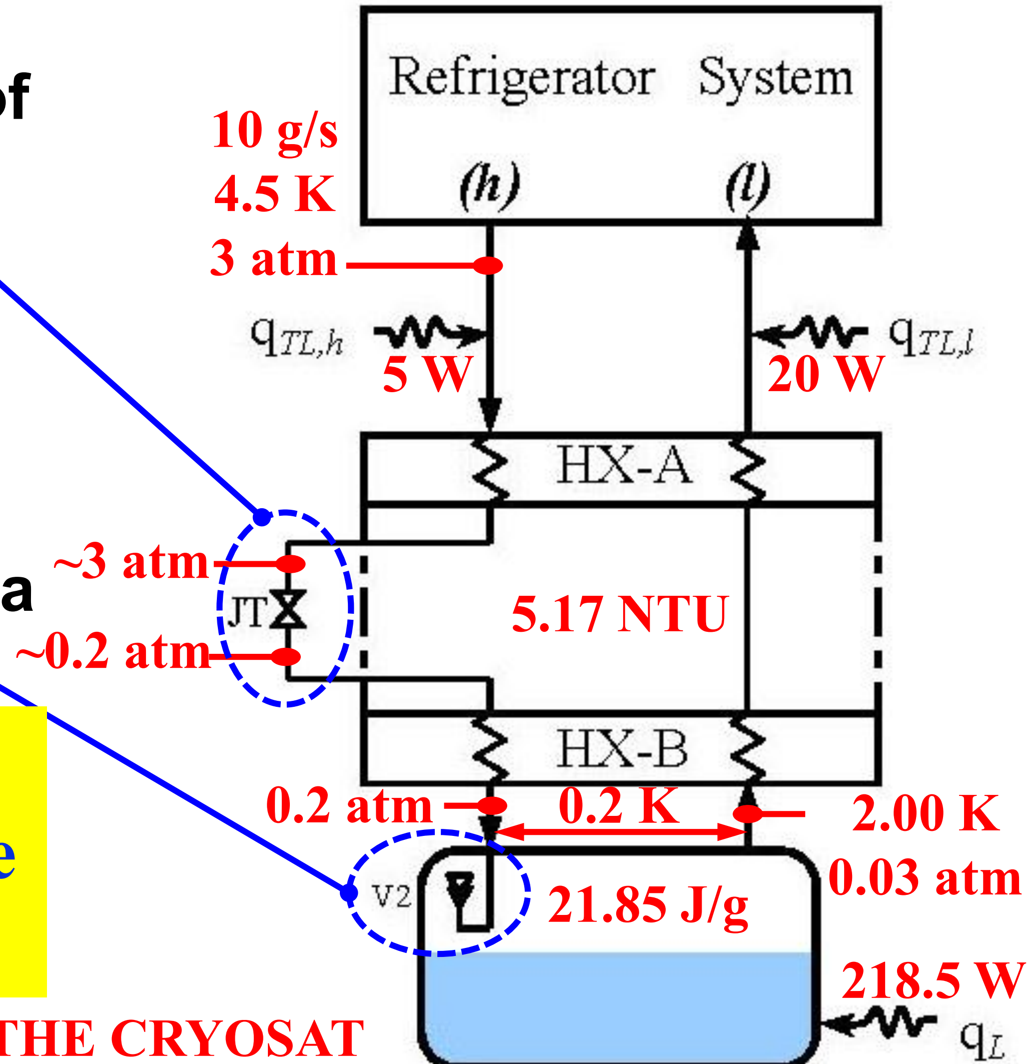


NOTE: HX & JT IS IN THE CRYOSAT

2-K Process Improvements (5), Very Soon?

- Incorporate JT valve in between two sections of the HX
- Also, incorporate a passive back-pressure device V2
  - —This can be a very simple device using a gravity weight

Another ~10% more refrigeration for the same wall plug power?



NOTE: HX & JT IS IN THE CRYOSAT

Test Unit at Jlab for FRIB

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Thank You for Your Kind Attention

May I Answer Your Questions ?

I gratefully acknowledge the contributions of the JLab cryogenic engineers, designers, technicians, and partner labs which made this technology possible