# HELIUM REFRIGERATION CONSIDERATIONS FOR CRYOMODULE DESIGN

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# Introduction

- ADS is presently based on SRF cavities operating at 2-K, which requires specialized helium refrigeration systems
  - They are cost intensive to produce and to operate.

- Some basic concepts and ideas for Cryomodule design to minimize the input power to the refrigeration system are discussed here

# Issues for Thought

- Cost of Energy
  - Could ignore inefficiencies in the past, but not anymore!
- Accumulation of system inefficiencies, due to,
  - Scaling up of the systems
    - A culture of duplication and scaling
      - (i.e., *‘give me another one of those but larger’*)
    - Inefficiencies of the earlier designs were scaled too!
  - Sub-systems mismatch
    - Boundaries between the sub systems
      - CM, Distribution, Refrigeration system
    - What are the correct shield temperatures and their match to the refrigerator design
  - Lack of component development for 2K applications
    - Connection designs between the sub systems; e.g., bayonets & valves
    - Efficient sub-atmospheric compression systems

# Outline

- Performance definitions
- “Quality” of energy
- Thermal shields & intercepts
- Helium properties below 4.5-K
- 2-K Refrigeration process
- 2-K Process improvements
- Cryomodule design
- Cryomodule production
- JLab helium distribution system
- SNS helium distribution system
- Generalized distribution system
- Conclusions

# Performance Definitions

- (Physical) exergy per unit mass is defined as,

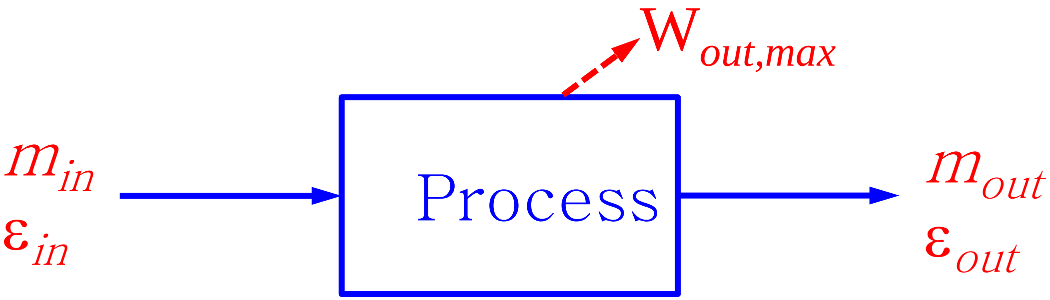
  $\varepsilon = h - T_0 \cdot s$

  - where, $T_0$ is the reference temperature; i.e., environmental temperature; say, 300 K
  - exergy ($\varepsilon$) is an intrinsic fluid property (…like *h* and *s*)

- The minimum input power theoretically required; or conversely, the maximum power output theoretically possible is,

  $\Delta E = W_{out,max} = -W_{in,min} = \Sigma\, m_{in} \cdot \varepsilon_{in} - \Sigma\, m_{out} \cdot \varepsilon_{out}$

  - also, known as the reverible (input or output) power



# Performance Definitions

- ***Exegetic efficiency*:**

  $\eta_C = \Delta E / W_{in}$

  **Where, $W_{in}$ is the actual (real) required input power**

- **A measure of process performance is the ratio of the input power required (either ideal or real) to the cooling provided [Watts / Watt];**
  - ***This is known as the inverse coefficient of performance***

**Ideal (theoretical),** $COP_{inv,i} = \Delta E / q_L$

**Real,** $COP_{inv,r} = W_{in} / q_L$

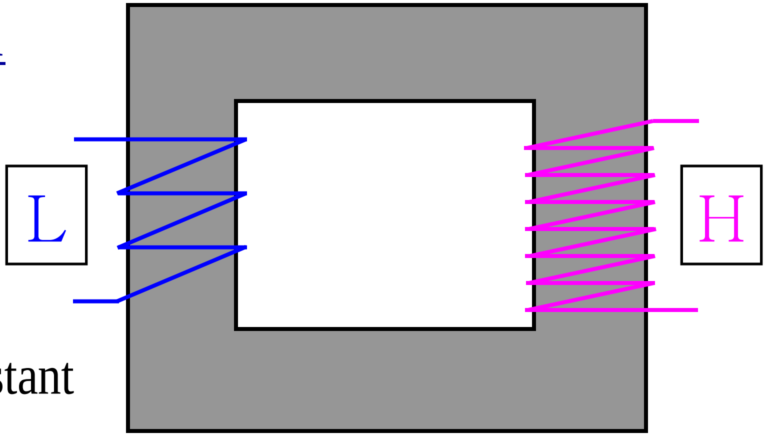
**Where, $q_L$ is the cooling (load) provided**

# Quality of Energy

## Ideal Electrical Transformer

$$\frac{V_H}{V_L} = \frac{I_L}{I_H}$$

$$P = V_H \cdot I_H = V_L \cdot I_L = \text{constant}$$



## Ideal 'Thermal' Transformer

$$\frac{T_H}{T_L} = \frac{Q_H}{Q_L}$$

$$S = \frac{Q_H}{T_H} = \frac{Q_L}{T_L} = \text{constant}$$

- **A thermal transformer that permits the heat energy transfer from cold temperature to hot temperature, with no input work *does not exist*.**

- **This 'transmission' (or transfer) limitation of heat energy between temperatures implies that there is a *'quality'* for *heat energy*.**

- **The *source* *and* *sink* temperatures sets this limit on the conversion *'quality'* *for the* *heat energy*.**

# Quality of Energy (Cont.)

## Clausius (In)equality (the 2nd Law of Thermodynamics)

$$\frac{Q_L}{T_L} = \frac{Q_H}{T_H}$$

*This equation is a statement of*

*thermal energy quality equivalence*

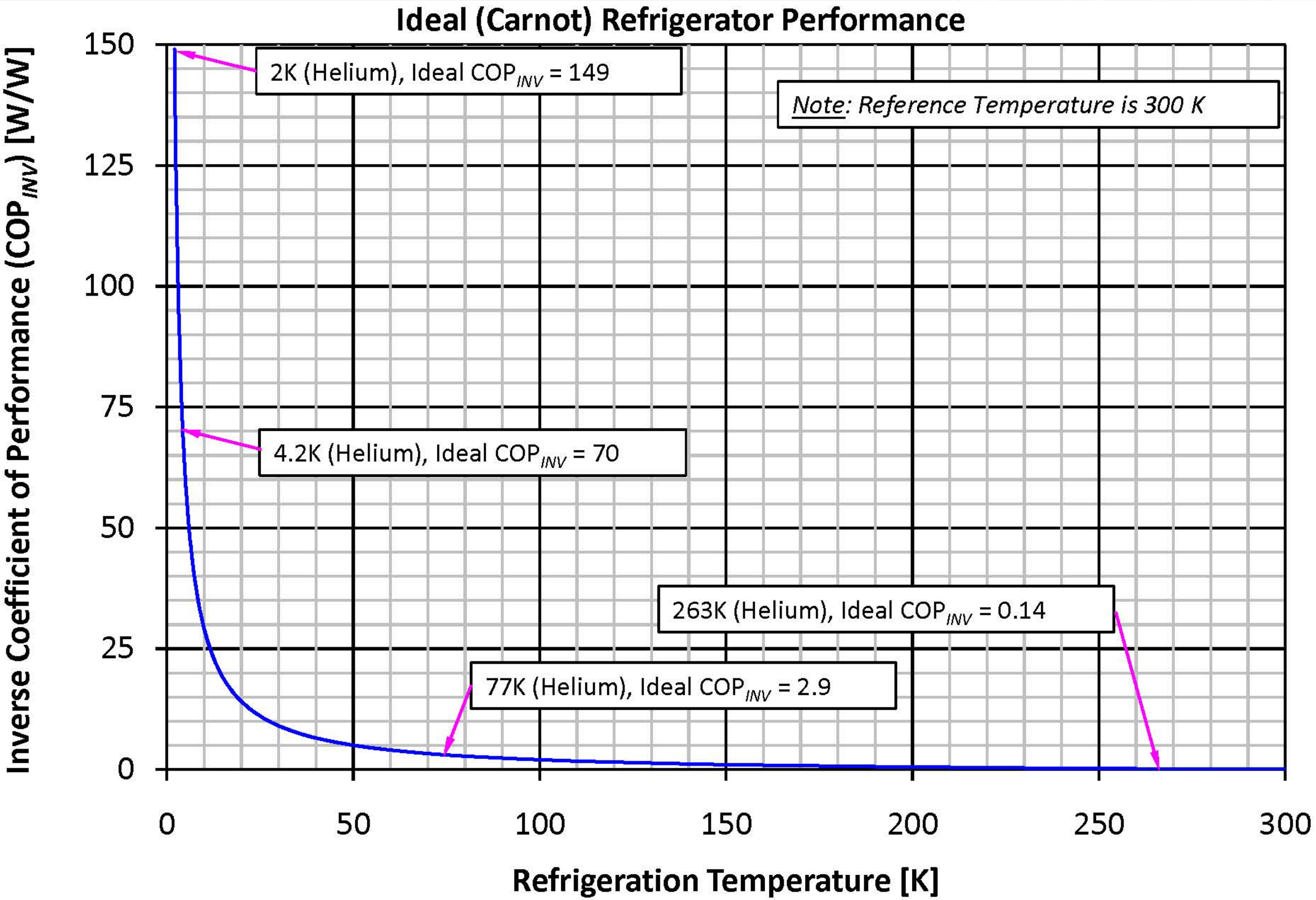
For example, $$\frac{300W}{300K} = \frac{4W}{4K} = \frac{2W}{2K}$$

Or, $Q_L$ = 1W at $T_L$ = 4.22 K is *equivalent in quality* as

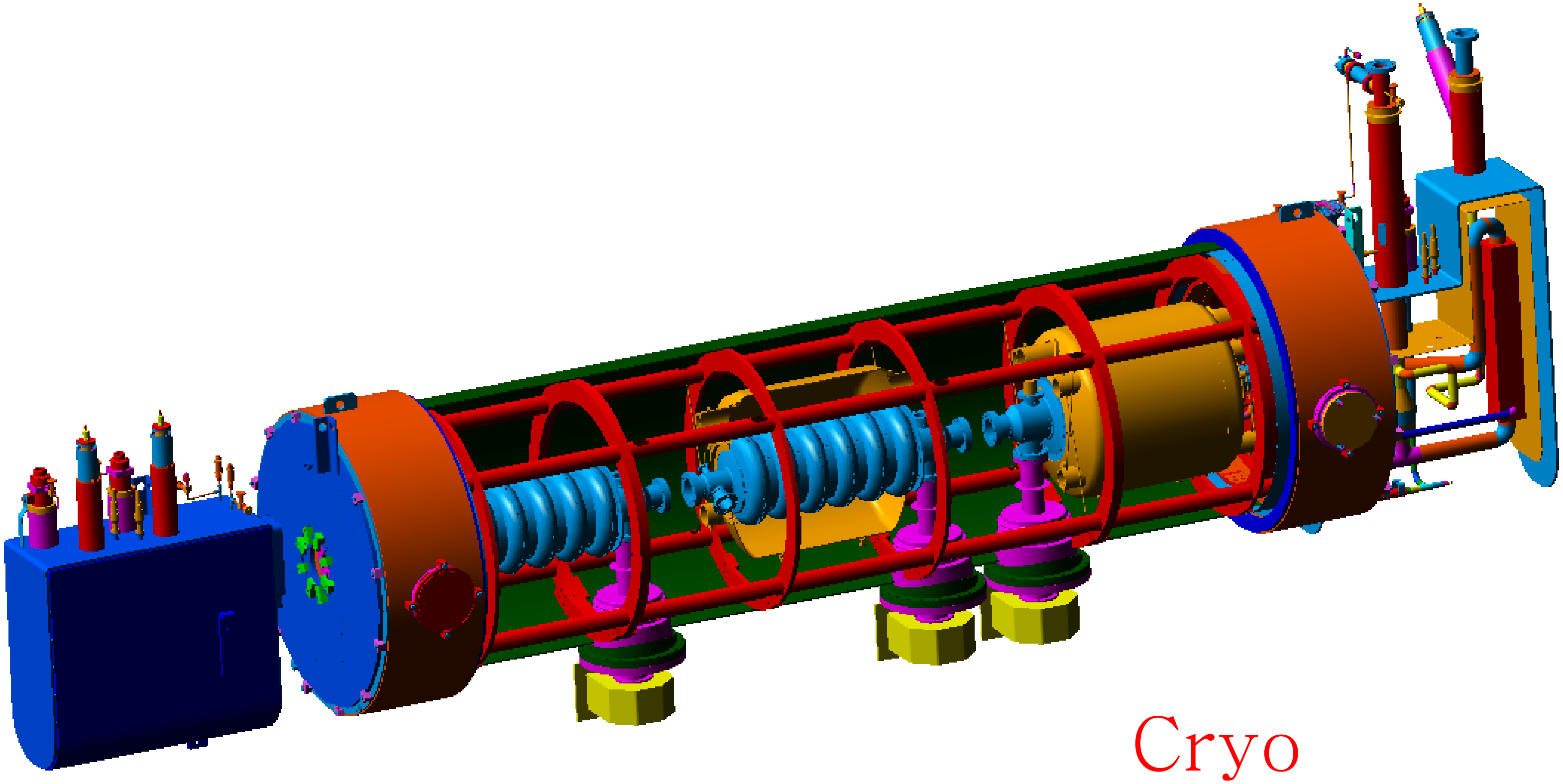
$Q_H$ = 70 W at $T_H$ = 300K

*So, the heat leak into a 2K transfer−line is 'worth' (equivalent to) over 2 times the heat leak into a 4.5K transfer−line!*

# Quality of Energy (Cont.)



# Cryomodule



Cryo
Module

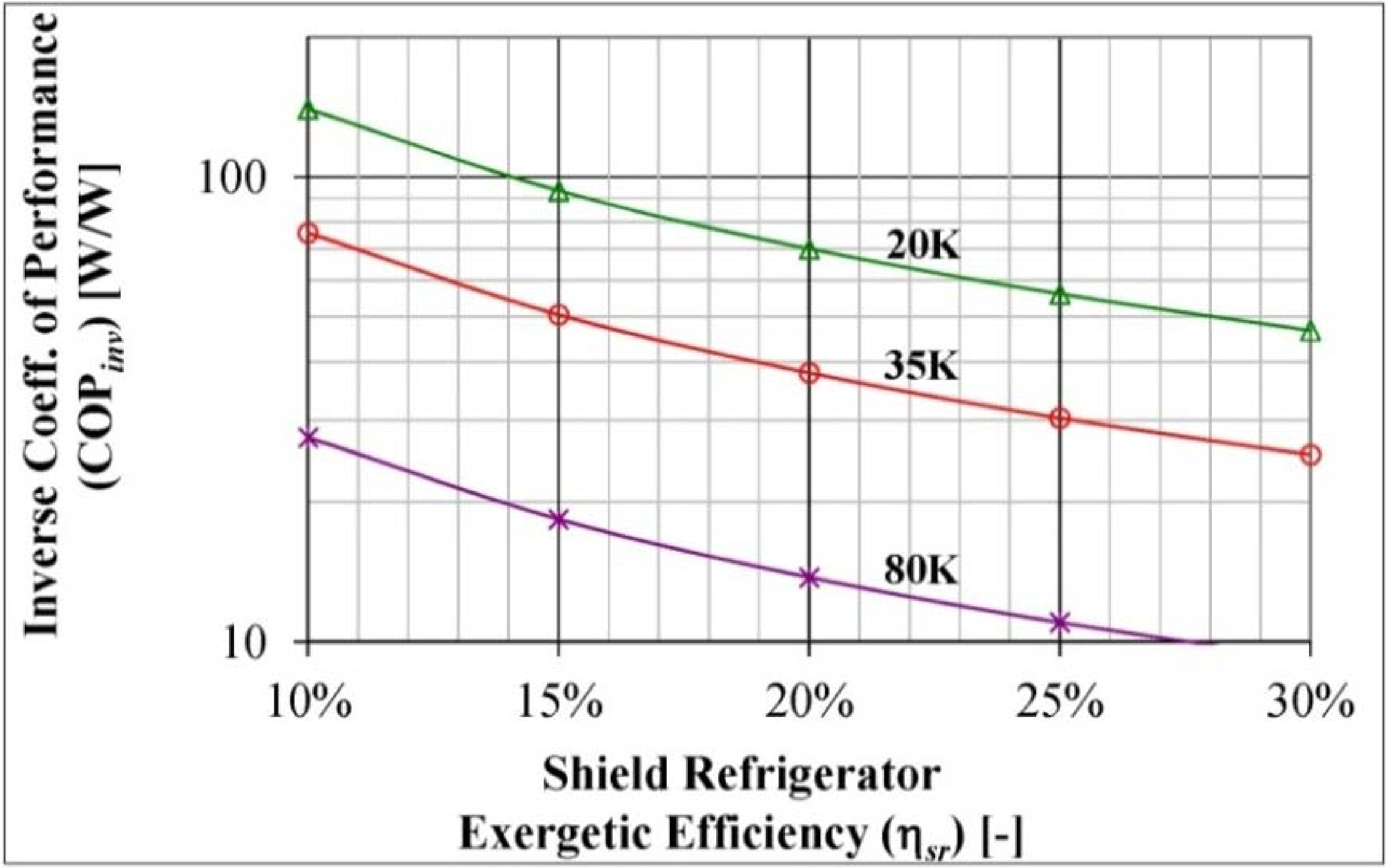
# Thermal Shields & Intercepts

- Radiation shields are used to reduce the static heat input to the load and supply to the load
  - LN is used where possible
- Ideal shield temperatures depends on
  - Amount of MLI (# layers, residual gas pressure, layer density, installation practices!)
  - Conduction path (material, ratio of cross-sectional area to length)
  - Exergetic efficiency of refrigeration at a given shield temperature
  - Number of shields
  - Load (coldest) temperature
- For single shields, it is,

  ~40K for 4.5-K loads

  ~20K for 2-K loads; $COP_{inv,2K} \approx (0.67)\cdot COP_{inv,4.5\text{-}K}$
  - Note: if $COP_{inv,2K} \approx COP_{inv,4.5\text{-}K}$, then it would be ~30K for 2-K loads

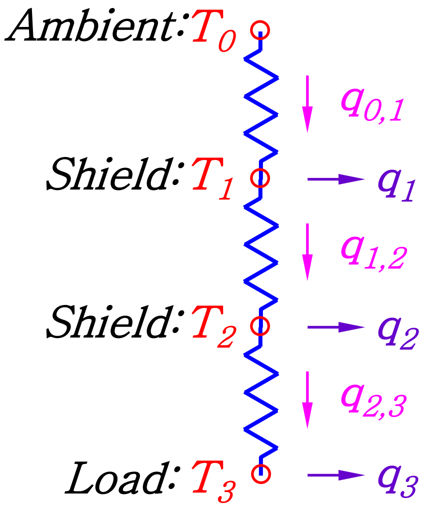
# Thermal Shields & Intercepts



**Shield Refigerator Performance**

# Thermal Shields & Intercepts

- **Optimum shield temperatures can be determined using empirical and analytical modeling**



*Nomenclature*:

| | |
|---|---|
| $q_{i,i+1} = R(T_i, T_{i+1}) \cdot \{f(T_i) - f(T_{i+1})\}$ | *Heat transfer from node 'i' to 'i+1'* |
| $R_{i,i+1}(T_i, T_{i+1})$ | *Thermal resistance between node 'i' and* |
| $f(T_i)$ | *Function of temperature* $T_i$ |
| $q_i = q_{i-1,i} - q_{i,i+1}$ | *Heat load at temperature* $T_i$ |
| $W_i = q_i \cdot \beta_i / \eta_i$ | *Refrigeration power required for* $q_i$ |
| $\beta_i = (T_0 - T_i) / T_i$ | *Ideal inverse coefficient of performance* |
| $\eta_i$ | *Refrigeration exergetic efficiency* |

$$\text{Minimize, } W_{tot}(T_1, T_2, \cdots, T_{N-1}) = \Sigma W_i$$

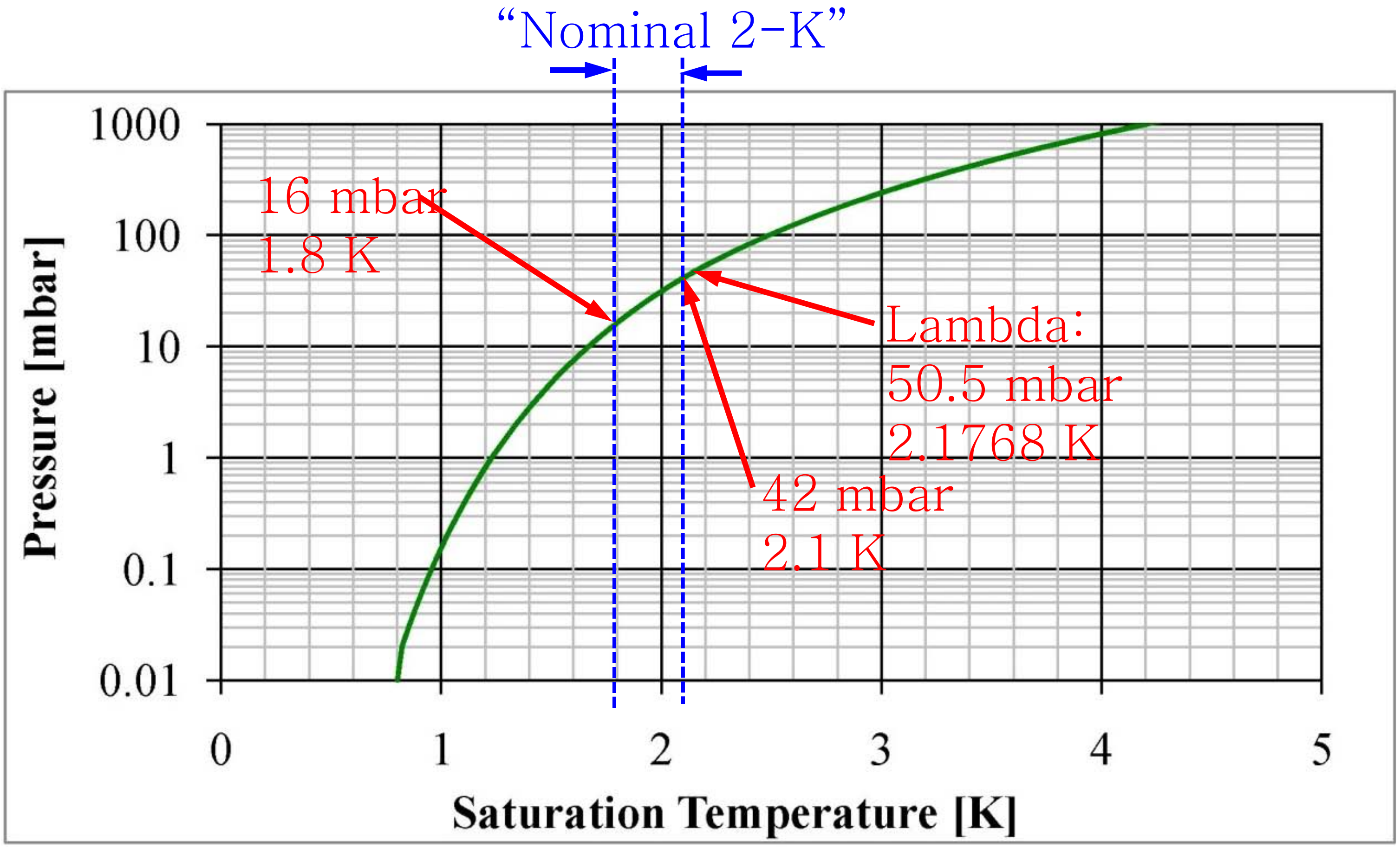
*Note*:

*For conduction:* $R_{i,i+1} = A_c / L$, $f(T_i) = K(T_i) = \int k(T) \cdot dT$

*For MLI: Spacer,* $f(T_i) \sim T_i$*; Radiation,* $f(T_i) \sim T_i^4$*; Gas Conduction (*$N_2$ *residual gas),* $f(T_i) \sim T_i^{1/2}$

*(Ref. C.W. Keller, G.R. Cunnington, A.P. Glassford, "Final Report – Thermal Performance of Multilayer Insulations, NASA CR-134477, April 1974)*

# Helium Properties: Saturation P vs. T



"Nominal 2-K"

16 mbar
1.8 K

Lambda:
50.5 mbar
2.1768 K

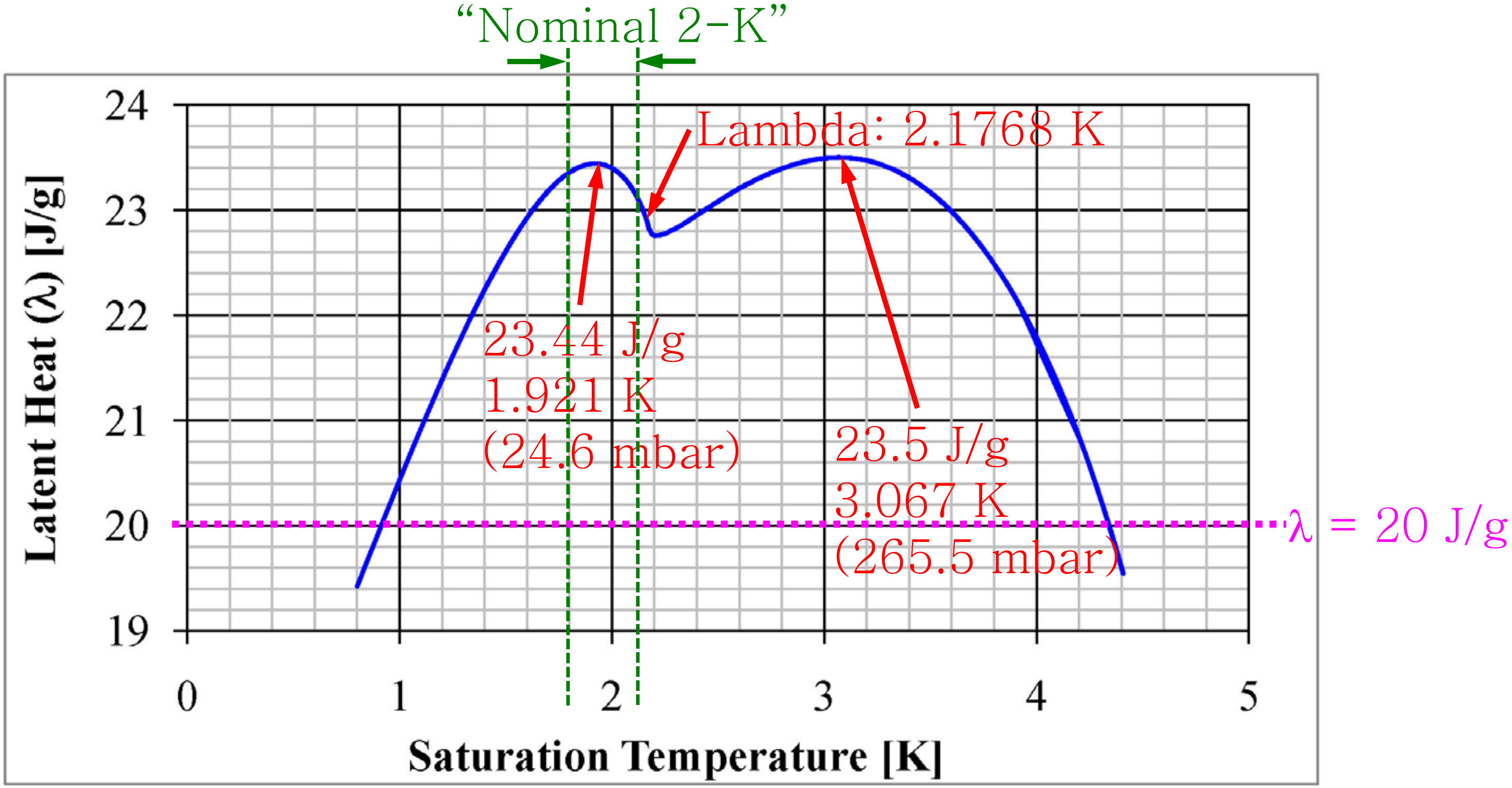
42 mbar
2.1 K

*<u>Note</u>: logarithmic scale for pressure; also, vapor density behavior is similar.*

*This has a dramatic effect on equipment size (to process the sub-atm flow)!*

# Helium Prop: Latent Heat of Vaporization

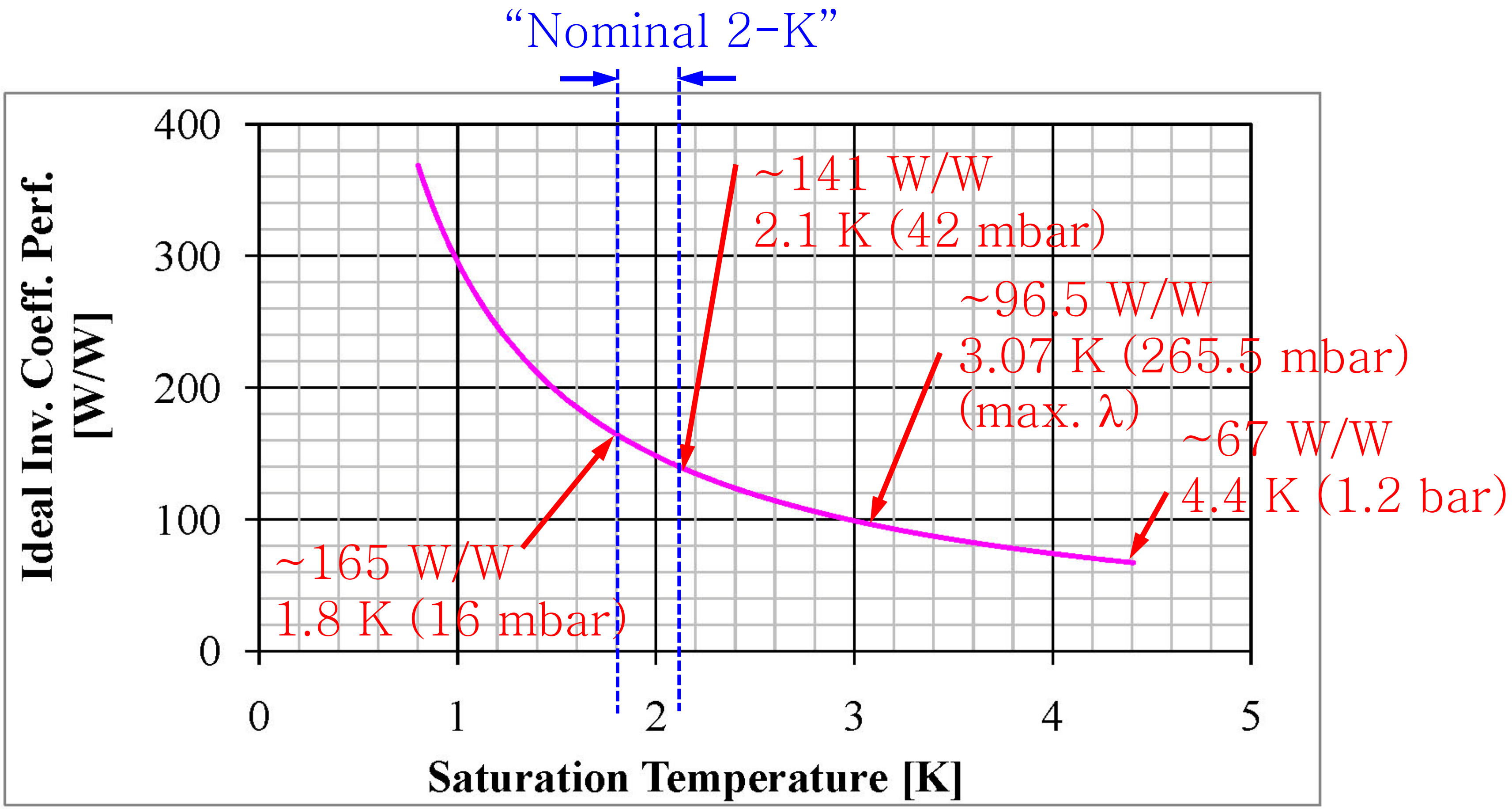
- To date we accept **λ ≈ 20 J/g** as the useful latent heat for most of the super-conducting applications; ***this leaves behind up to ~17% of un-utilized latent heat potential!***



# 2-K Refrigeration Process

- Refrigeration below 4.5-K typically involves sub-atmospheric helium at some point in the process
  - Typically, $COP_{inv,2\text{-}K} \approx (0.67) \cdot COP_{inv,4.5\text{-}K}$
  - i.e., 1 watt (of refrigeration) at 2-K = 3 watts at 4.5K
- 2-K refrigeration processes typically,
  - Use a 4.5-K refrigerator
  - Do not produce additional refrigeration (i.e., involve expansion work) below 4.5-K
- Since processes used for large accelerators operate at 1.8 to 2.1 K (i.e., 16 to 42 mbar), will refer to these as nominal 2-K systems

# 2-K Refrigeration Process



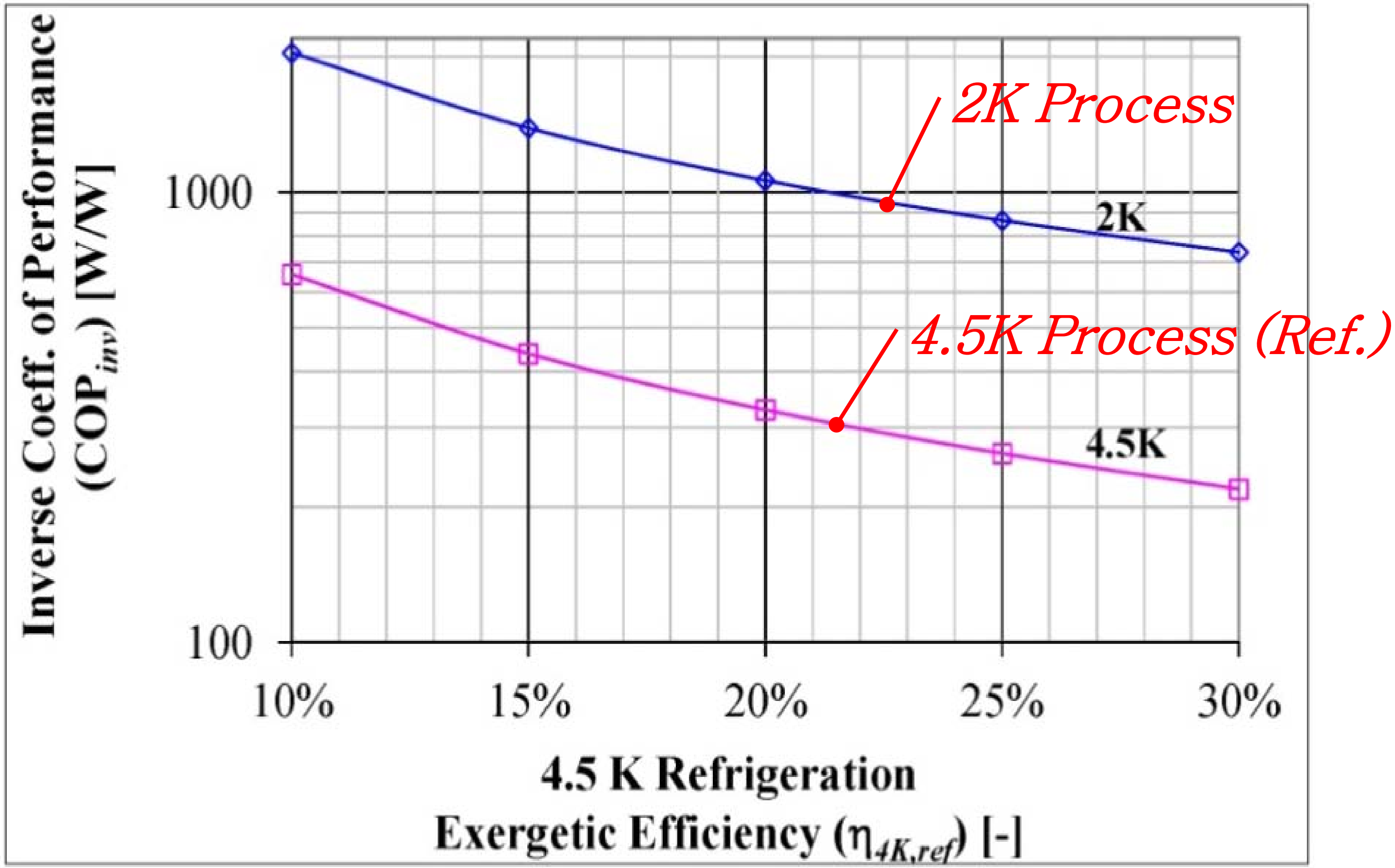
*Ideal inverse coefficient of performance for isothermal refrigeration below 4.5-K*

# 2-K Refrigeration Process

- **Lowering the load temperature is expensive, as well as, increases the equipment sizes!**
  - **Compared to a 4.4 K (1.2 atm) load (which is at positive pressure), the factor increase in *ideal* input power for the same load, $(COP_{inv,i})_{ratio}$, and vapor density ratio, $\rho_{ratio}$ (as compared to 1.2 atm), is**

| | T [K] | p [mbar] | $(COP_{inv,i})_{ratio}$ | $\rho_{ratio}$ |
|---|---|---|---|---|
| Reference ▶ | 4.4 | 1200 | 1.0 | 1.0 |
| | 3.07 | 266 | 1.4 | 4.1 |
| | 2.1 | 42 | 2.1 | 20 |
| | 1.8 | 16 | 2.5 | 45 |

# 2-K Refrigeration Process



*2K Process*

*4.5K Process (Ref.)*

*Note*: $COP_{inv,2-K} \approx (0.67) \cdot COP_{inv,4.5-K}$

Real Inverse Coefficient of Performance vs.
4.5 K Refrigerator Exergetic Efficiency

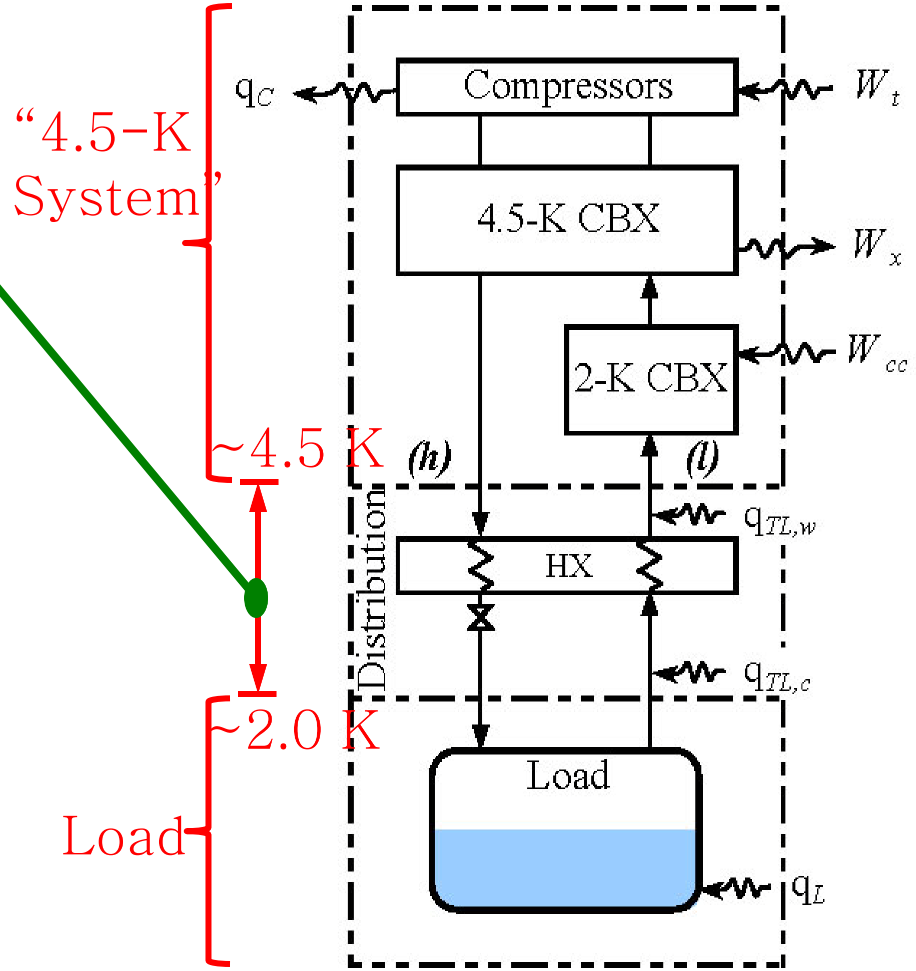
# 2-K Refrigeration Process

## *Basic 2-K Helium Process*

- **Since there is typically no work extraction between the 4.5-K refrigerator and 2-K load…**
- ***Question: can the 2-K load capacity be increased by any process changes in between these temperature levels?***

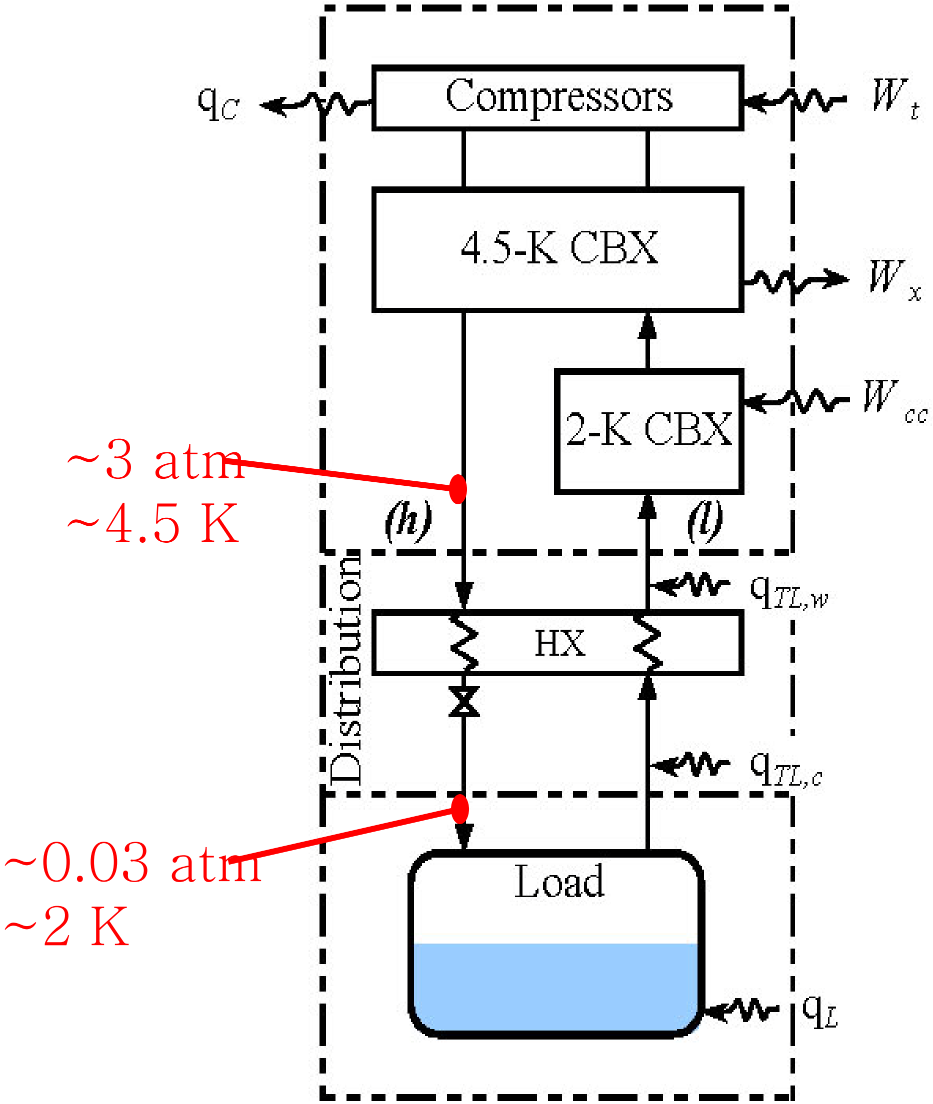
*Nomenclature:*

| | |
|---|---|
| 4.5-K CBX | *4.5-K Cold box* |
| 2-K CBX | *2-K Cold box* |
| HX | *Nominal 4.5 to 2 K heat exchanger* |
| $q_C$ | *Compressor heat removed* |
| $W_t$ | *Compressor input power* |
| $W_x$ | *Expander output power* |
| $W_{cc}$ | *Cold compressor input power* |
| $q_{TL,w}$ | *Warm-end distribution heat in-leak* |
| $q_{TL,c}$ | *Cold-end distribution heat in-leak* |
| $q_L$ | *Load heat input* |



# 2-K Process Improvements

- **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 ?)…***



~3 atm
~4.5 K

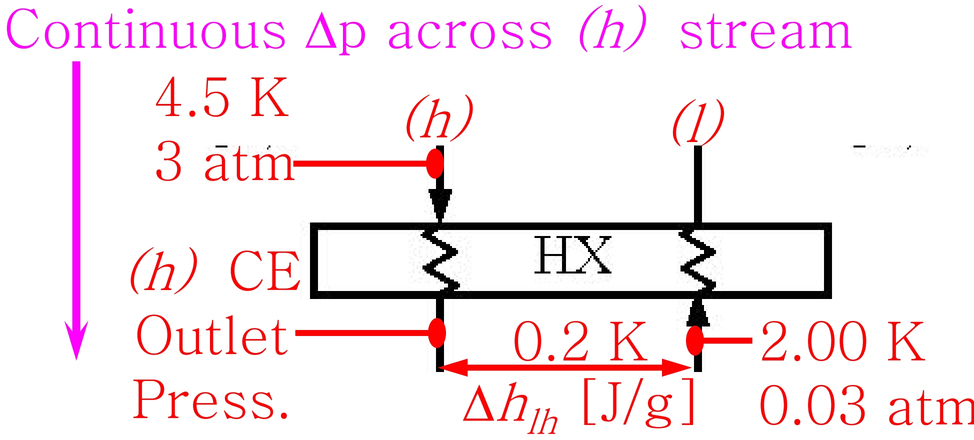
~0.03 atm
~2 K

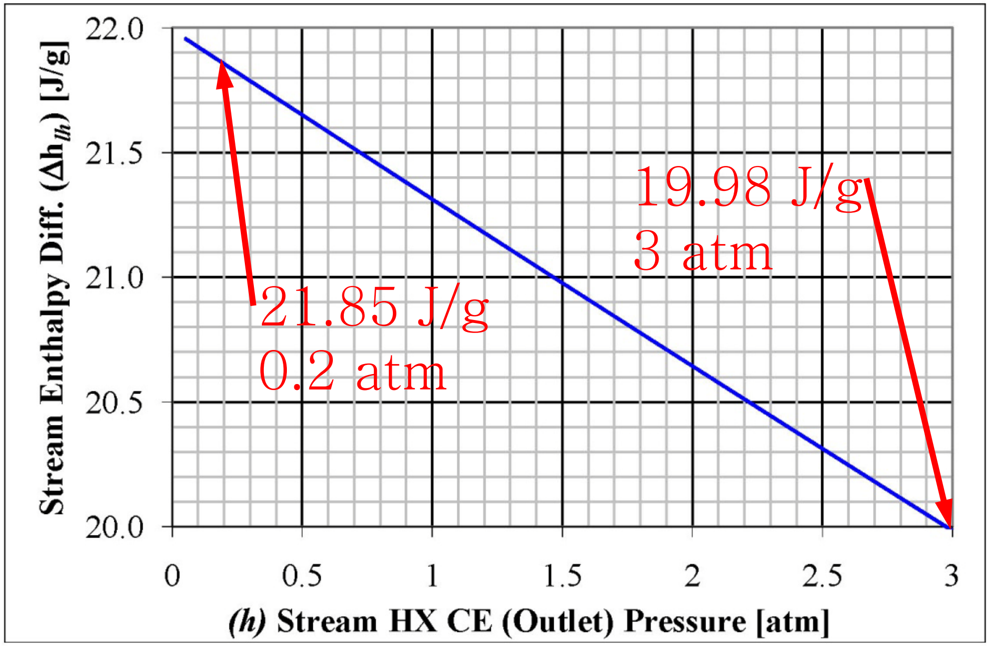
# 2-K Process Improvements

- **This suggests a constructive use of the *(h)* stream pressure drop through the HX, rather than across the JT valve**

- **Figure shows the enthalpy flux at the HX cold (load) end temperature difference of 0.2 K**

- **<u>Note</u>: use 0.2 K to provide sufficient stream temperature difference for heat transfer and to avoid super-fluid in HX**

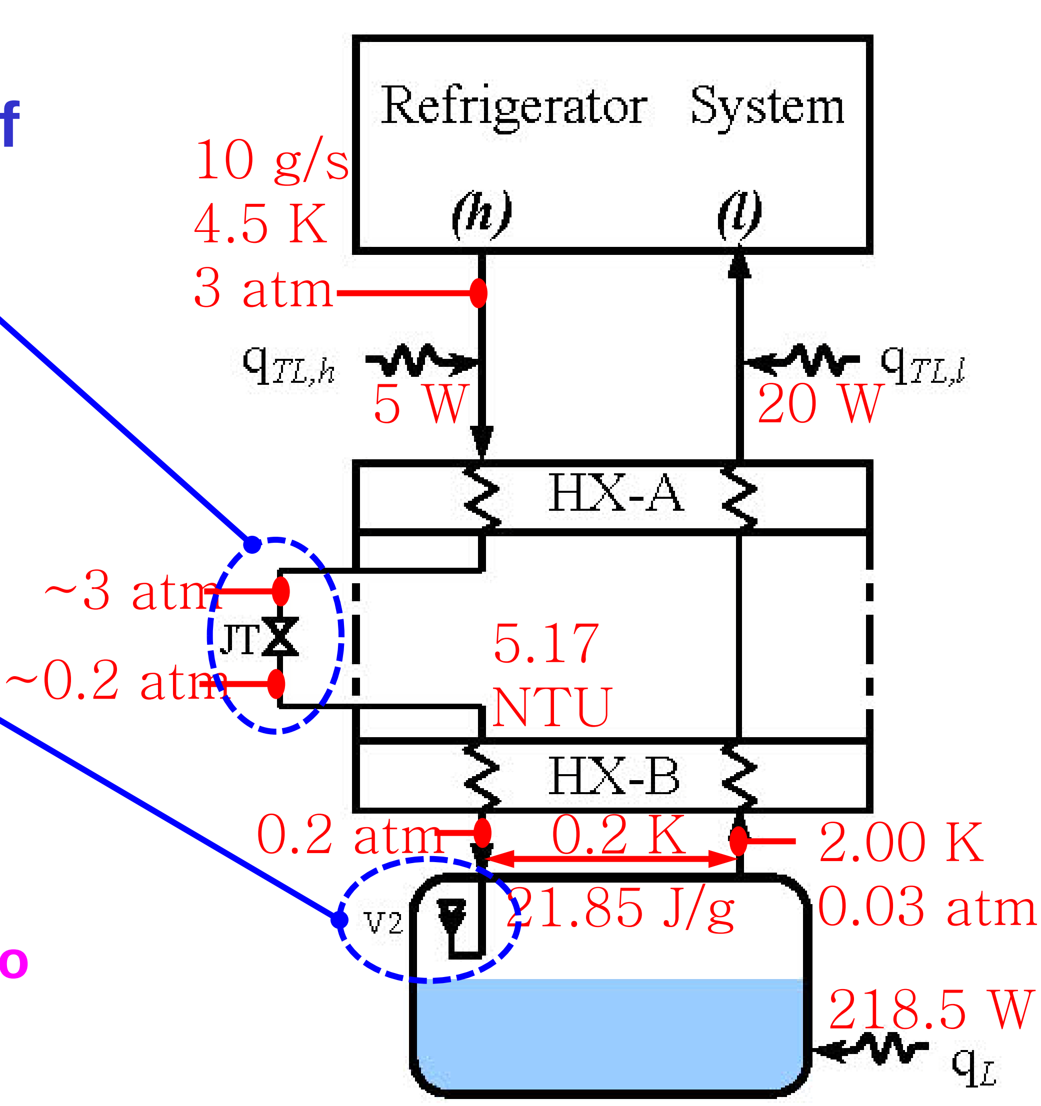




# 2-K Process Improvements

- **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**

- **Note: Incorporation of these does NOT diminish the performance (as compared to the continuous pressure drop through the HX)**



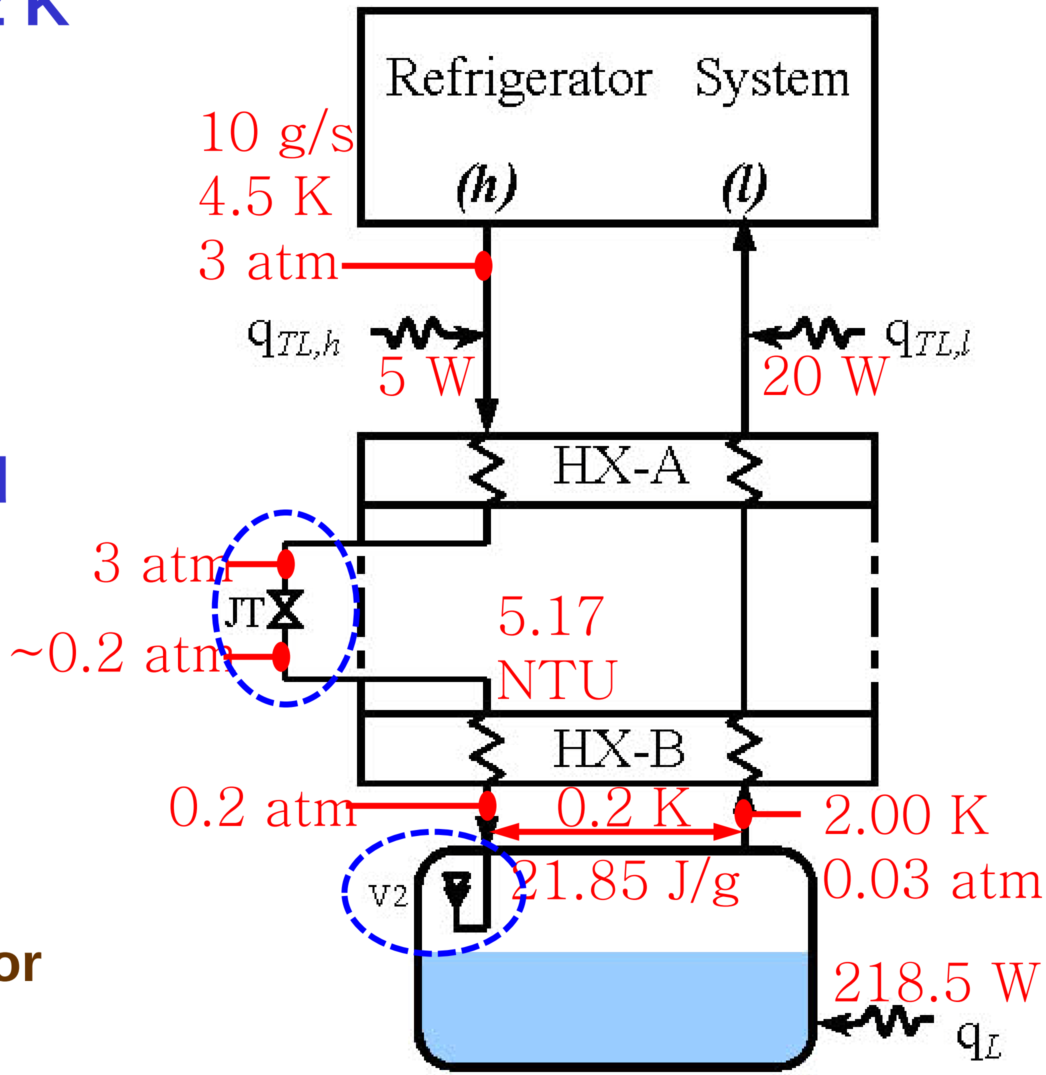
# 2-K Process Improvements

- **Saturation pressure at 2.2 K is 0.0514 atm**
  - **So, why not 0.0514 atm, instead of 0.2 atm…?**
- **Because the required HX size (which is quantified using NTU's or UA) would be too large**

  **NTU or (UA)►∞,** as the *pressure* ► **0.0514 atm**
- ***Note*:**

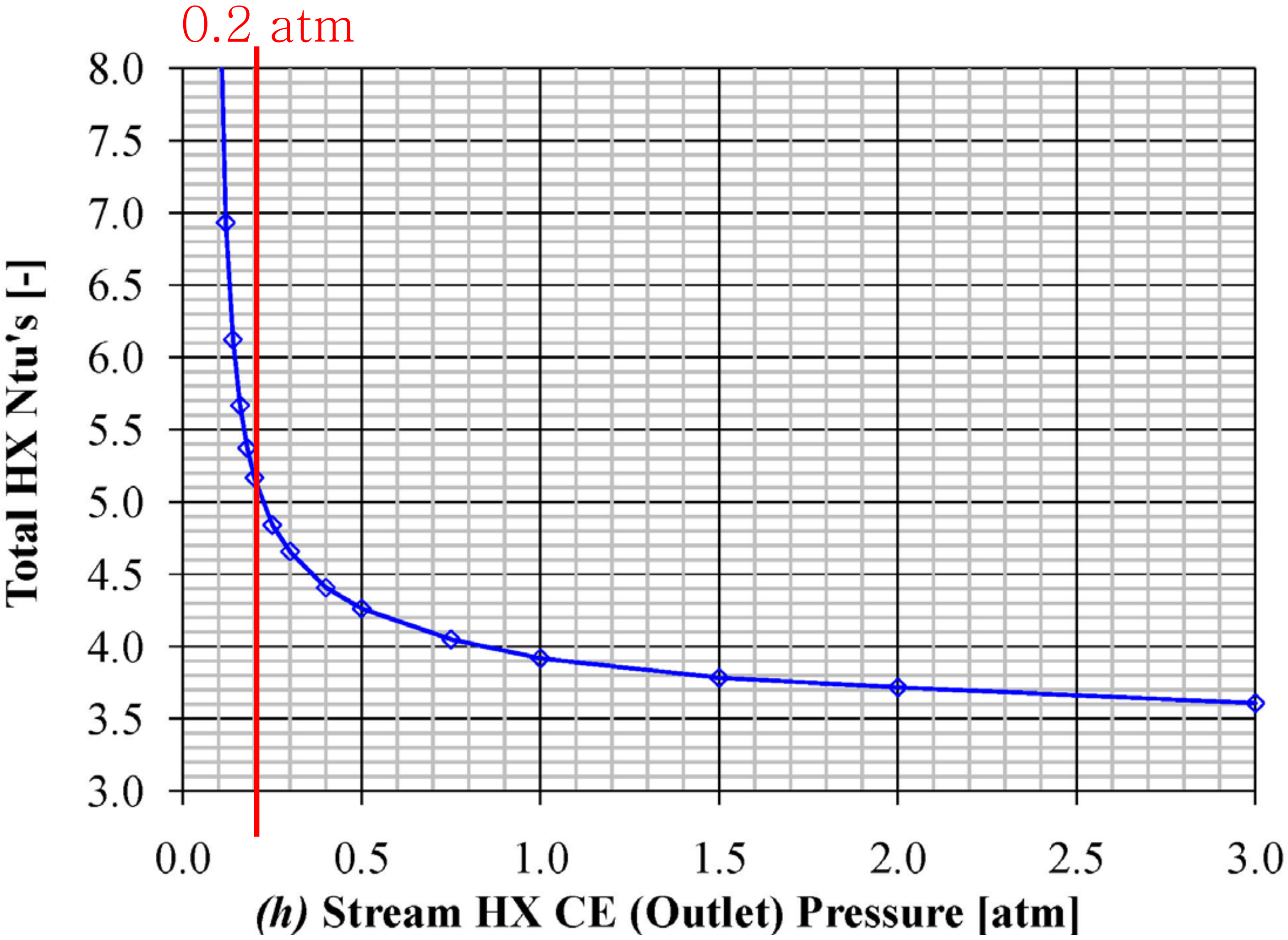
  **NTU ~ HX length**

  **(UA) ~ HX flow cross-section or total volume**



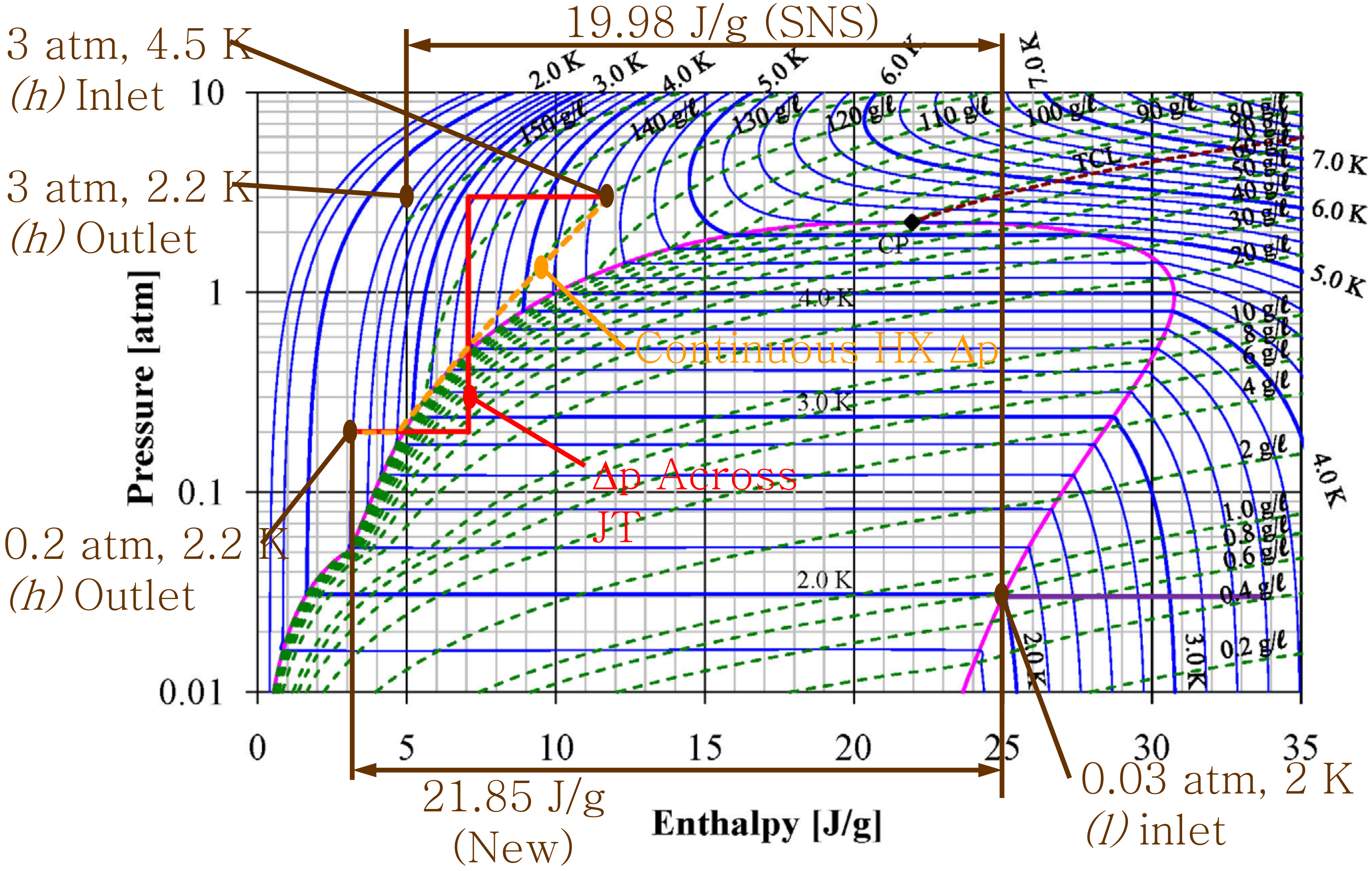
# 2-K Process Improvements

- **HX total NTU's vs. *(h)* stream HX CE (outlet) pressure**



# 2-K Process Improvements

- **Why does a $\Delta p$ in the *(h)* stream increase the $\Delta h_{lh}$ ?**



19.98 J/g (SNS)

3 atm, 4.5 K
*(h)* Inlet

3 atm, 2.2 K
*(h)* Outlet

Continuous HX $\Delta p$

$\Delta p$ Across JT

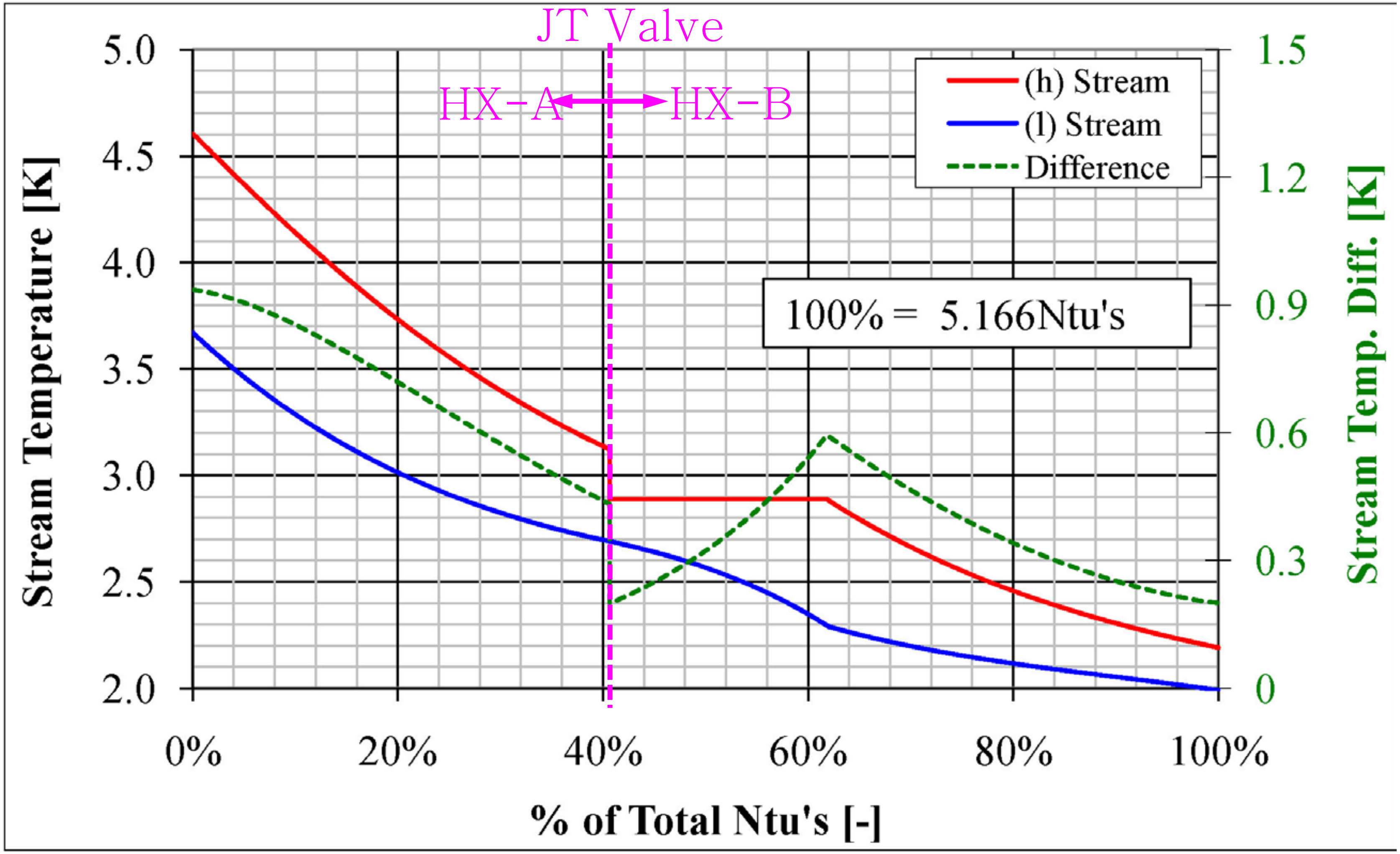
0.2 atm, 2.2 K
*(h)* Outlet

21.85 J/g
(New)

0.03 atm, 2 K
*(l)* inlet

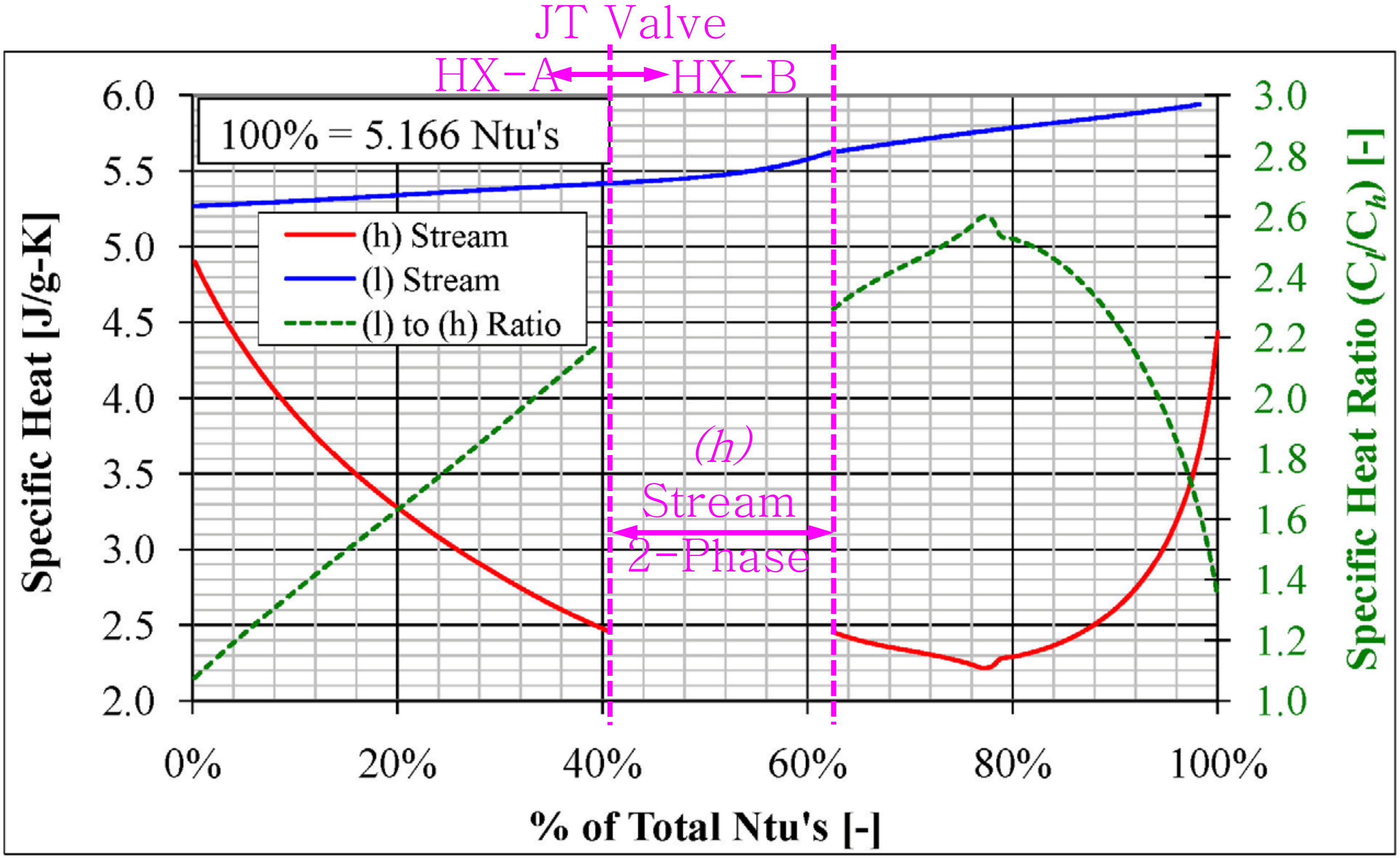
# 2-K Process Improvements

- **Cooling curve for HX (i.e., HX-A and HX-B)**



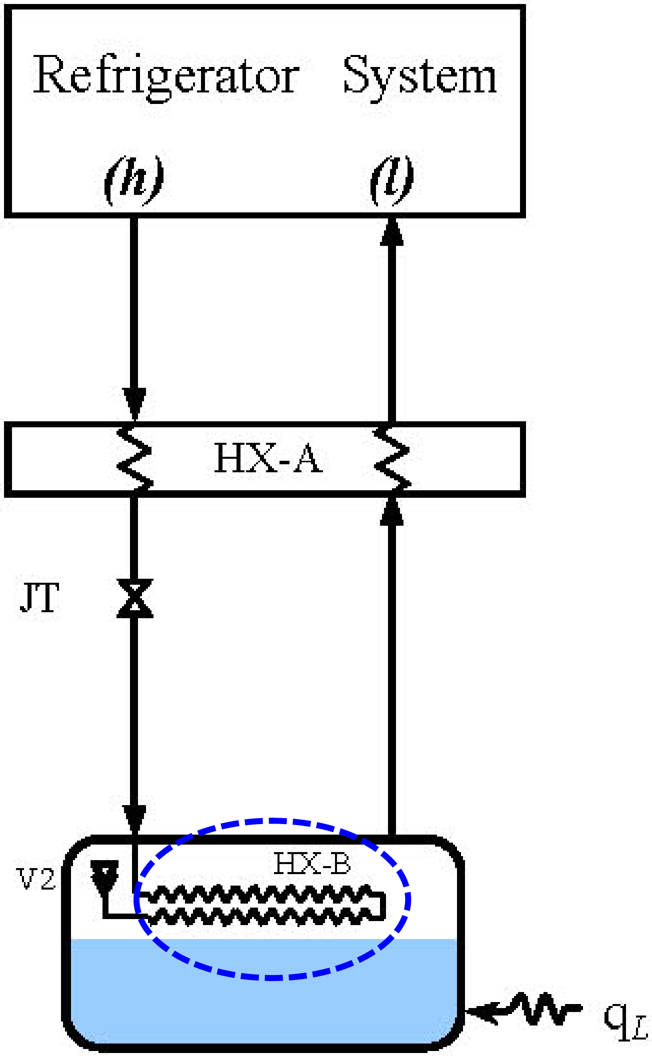
# 2-K Process Improvements

- **Average $C_{p,h}$ , $C_{p,l}$ and $(C_{p,l} / C_{p,h})$**



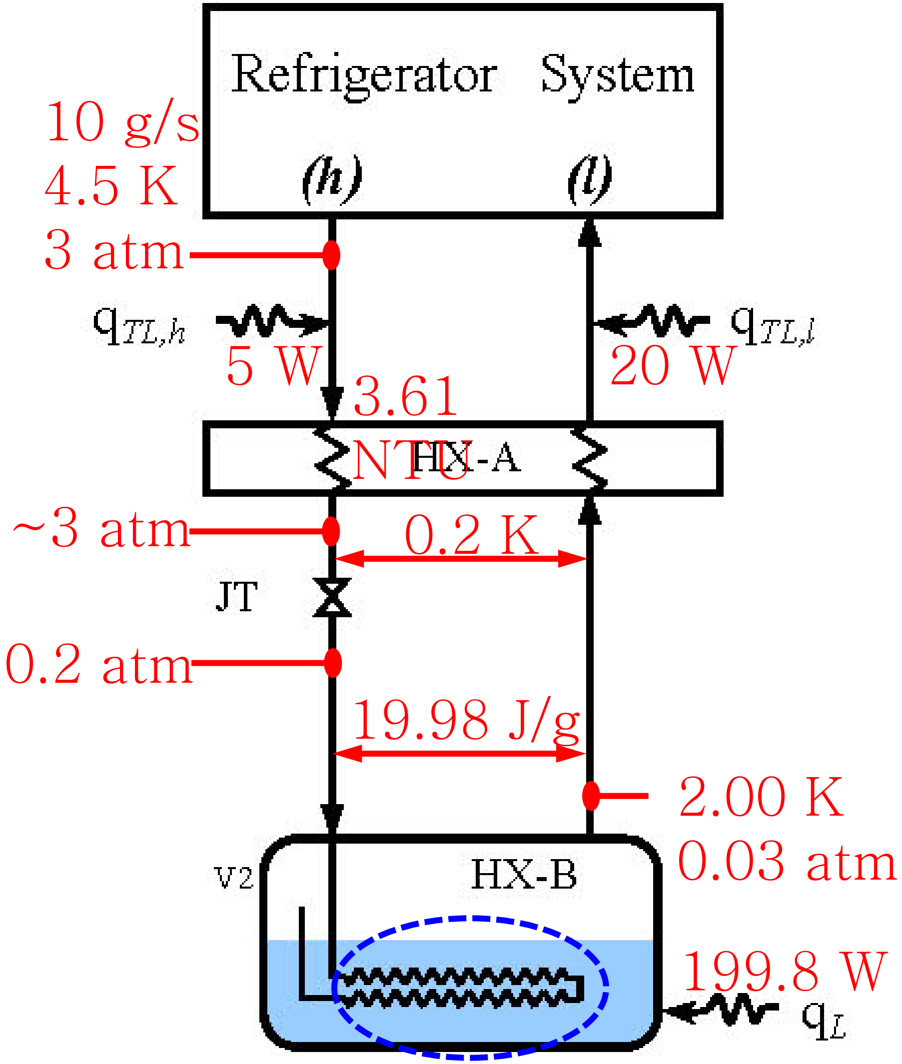
# 2-K Process Improvements

- A slight variation that may prove to be more practical in some configurations
  - Move HX-B (lower HX section) into load, where the *vapor* cools the *(h)* stream
  - Note: Since this is “cross-flow” heat exchange (as opposed to “counter-flow”) we are taking advantage of the difference in the specific heat between the *(h)* stream and the *(l)* vapor



# 2-K Process Improvements

- It is important to note that if HX-B is immersed into (2-K) ***liquid bath***, that this configuration becomes the same as the ‘SNS Design’
  - **HX-B duty goes into the liquid, so it is now part of the load!**



# 2-K Process Improvements

Present development work

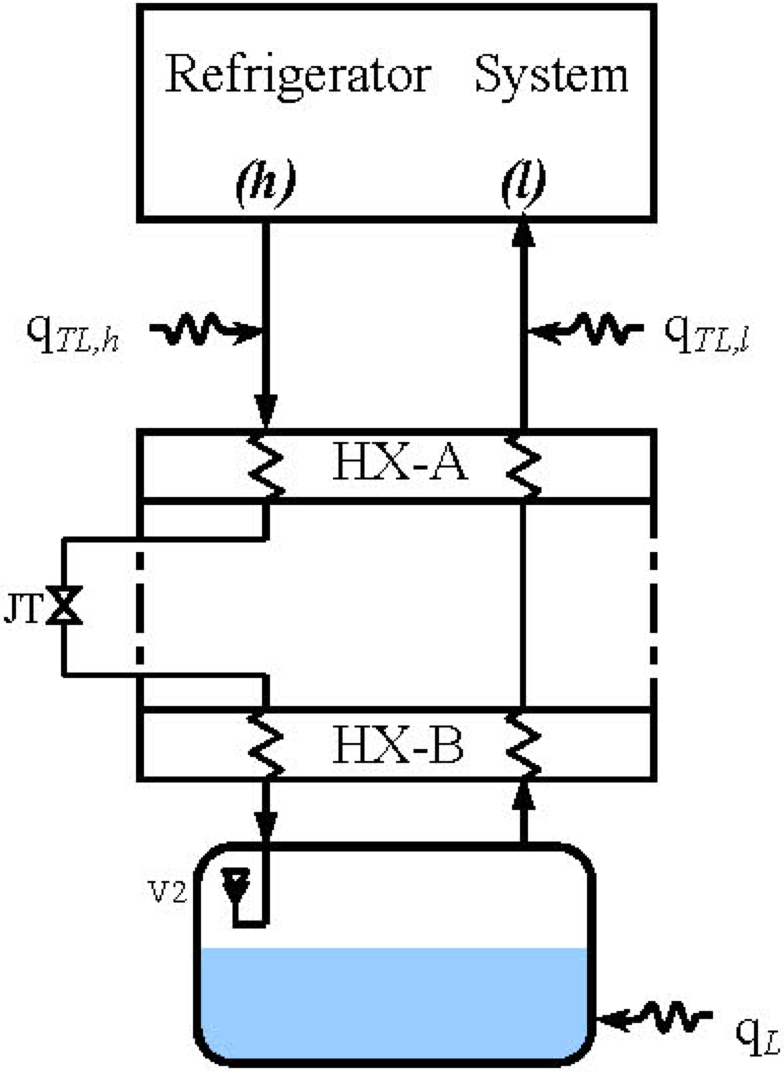
**A prototype HX**

**of ~5 g/s**

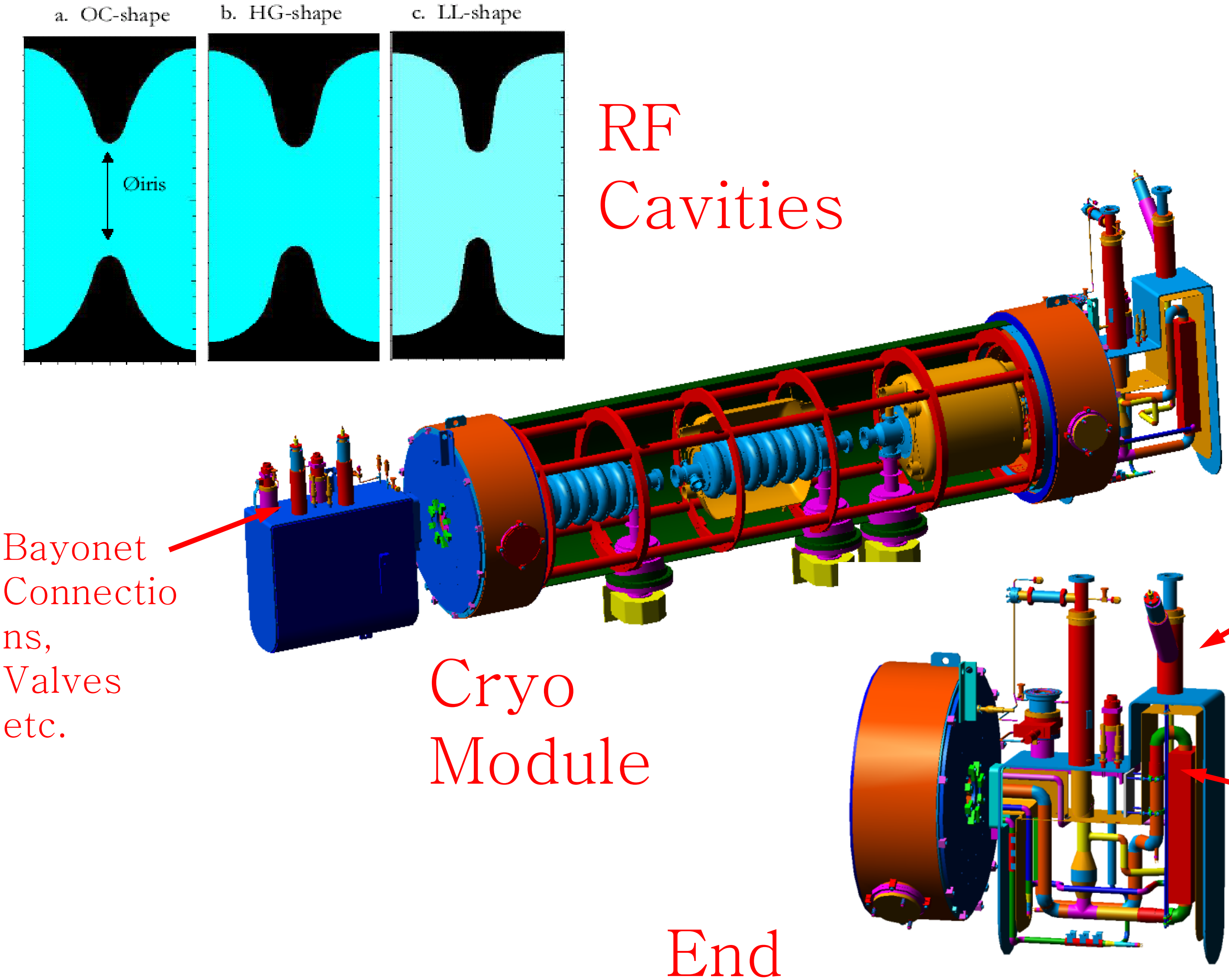
**is under construction**

**at JLab**

**for MSU FRIB**



# Cryomodule Design



RF Cavities

Bayonet Connections, Valves etc.

Cryo Module

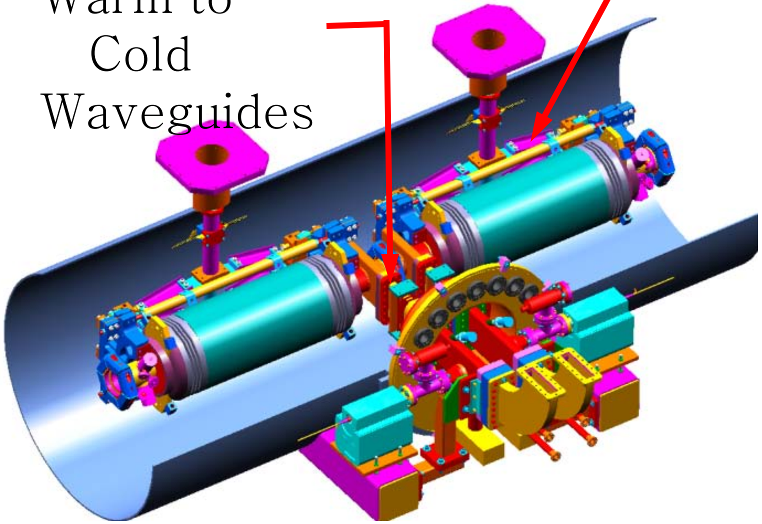
Bayonet Connections, Valves etc

4-2K HX

[10 x 15 x 65 cm]

End Can

# Cryomodule Design



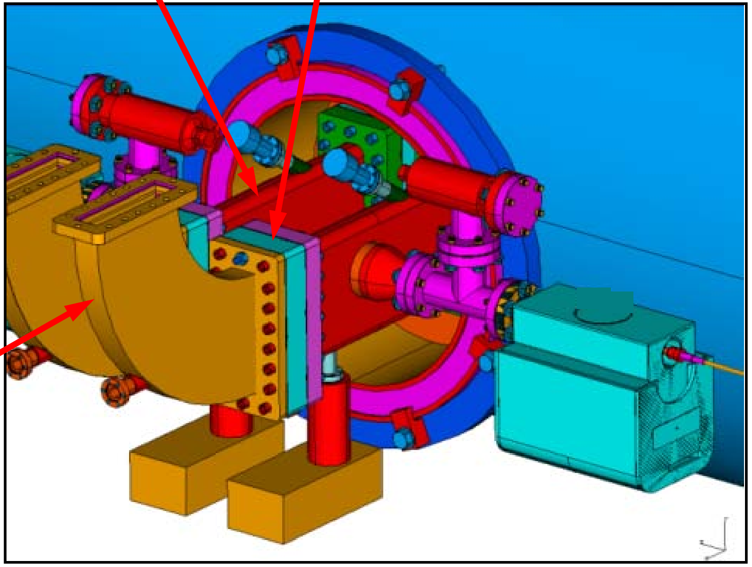
Warm to Cold Waveguides

Tuners

Cutaway of Cryomodule

Vacuum Waveguides

warm window



Air Waveguides

# Cryomodule Production


Closed Chemistry Cabinet


Electropolish Cabinet

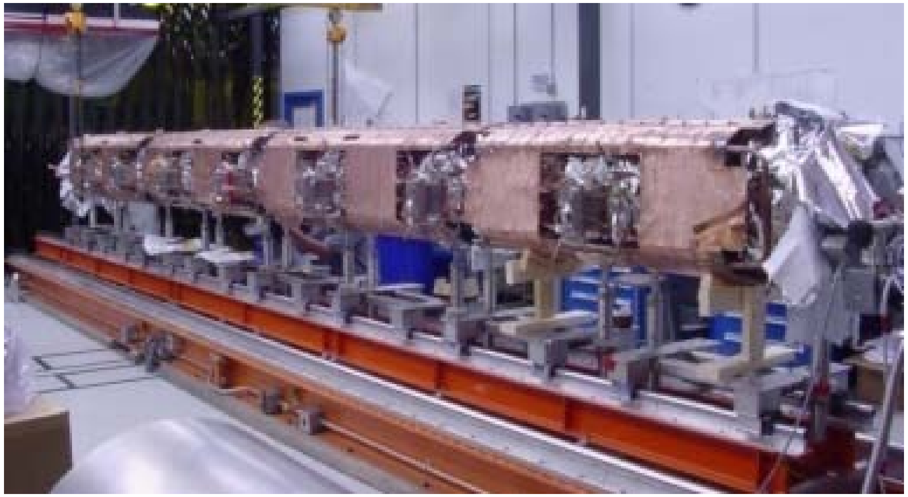

Hi Pressure Rinse Cabinet

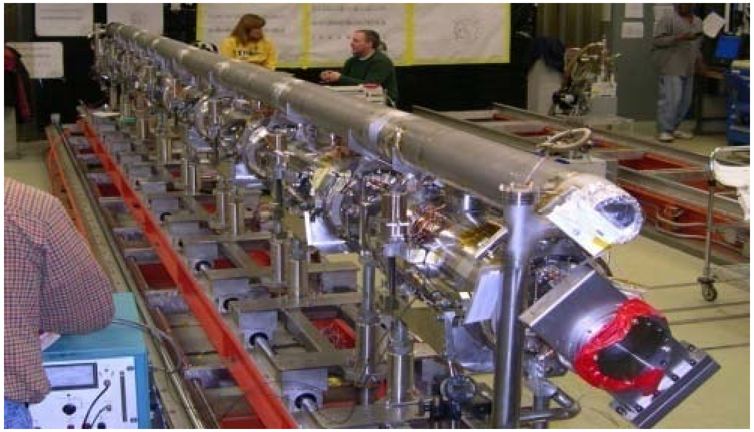

Class 100 & 10 Clean Rooms

2600 ft$^2$ Clean Room

Ultra-Pure Water Supply
2000 G/day with 1500 G Tank

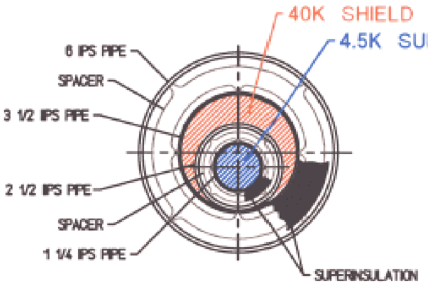
# Cryomodule Production



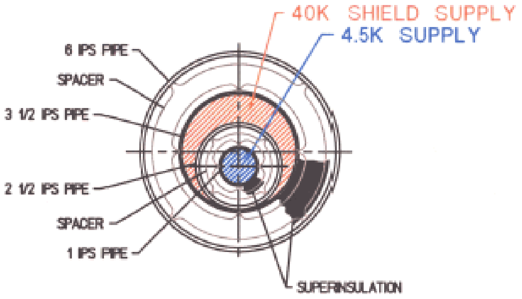


# JLab Helium Distribution System

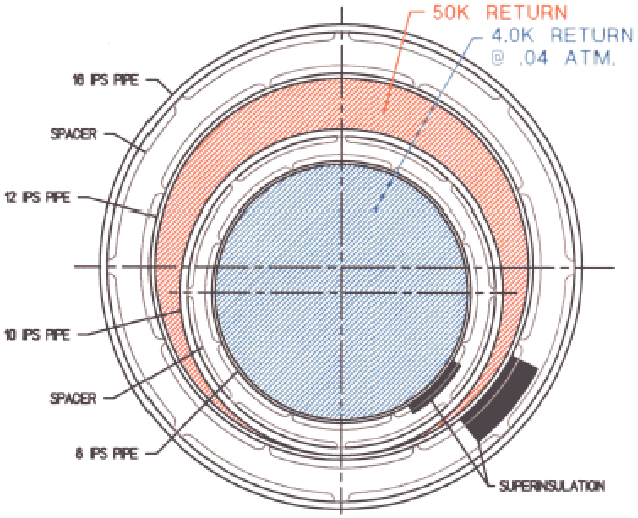
## *JLab Transfer-Line Cross-Sections*



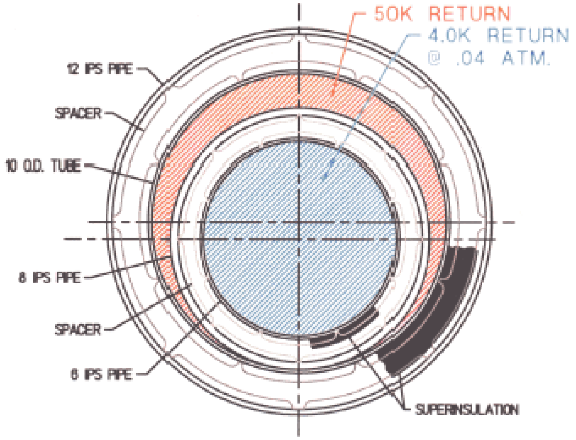
CHL SUPPLY TRANSFER LINE



LINAC SUPPLY TRANSFER LINE

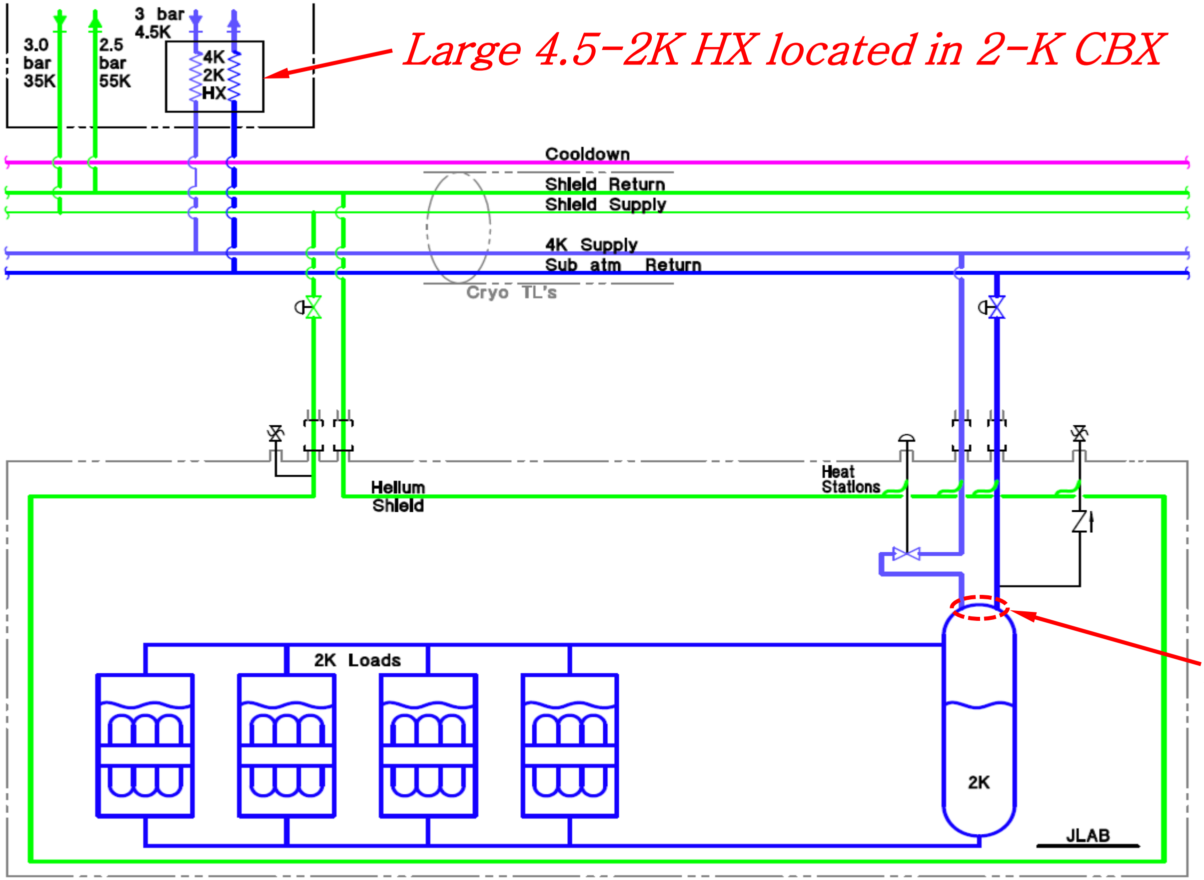


CHL RETURN TRANSFER LINE



LINAC RETURN TRANSFER LINE

# JLab Helium Distribution System



*Large 4.5–2K HX located in 2-K CBX*

*$\Delta h_{lh} \approx 18.5$ J/g*

CEBAF distribution system heat in leak of ~12W per CM + CM Static heat in leak of ~18W per CM is adsorbed at 2-K

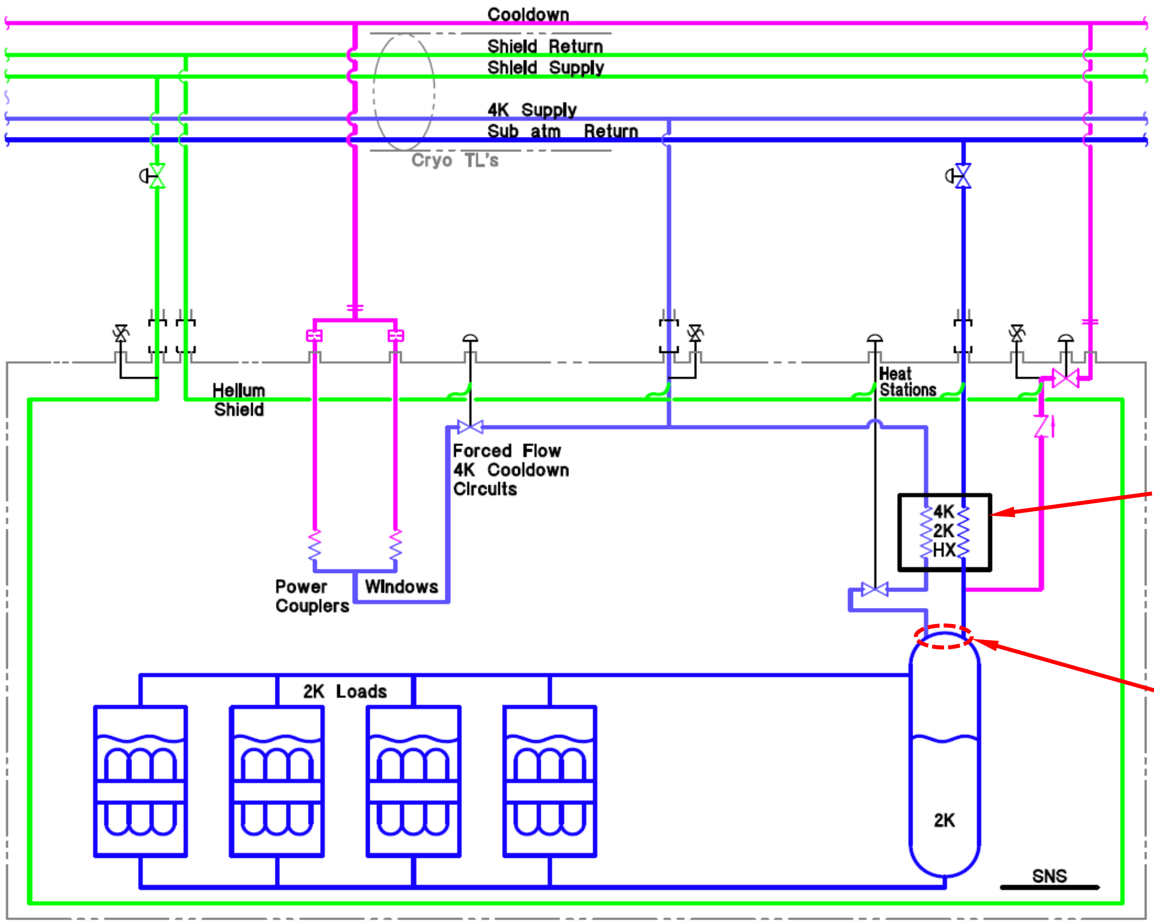
# JLab Helium Distribution System

Transfer lines at CEBAF connecting the cryomodules to the refrigerator

# JLab Helium Distribution System

CEBAF Linac

# SNS Helium Distribution System

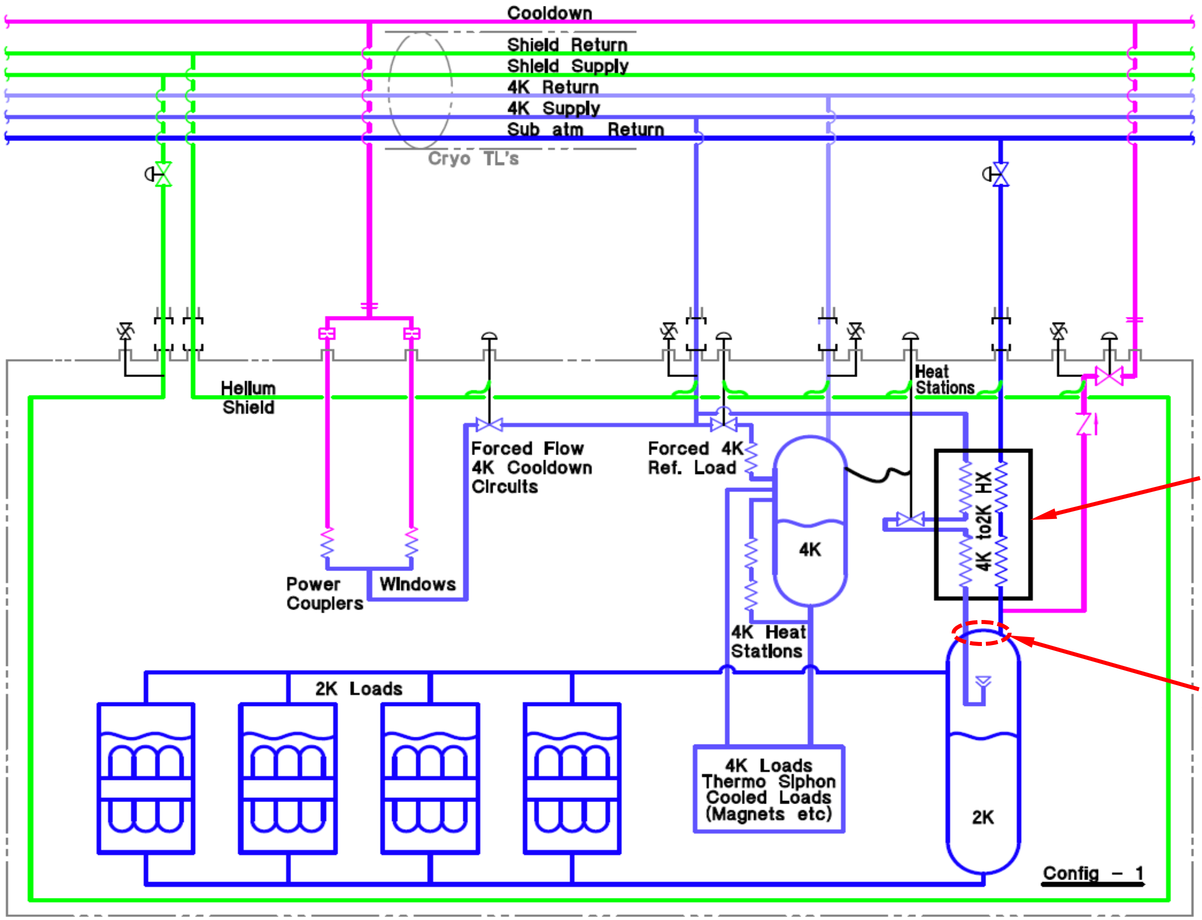


*4.5-2K HX located in each CM*

$\Delta h_{lh} \approx 19.5\ J/g$

SNS distribution system heat in leak ~10W per CM is adsorbed at ~4-K (which is equivalent to ~3W at 2-K)

# Generalized Distribution System



*New 4.5–2K HX located in CM*

*$\Delta h_{lh}$=21.85 J/g*

2-K capacity can improve ~9.3% (for the same mass flow rate) as compared to SNS

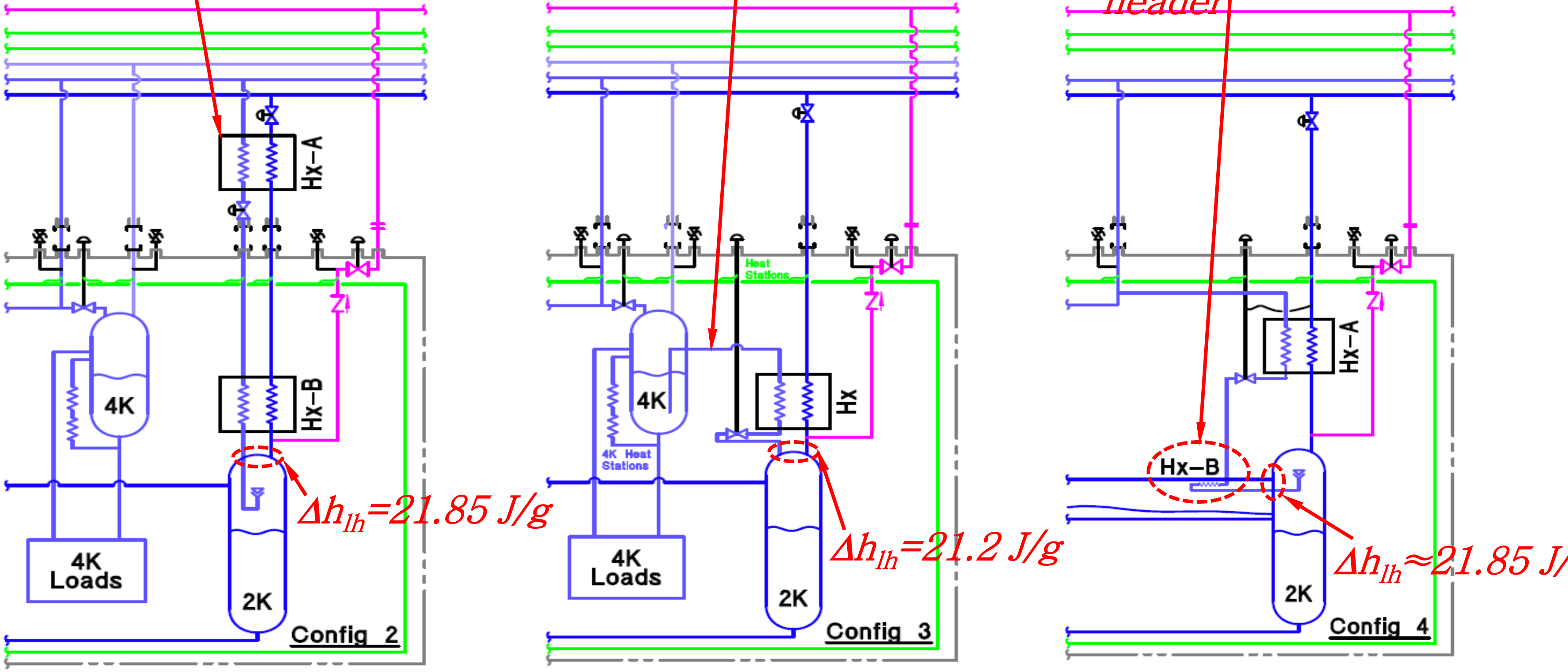
# Generalized Distribution System

## *Options*

*Upper HX section located externally to CM*

*~1.2 atm sat. liq. supply (only one HX section)*

*Lower HX section located in CM vapor header*



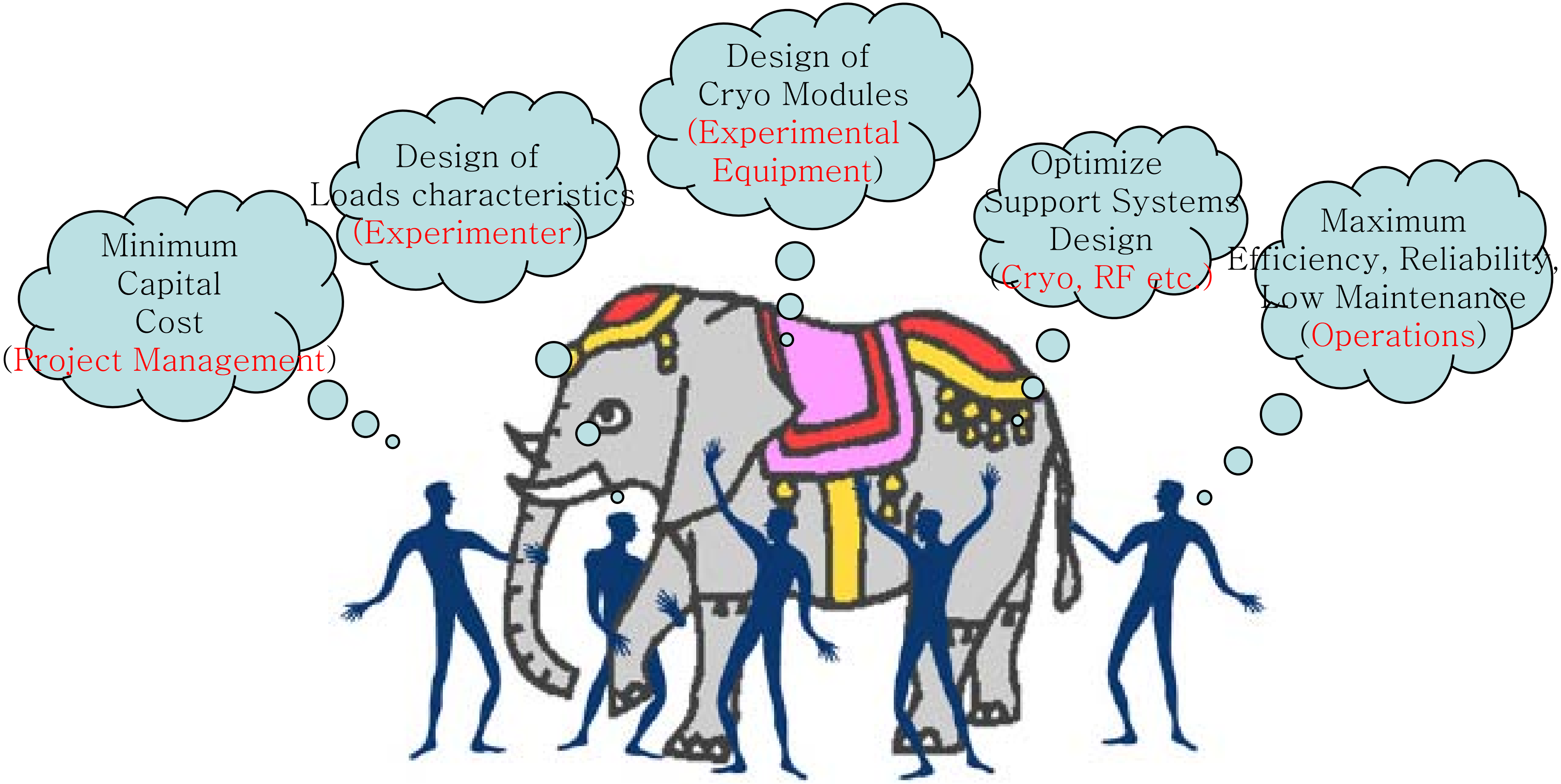
*$\Delta h_{lh}$=21.85 J/g*

*$\Delta h_{lh}$=21.2 J/g*

*$\Delta h_{lh}$≈21.85 J/*

Config-3: Enthalpy difference supplied to 2-K is ~6% greater as compared to SNS

# Conclusions



Minimum
Capital
Cost
(Project Management)

Design of
Loads characteristics
(Experimenter)

Design of
Cryo Modules
(Experimental
Equipment)

Optimize
Support Systems
Design
(Cryo, RF etc.)

Maximum
Efficiency, Reliability,
Low Maintenance
(Operations)

What is an “Optimal” System?

# Conclusions

- Required load characteristics determine the cryomodule design and cryogenic system requirements

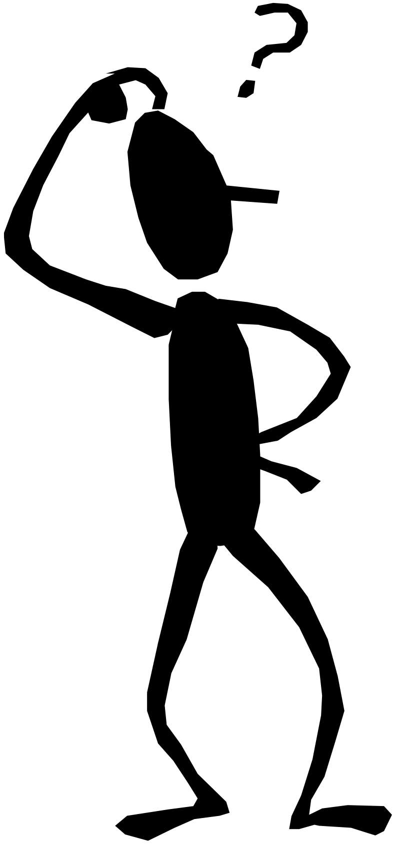
- Users need a recognition of the complexity and expensiveness of cryogenics as a utility
  - It is the “blood - circulatory” system for super conducting accelerators

- Must *collectively* optimize the cryomodule – distribution and refrigeration systems

- Support is needed for fundamental technology developments in the cryogenic systems to advance efficiency and reliability

- Energy is a precious commodity and in decreasing supply!
  - Accomplish the same *end goal* with a *minimal carbon foot print*

# Questions?



Thank you all for the interest