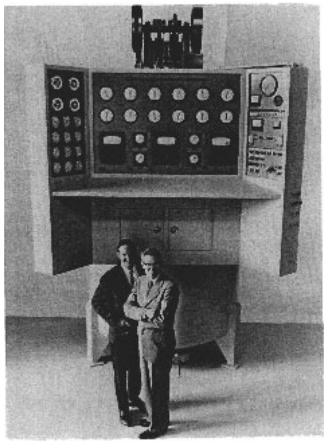
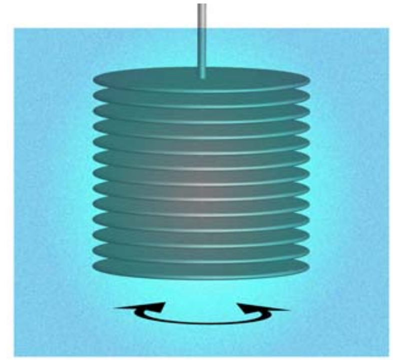
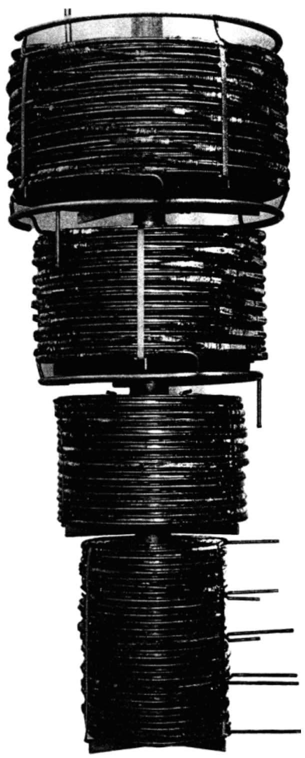
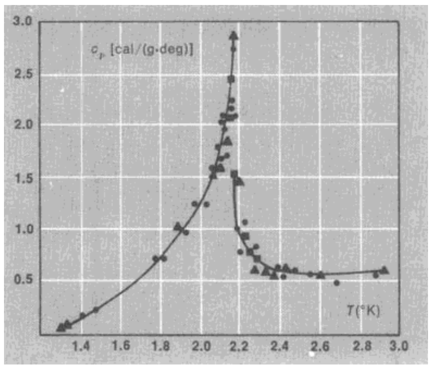
# Cold End Process Options for Nominal 2-K Helium System Improvements

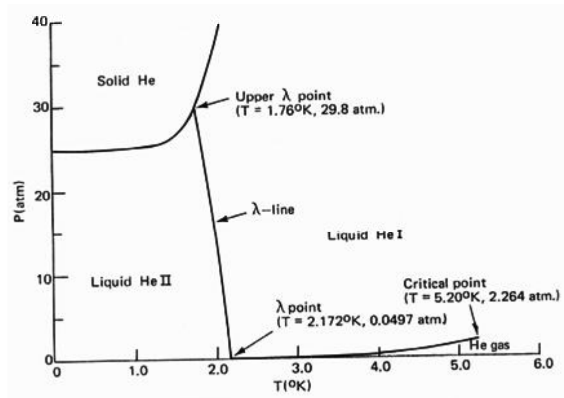


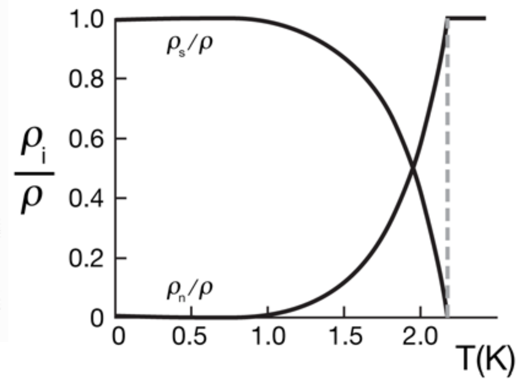


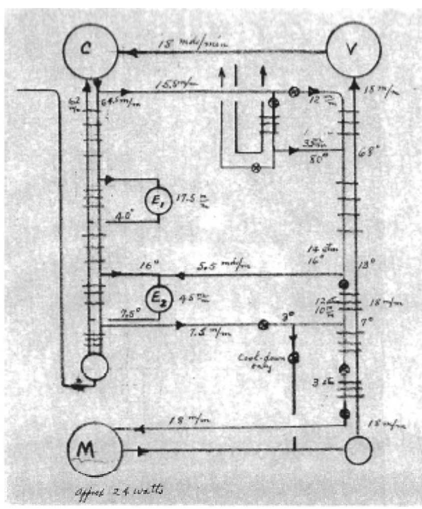


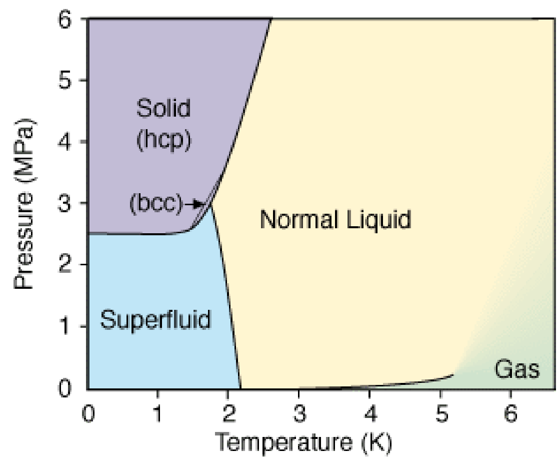
LOW PRESSURE HEAT EXCHANGER

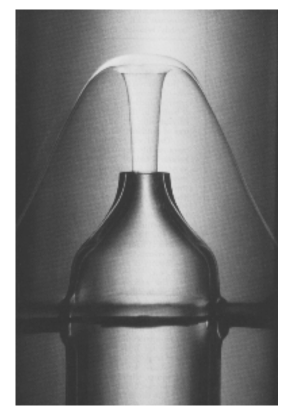


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# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

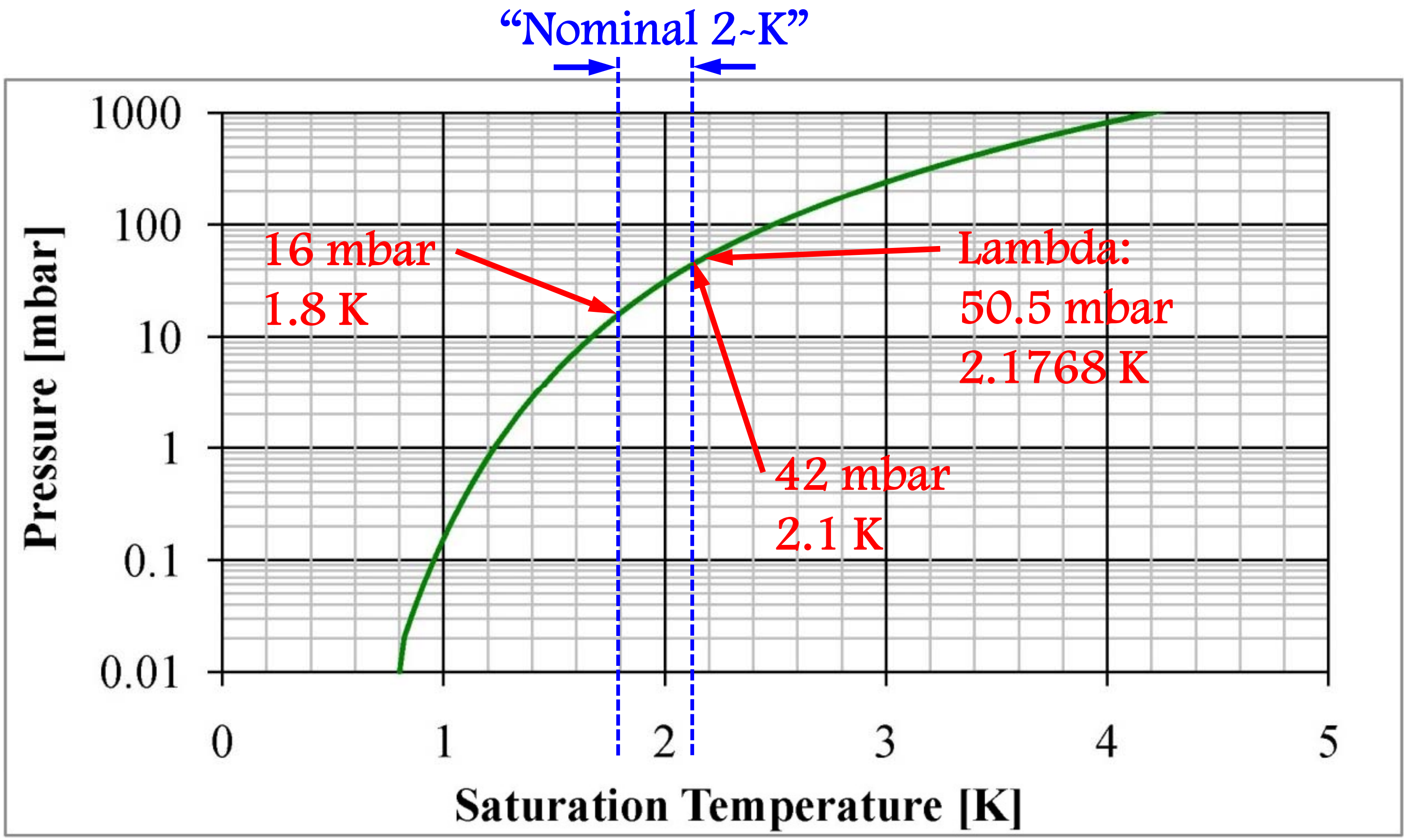
- Introduction
  - Refrigeration below 4.5-K typically involves *sub-atmospheric helium* at some point in the process
  - Since processes used for large accelerators operate typically between 1.8 to 2.1 K (i.e., 16 to 42 mbar), will refer to these as *nominally 2-K*

# Cold End Process Options for 2-K Helium System Efficiency Improvements

- Helium: Saturation temperature vs. pressure

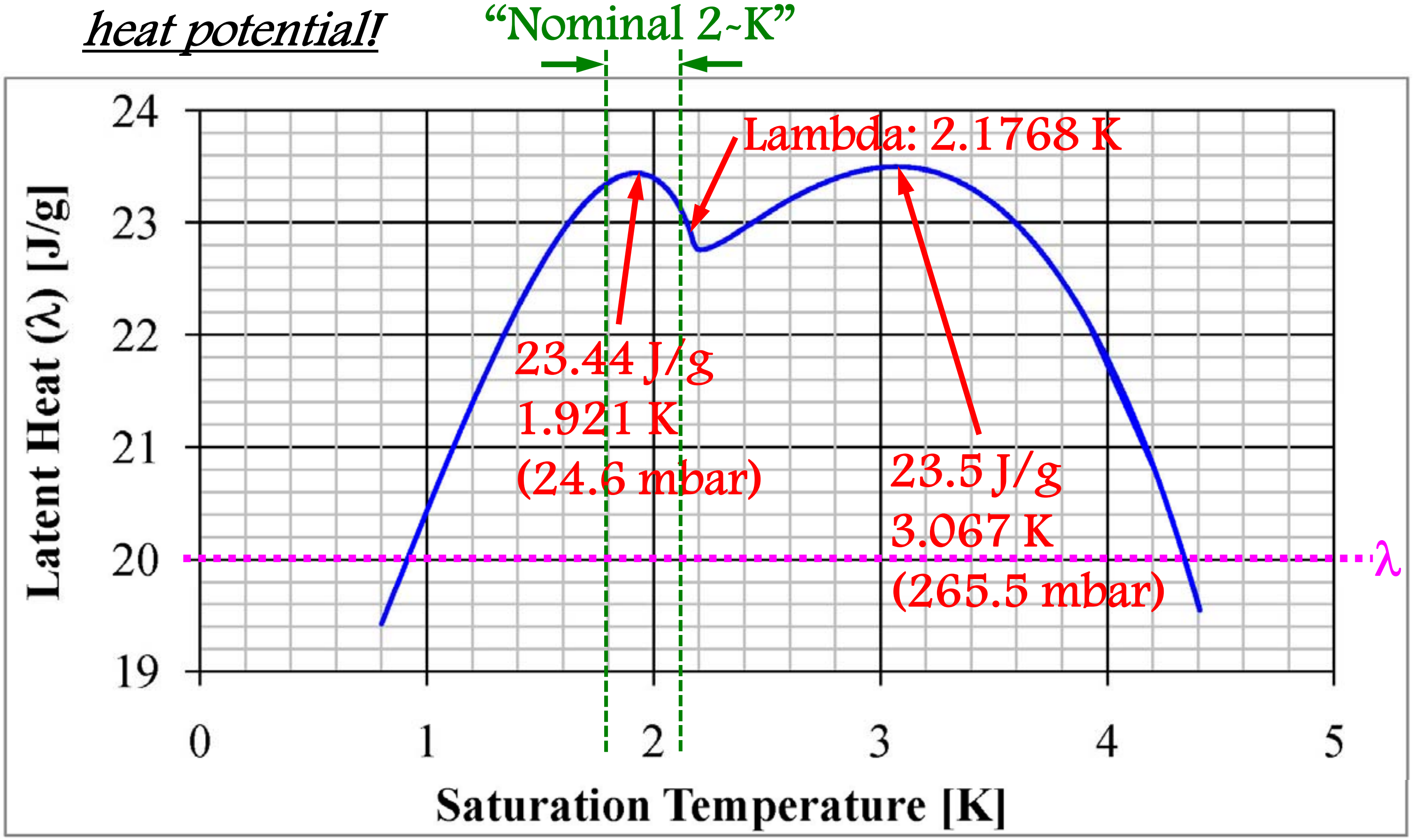
*<u>Note</u>: logarithmic scale for pressure; also, vapor density behavior is similar.*

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



# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- Helium: Latent heat of vaporization
  - To date we accept $\lambda \approx 20$ 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!***



# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

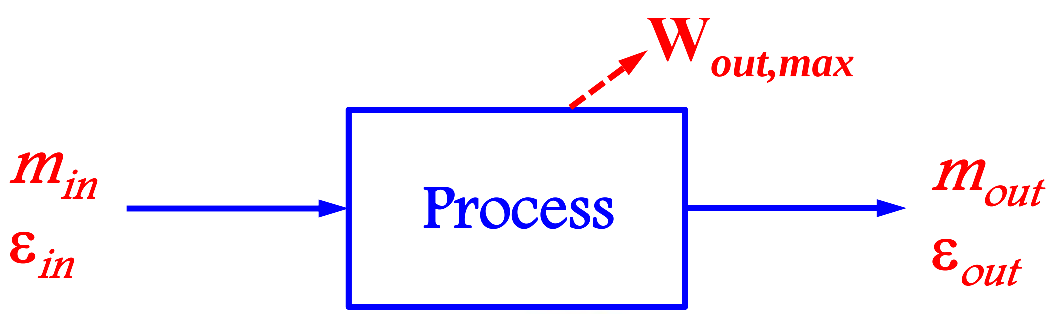
- (Physical) exergy per unit mass is defined as,

  $$\varepsilon = h - T_0 \cdot s$$

  - 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 reversible (input or output) power



# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- A common measure of process efficiency is the ratio of the ideal (or theoretical) input power to the actual (or real) input power required; known as the *overall exegetic efficiency*,

  $\eta_C = \Delta E \, / \, \mathbf{W}_{in}$

  – Where, $\mathbf{W}_{in}$ is the actual (real) required input power

- One measure of process performance is the ratio of the input power required (either ideal or real) to the cooling provided; known as the *inverse coefficient of performance*,

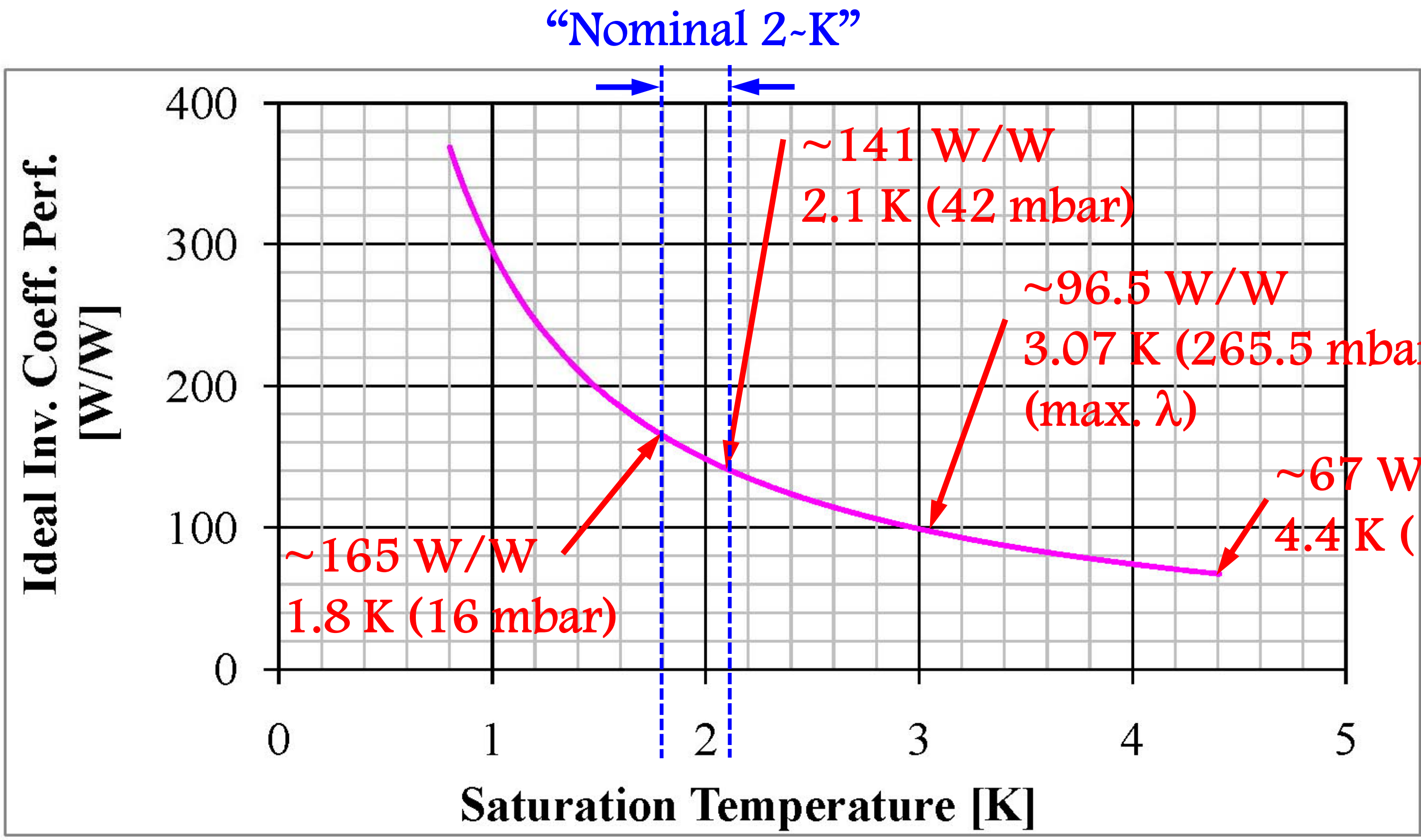
  Ideal (theoretical), $\mathbf{COP}_{inv,i} = \Delta E \, / \, \mathbf{q}_L$

  Real, $\mathbf{COP}_{inv,r} = \mathbf{W}_{in} \, / \, \mathbf{q}_L$

  – Where, $\mathbf{q}_L$ is the cooling (load) provided

# Cold End Process Options for 2-K Helium System Efficiency Improvements

- Ideal (theoretically minimum) $COP_{inv,i}$ for helium (isothermal) refrigeration,



# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- 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 |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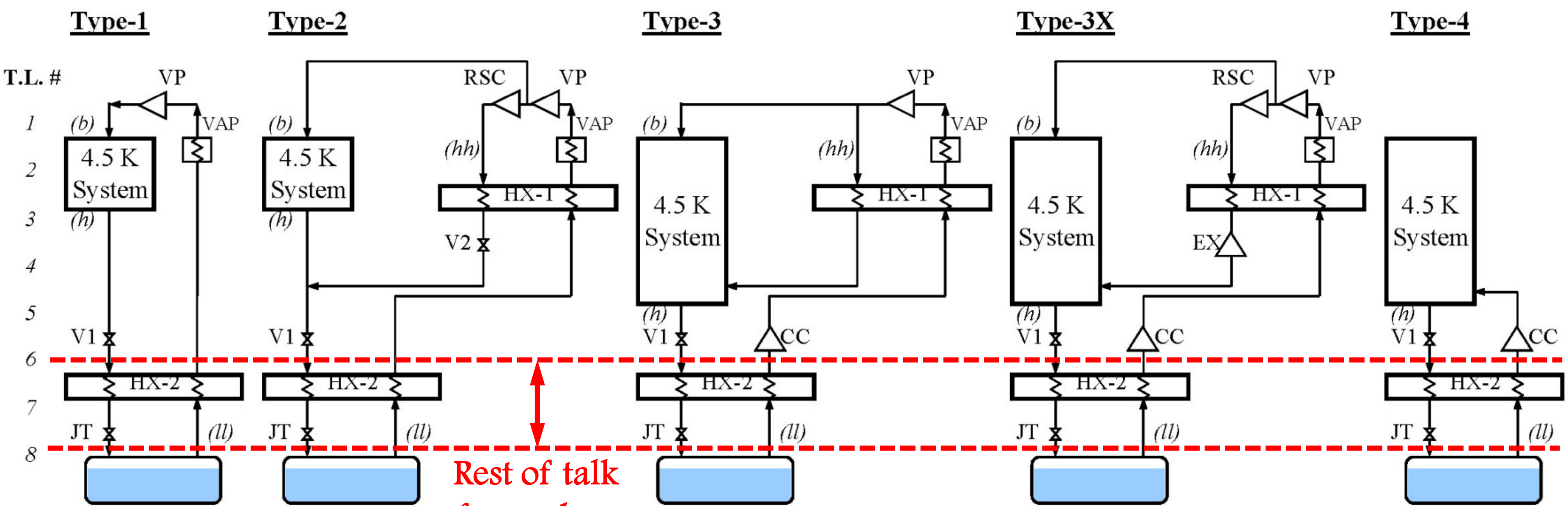
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

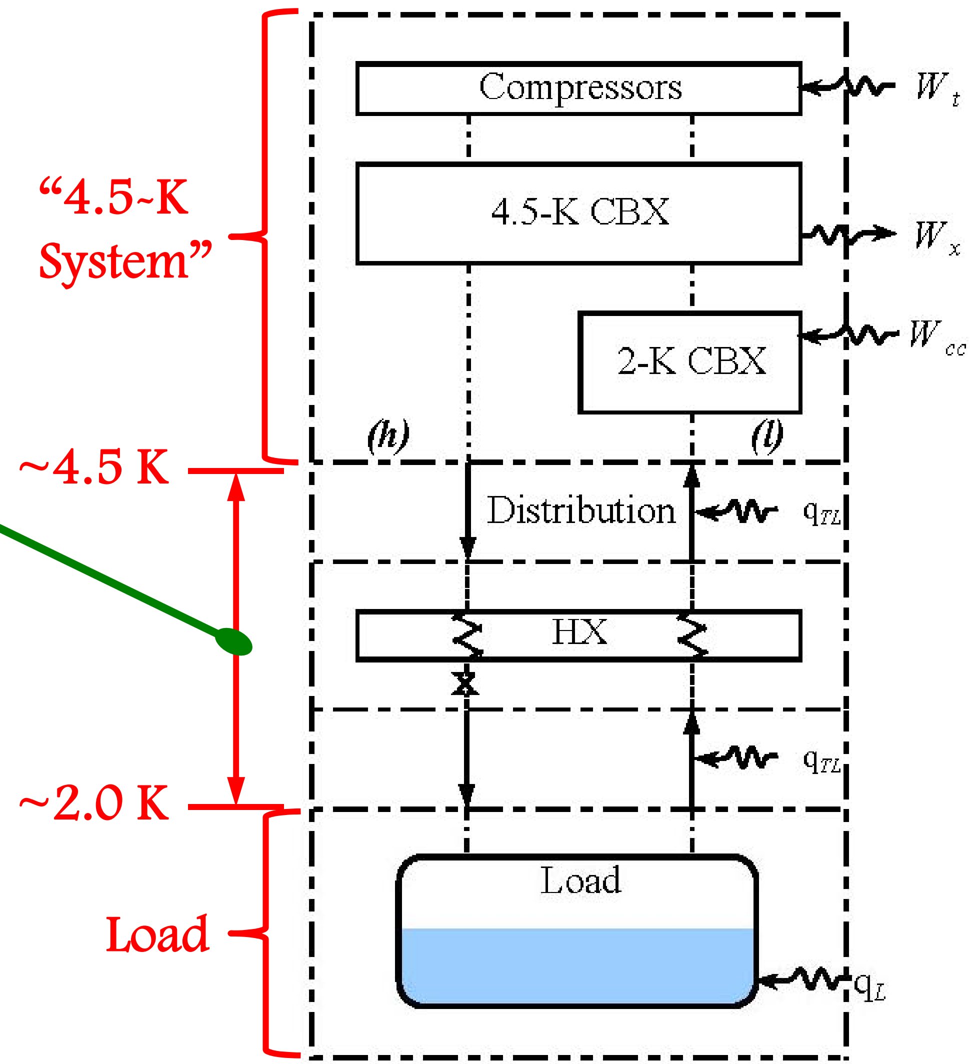
- Four basic configuration types of processes for nominal 2-K helium systems
  - Type-1: Direct vacuum pumping (with or without a 4.5 to 2-K HX); e.g., Triumf E-Linac
  - Type-2: Utilizes an unbalanced refrigeration recovery HX and NO cryogenic rotating machinery; e.g., DESY TTF
  - Type-3: Has several variants, but each uses partial cold compression (1 to 3 stages) and an unbalanced refrigeration recovery HX; one incorporates an expander (-3X); e.g., CERN LHC, Rosendorf-Elbe, MSU-FRIB, etc.
  - Type-4: Uses all cold compression (four stages); e.g., JLab, SNS



# Cold End Process Options for 2-K Helium System Efficiency Improvements

- Since there is typically no work extraction between the 4.5-K refrigerator and 2-K load…

- *<u>Question</u>: can the 2-K load capacity be increased by any process changes in between these temperature levels?*



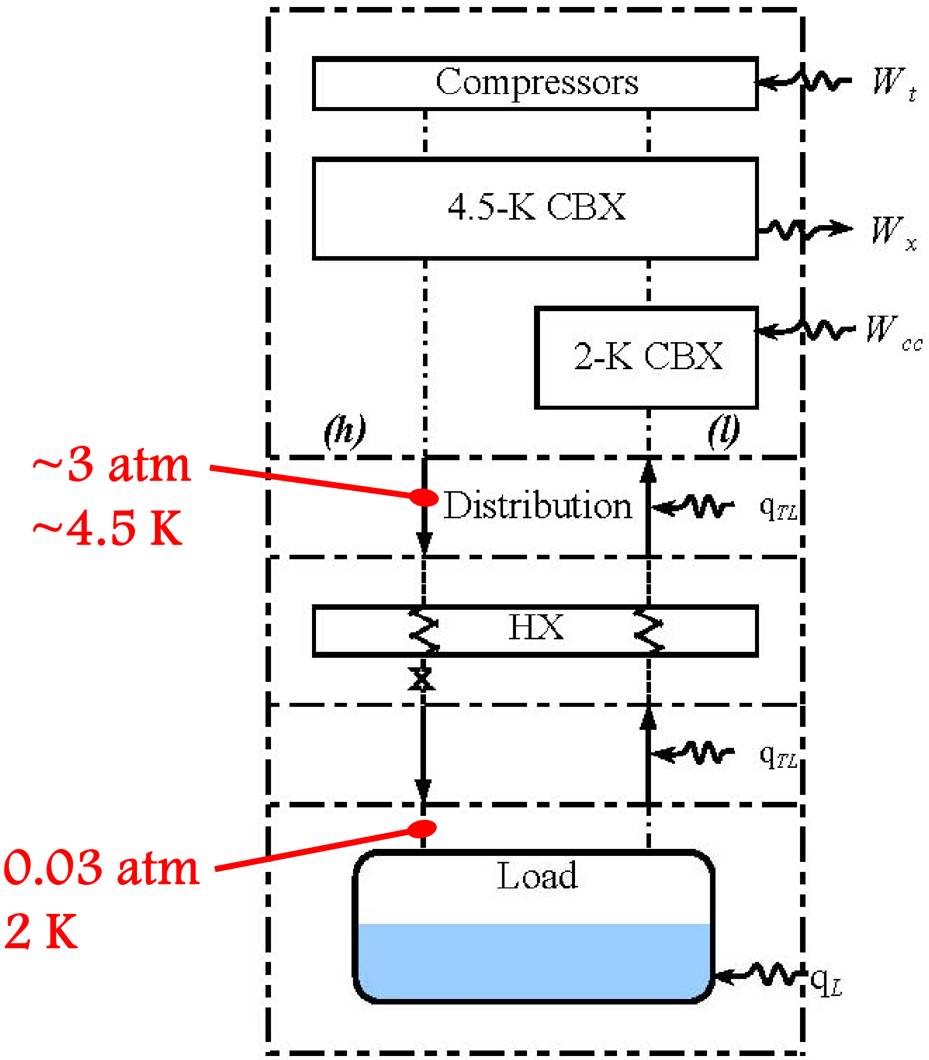
# Cold End Process Options for 2-K Helium System Efficiency Improvements

- For thermo-hydraulic reasons, the supply pressure to the load is usually

  ~3 atm (super-critical) for large systems and,

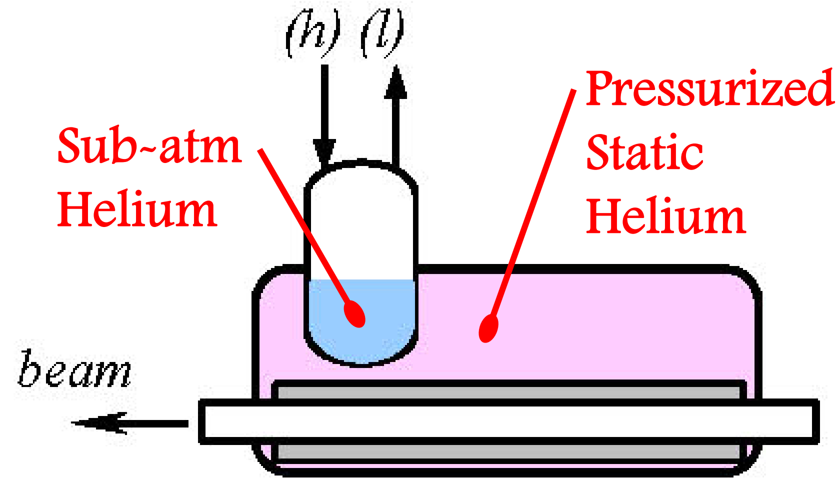
  ~1.2 atm (saturated liquid) for small systems

- 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*?)…

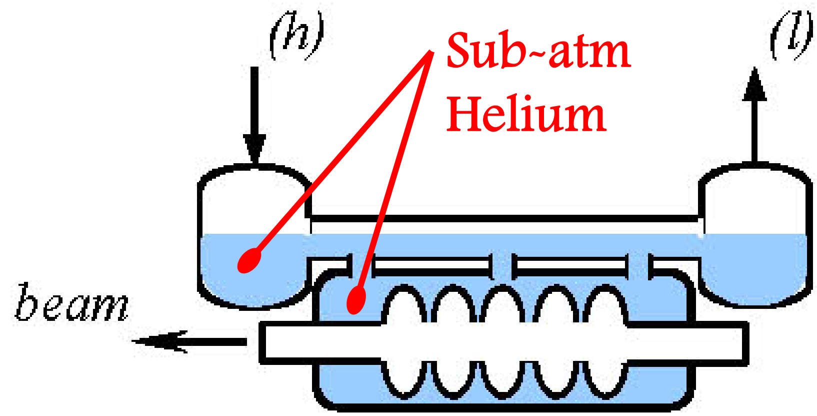


# Cold End Process Options for 2-K Helium System Efficiency Improvements

- A side note…
  - The “Load” is usually either a magnet string (i.e., a sub-atmospheric bath that cools via. super-fluid conduction a ‘pressurized’ (~1 atm) static helium reservoir surrounding the magnet); e.g., CERN LHC

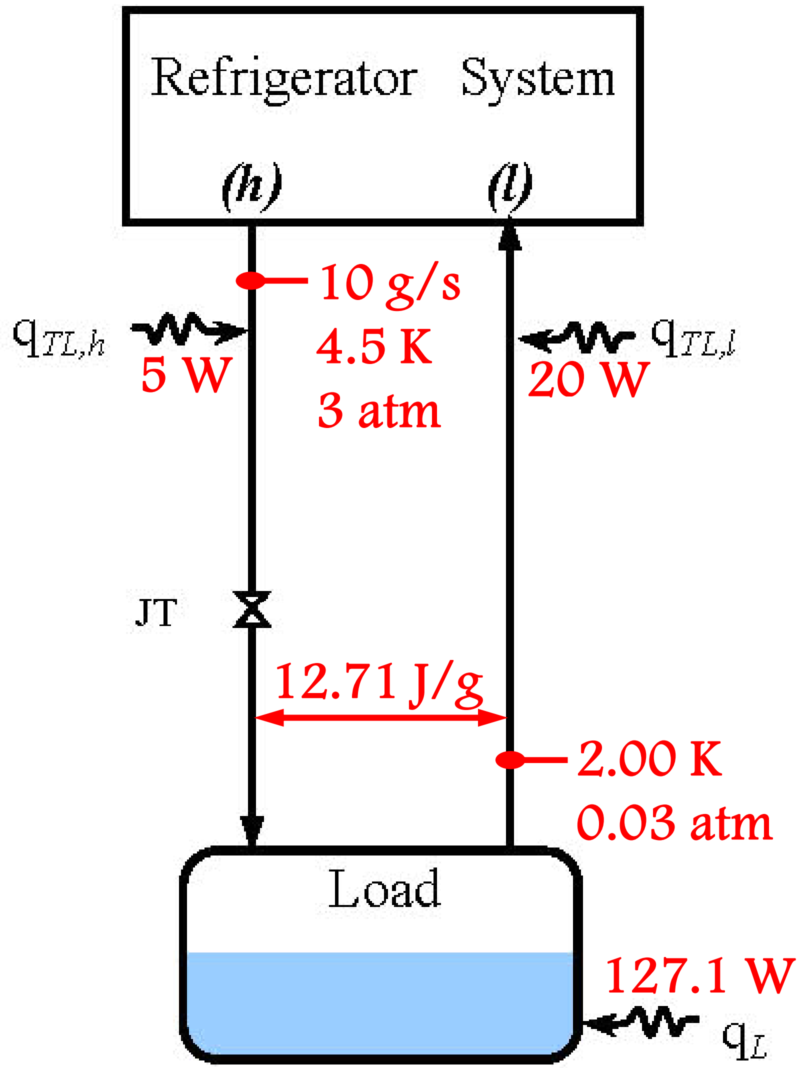



  - Or, a super-conducting radio frequency (SRF) cavity (i.e., a niobium ‘cavity’ is immersed in sub-atmospheric liquid); e.g., JLab



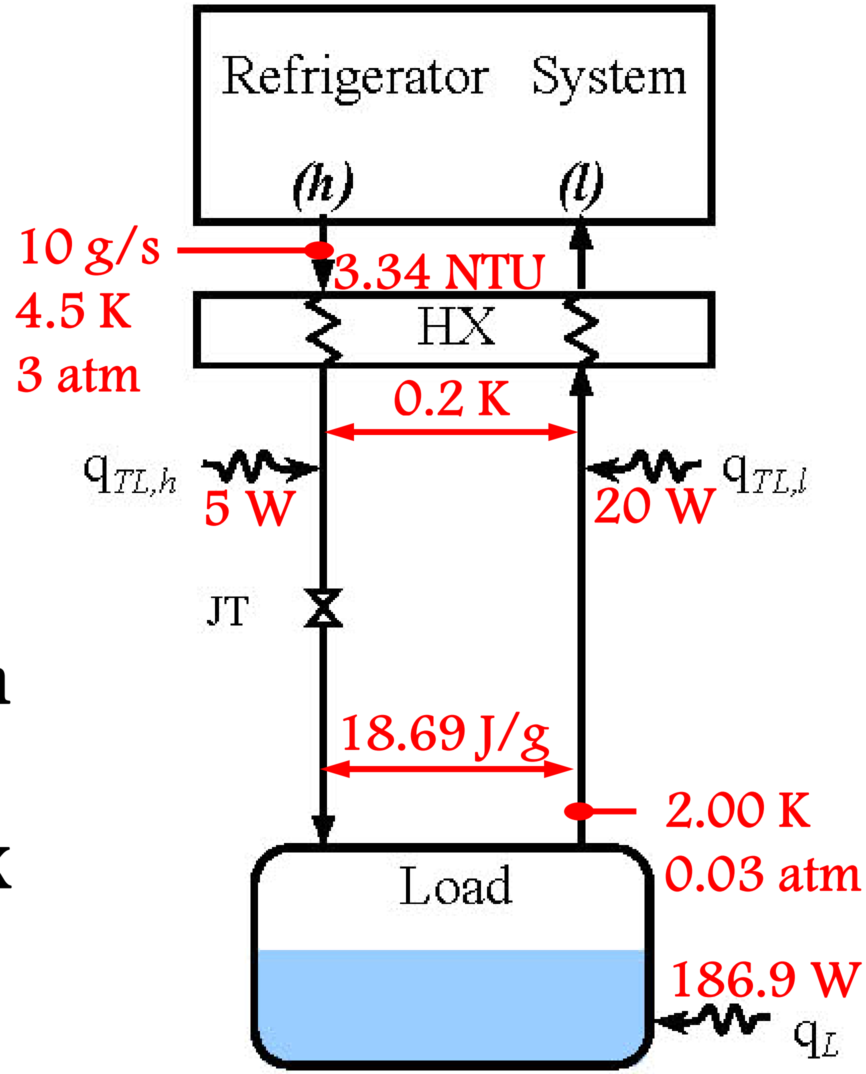
# Cold End Process Options for 2-K Helium System Efficiency Improvements

- 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



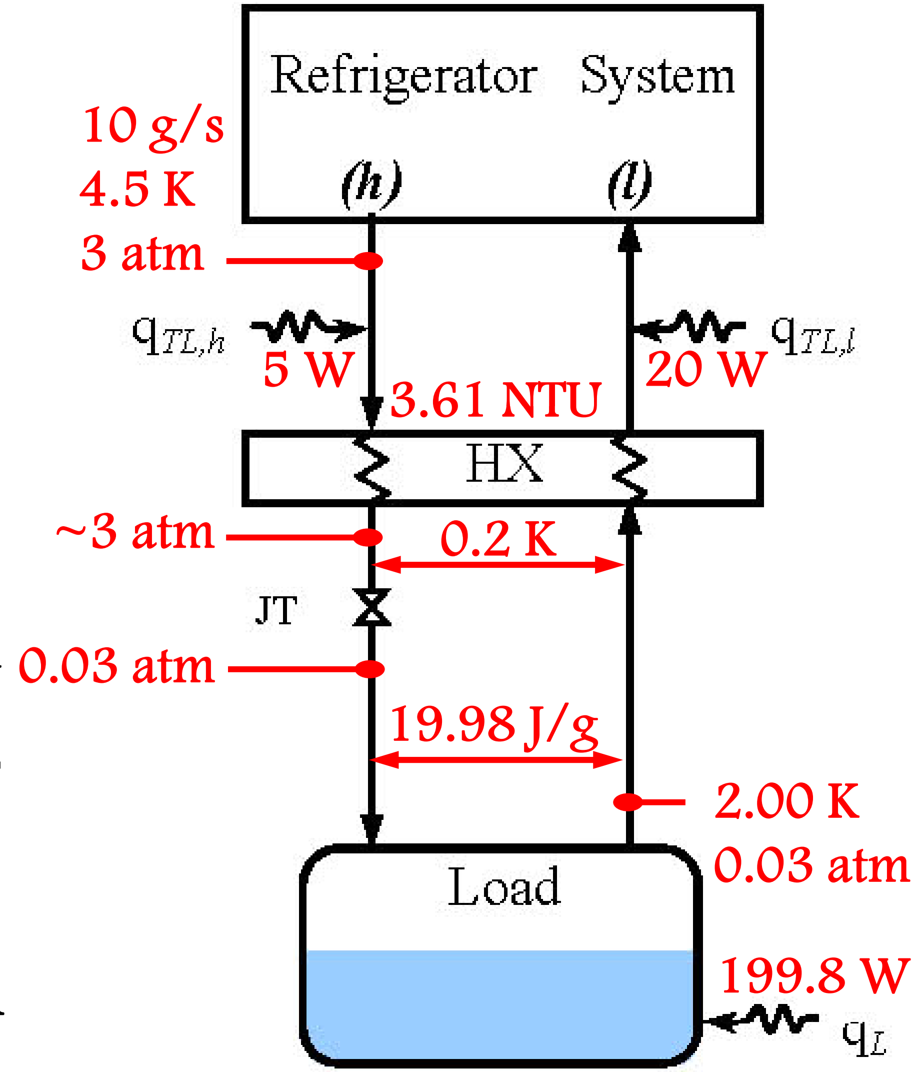
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- JLab 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



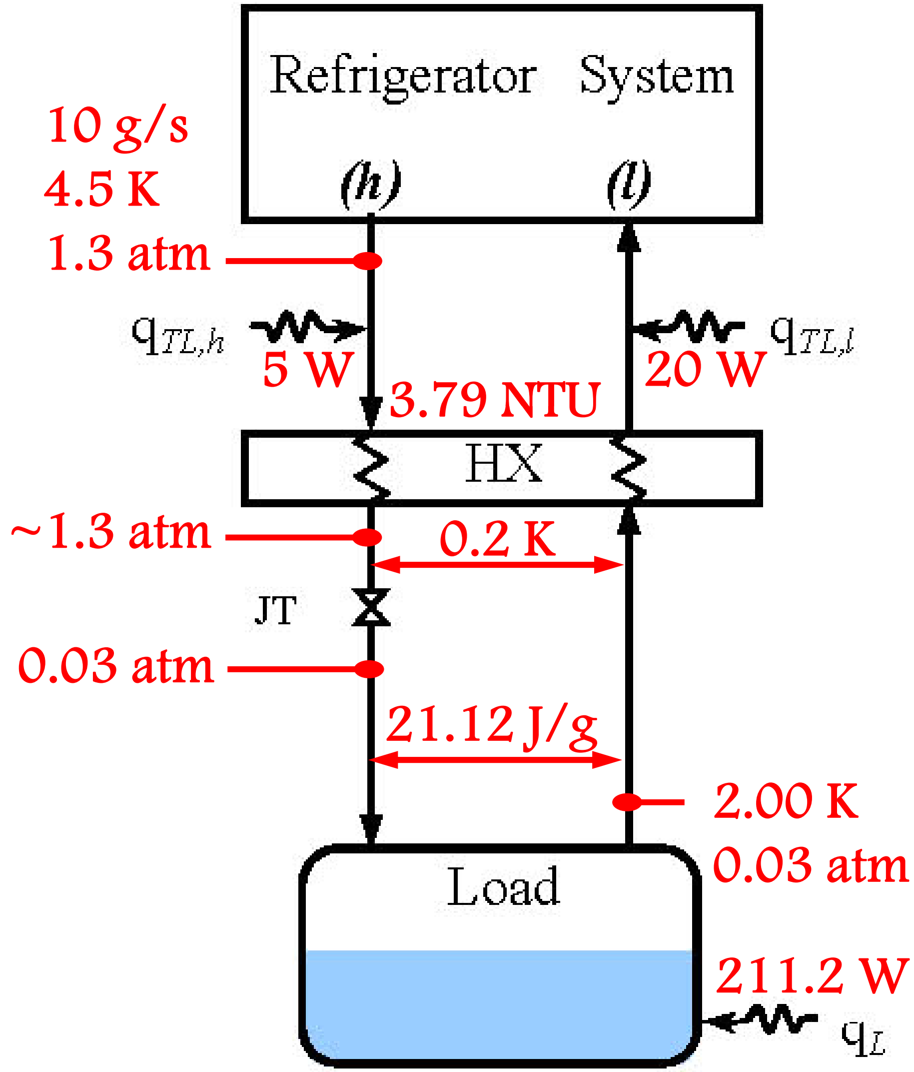
# Cold End Process Options for 2-K Helium System Efficiency Improvements

- 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 '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…



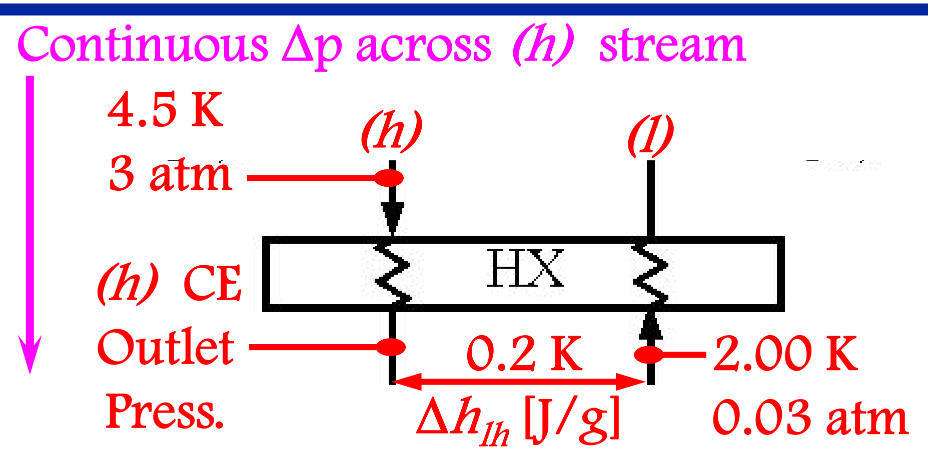
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

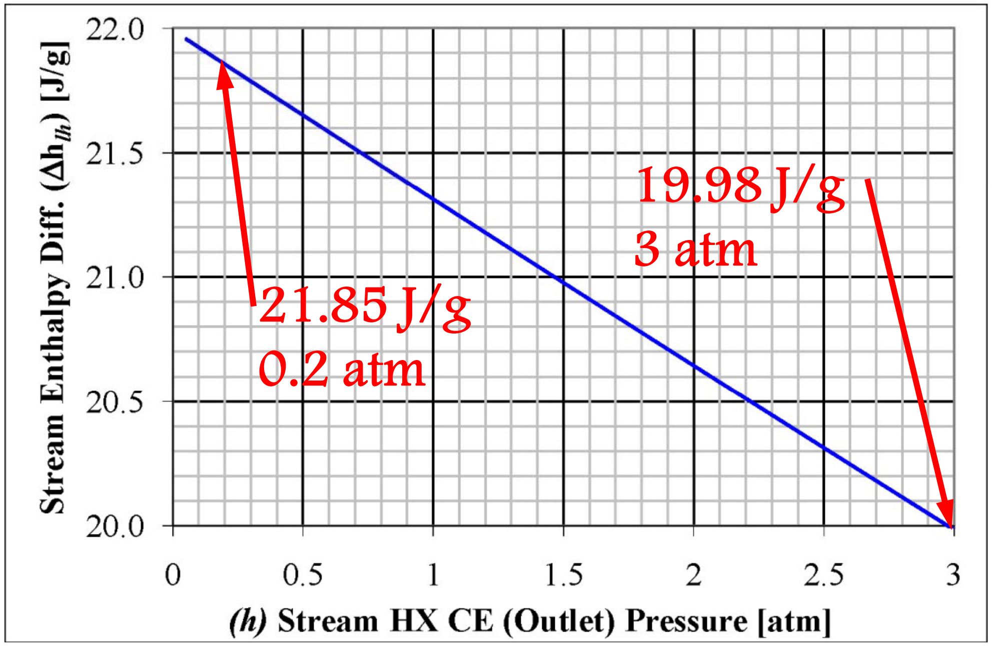
- For 2-K systems where it is acceptable for the refrigerator system to supply (say) ~1.3 atm saturated liquid (4.5-K)
  - Load increase of ~6% compared to SNS design
  - *We are analyzing whether to recommend to SNS dropping their supply pressure from 3 to ~1.3 atm*
- Note: for thermo-hydraulic stability reasons, a supply pressure of 1.3 atm may not be practical



# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

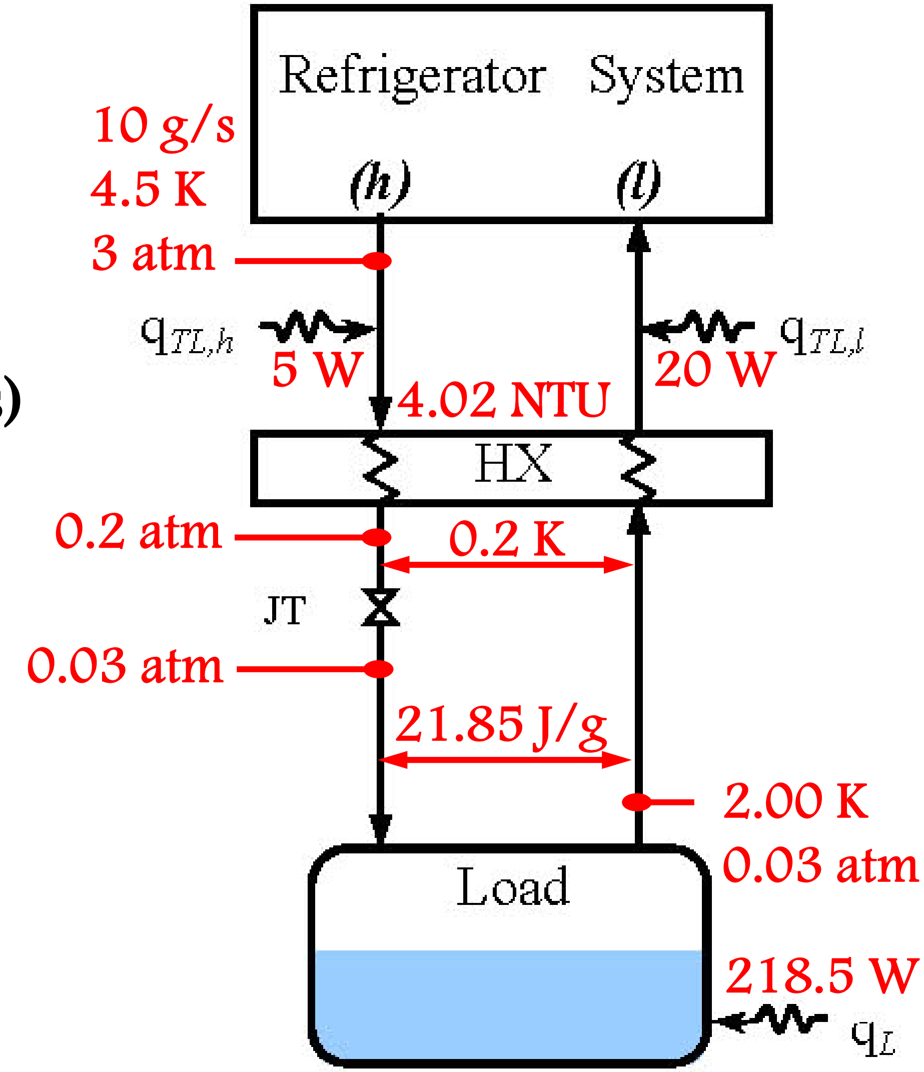
- This could suggest a (exergetically) constructive use of the *(h)* stream pressure drop through the HX, rather than across the JT valve
- Figure shows the enthalpy flux at the HX cold (load) end as a function of the CE (outlet) pressure, for a stream CE temperature difference of 0.2 K
- Note: use 0.2 K to provide sufficient stream temperature difference for heat transfer and to avoid super-fluid in HX…this could be somewhat more or less than this value



# Cold End Process Options for 2-K Helium System Efficiency Improvements

- So, if there is a (built-in) pressure drop across the *(h)* stream of the HX from 3 to 0.2 atm, the load can be increased by ~9.5% over the SNS design (for the same supply conditions)
- Note that this is *not* a practical design
- Why was an outlet pressure of 0.2 atm chosen?

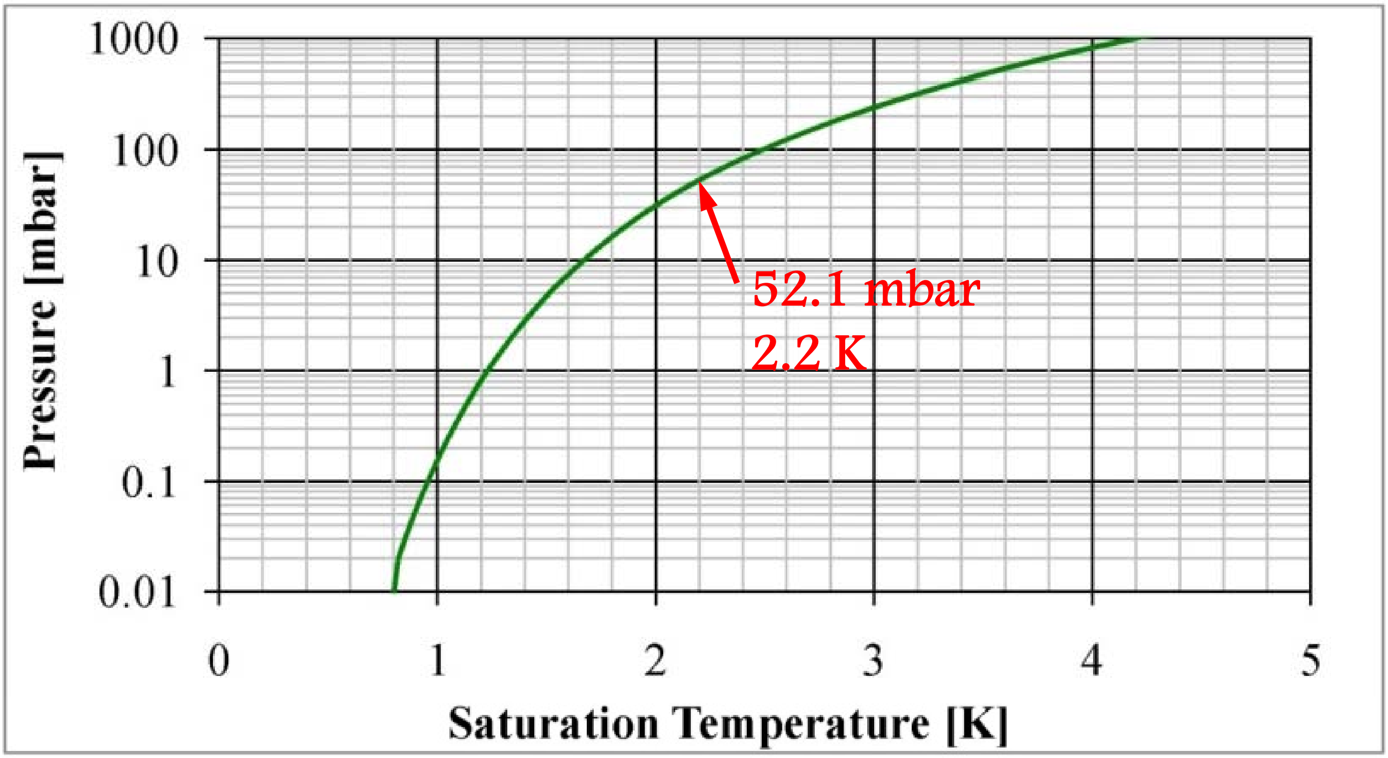


# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- That is,
  - Why stop at 0.2 atm…
  - and not take the pressure drop through the *(h)* stream of the HX from 3 atm, all the way down to 0.03 atm…
  - getting the entire latent heat for the load (i.e., 23.42 J/g, or in the examples given, 234.1 W)?

# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- First, the HX CE stream temperature difference of 0.2 K (which represents a practical value to design the HX around) presents a fluid property limit of 0.0514 atm as the saturation temperature at (2.0 + 0.2 =) 2.2 K

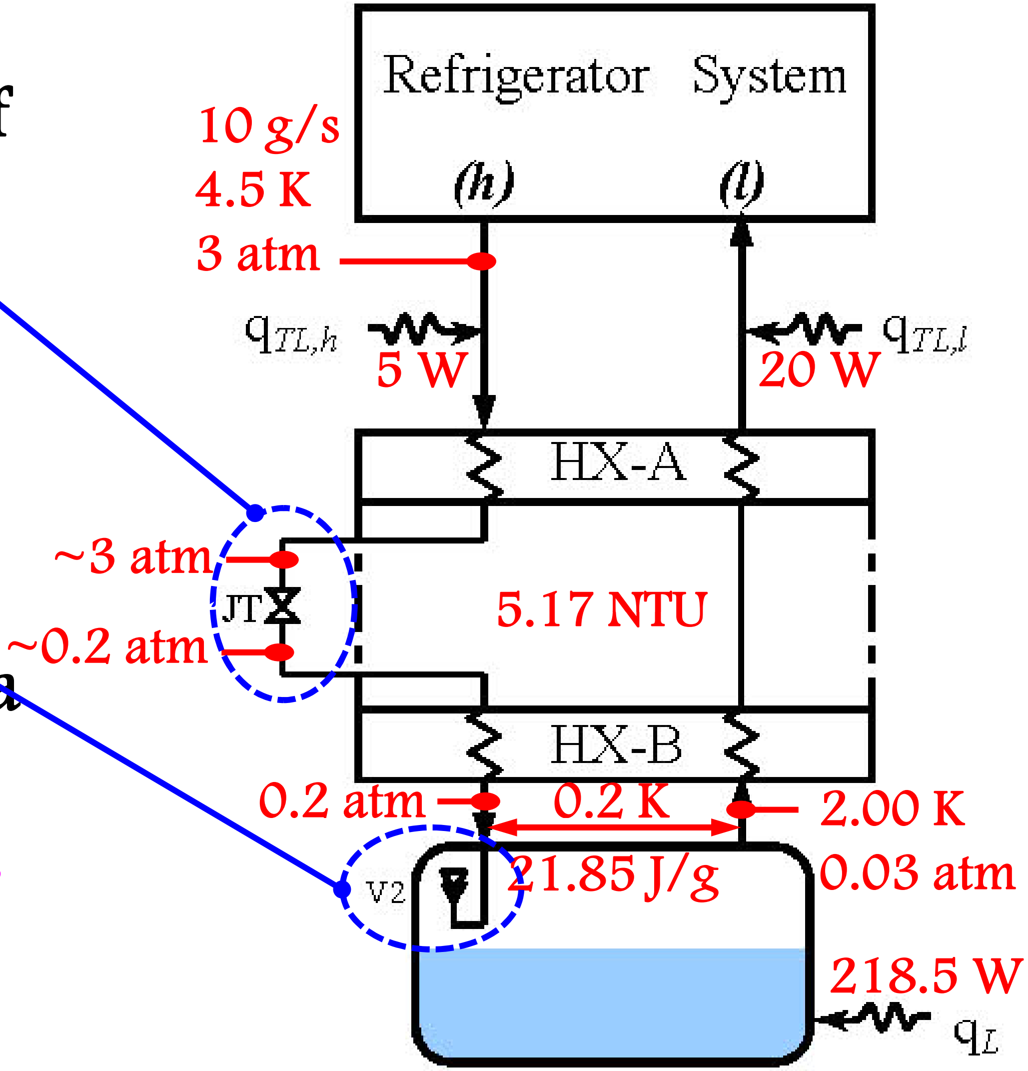


# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- Second, designing a HX with a specific pressure drop,
  - especially under nominal variations expected in design vs. actual hardware (and loads),
  - and under transient conditions, such as cool-down,
  - *is not practical*
- So, a variation of the design is needed to practically implement this idea…

# Cold End Process Options for 2-K Helium System Efficiency 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)



# Cold End Process Options for 2-K Helium System Efficiency Improvements

- So, why not 0.0514 atm, instead of 0.2 atm…?

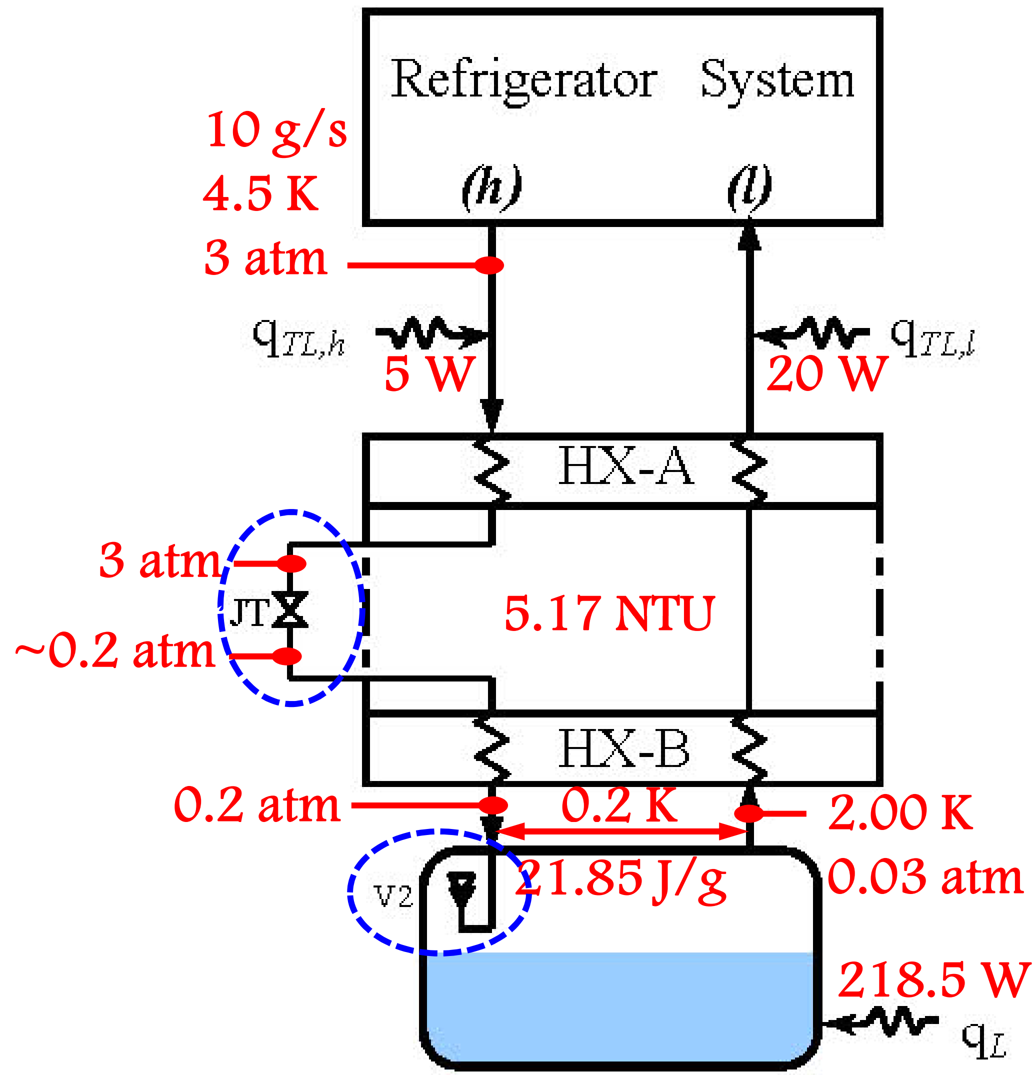
- Because the required HX size (which is quantified using NTU's or UA) would be too large

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

- *Note*:

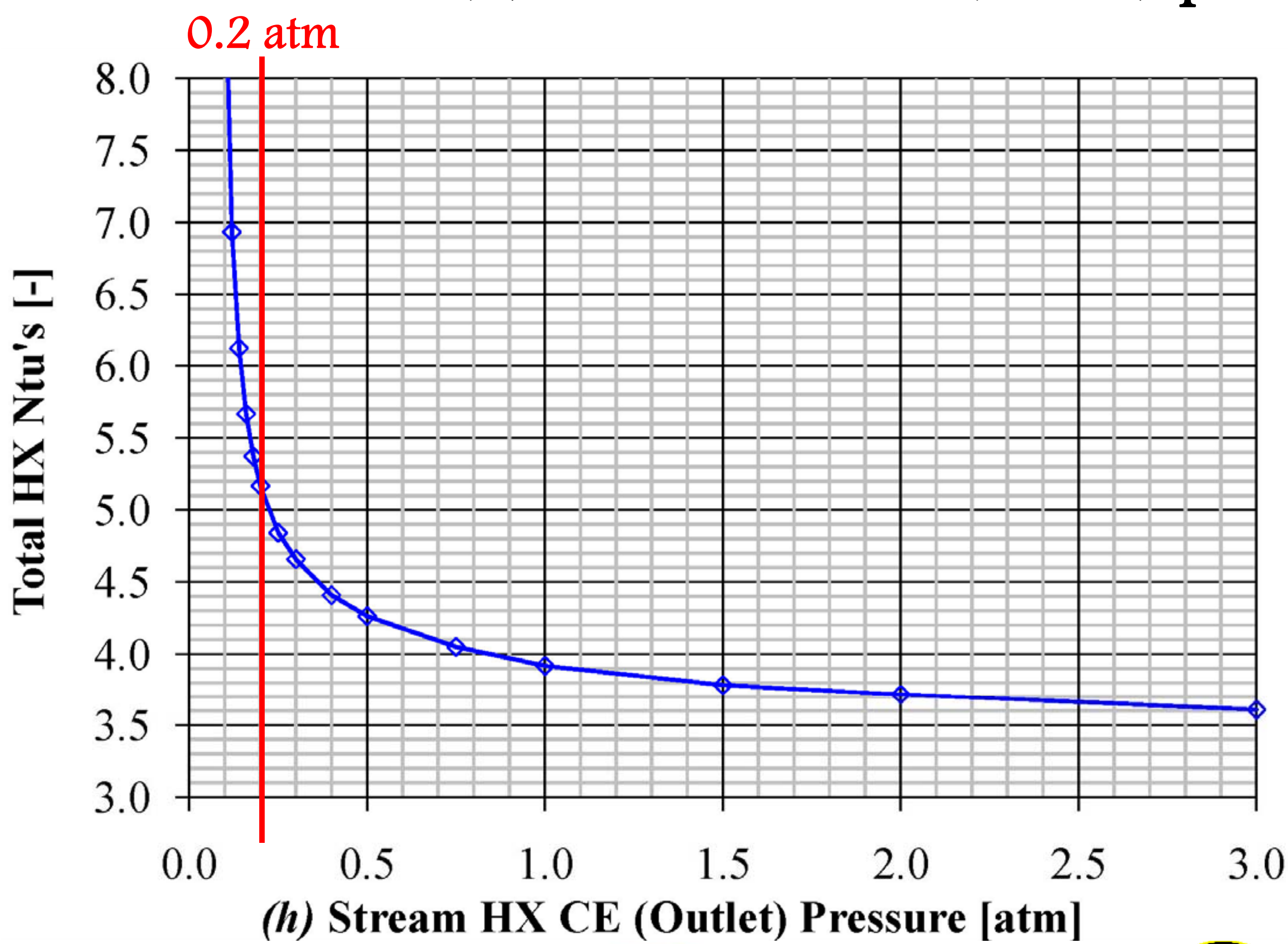
  NTU ~ HX length

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



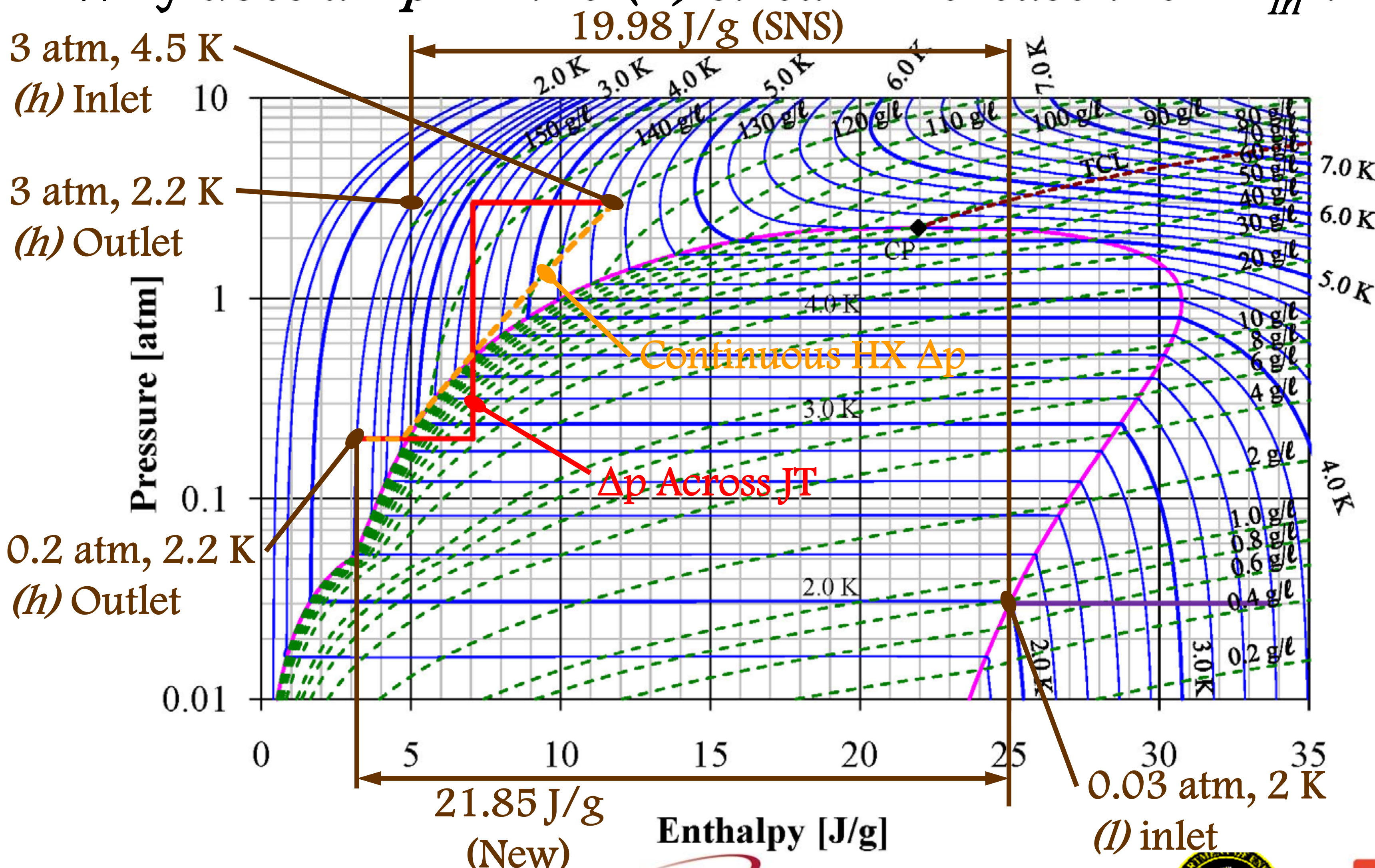
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

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



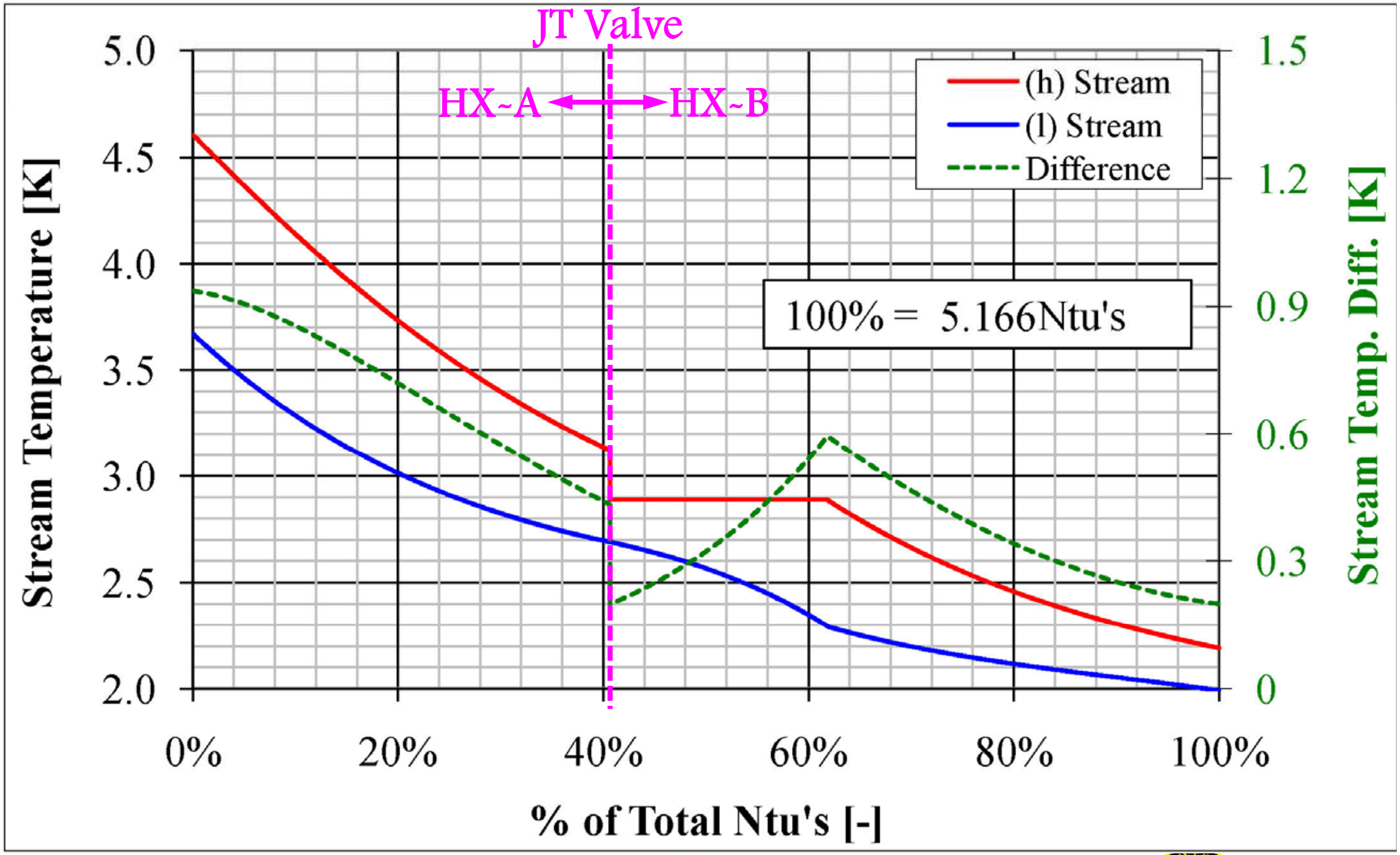
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

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



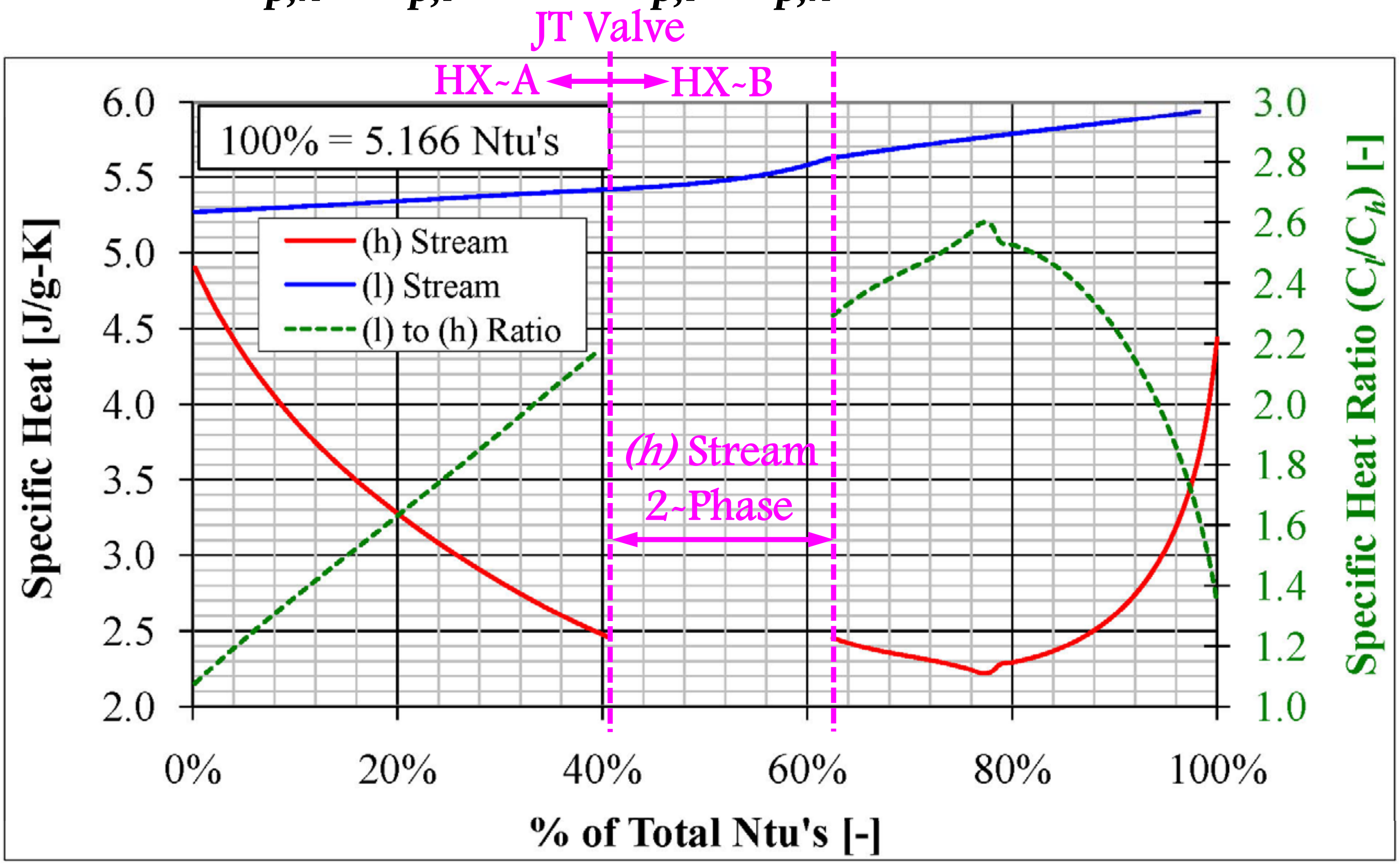
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

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



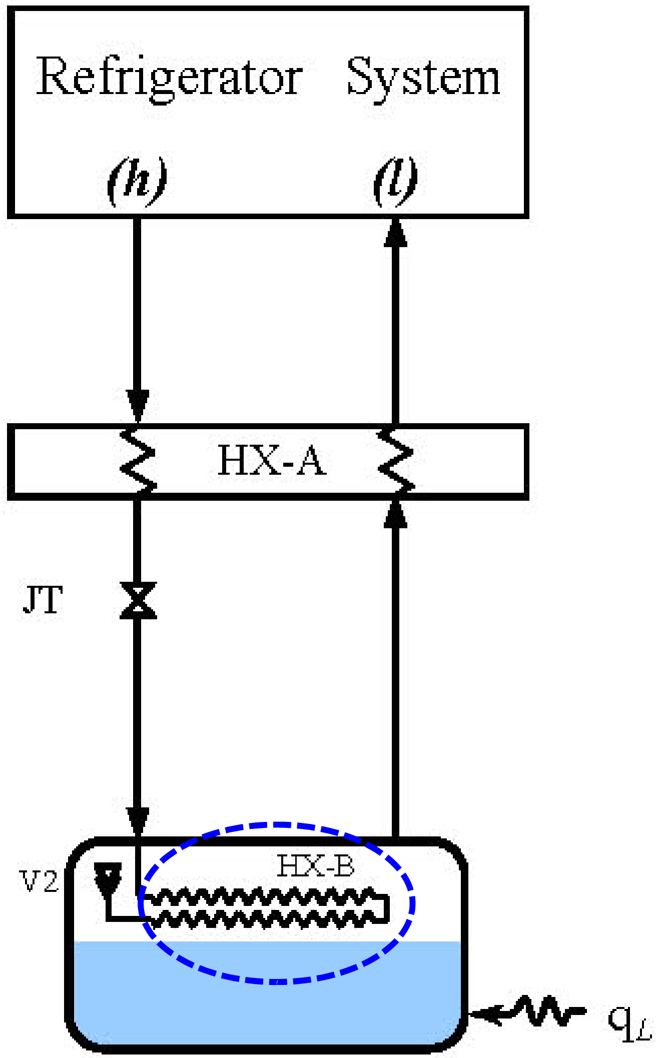
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

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



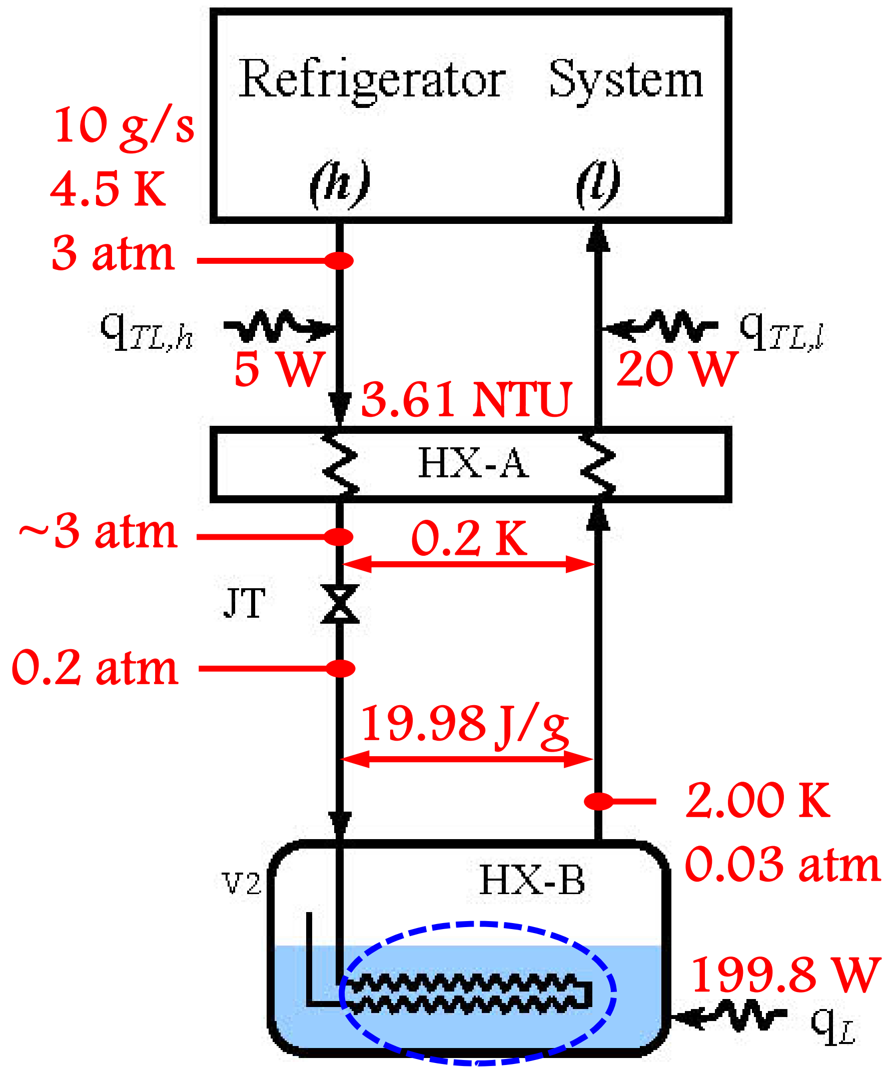
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- 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



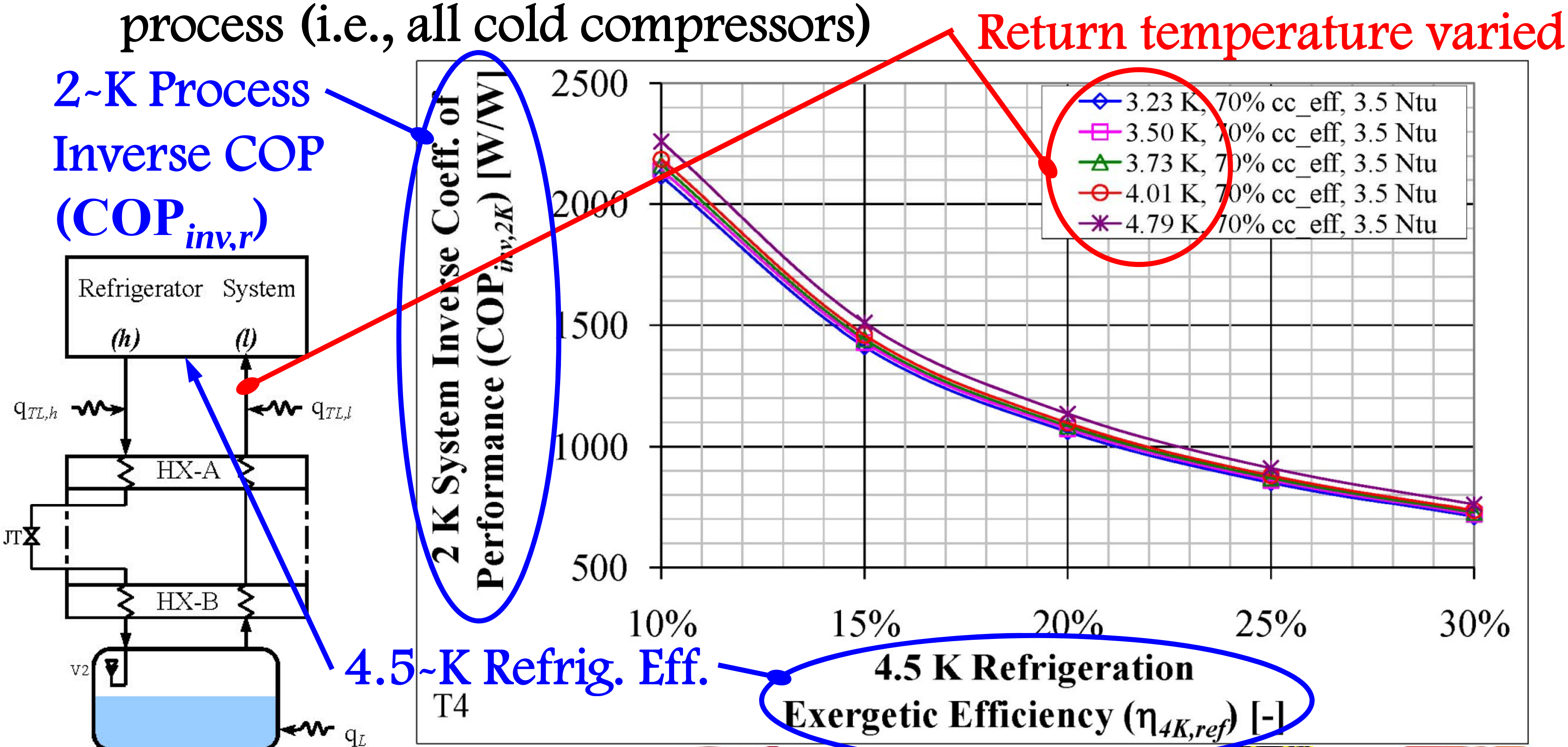
# Cold End Process Options for 2-K Helium System Efficiency Improvements

- 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!



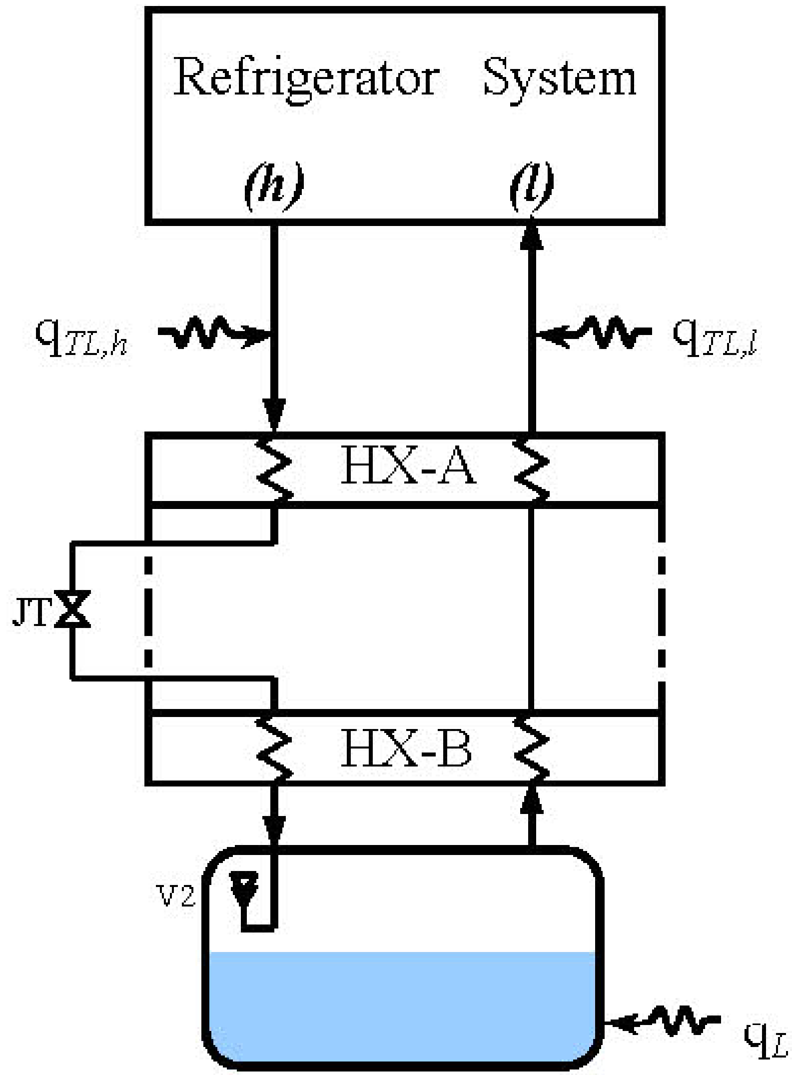
# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- Side note:
  - Sensitivity of *(l)* stream return temperature (out of warm-end of HX) to overall 2-K process efficiency is small; e.g., type-4 process (i.e., all cold compressors)



# Cold End Process Options for 2-K Helium System Efficiency Improvements

- Present development work
  - Designing concept validation prototype for MSU FRIB (~5 g/s)
  - HX dimensions, approx. 7 in diameter by 4 ft long
  - JT valve can be JLab type or commercial
  - Back-pressure valve (V2) is similar to a 'gravity' check valve



# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- Retro-fit of existing systems
  - Probably possible in many circumstances
  - But would need to be examined to see if the operational cost savings (from implementing modifications) reimburse the capital cost of re-work and operational cost of down-time in an acceptable period
  - If the existing system is similar to JLab's design, the implementation of this process could result in *~17% increase* in load capacity (for the same input power)

# *Cold End Process Options for 2-K Helium System Efficiency Improvements*

- Summary: This cold end process improvement is applicable for *all* nominal 2-K helium systems and could result in,
  - A 9.3% load capacity increase for the same input power for the 3 atm supply (as would be common in large systems)
  - or conversely, a 9.3% power reduction for the same load (supplied at 3 atm)
  - For a system that is roughly the size of MSU FRIB; i.e. 18 kW of 4.5-K refrigeration (equivalent),
    - Capital cost reduction ~6%; e.g., 6% of \$40M = \$2.4M
    - Operational cost reduction; e.g., 9.3% of 4.3 MW = 400 kW
      - » At \$0.05 kWh, ~\$175k per year (for 8760 h)

    - Ref. Knudsen, P., Ganni, V., "Cold End Process Options for Nominal Efficiency Improvements," JLab Technical Note 11-014, 2011