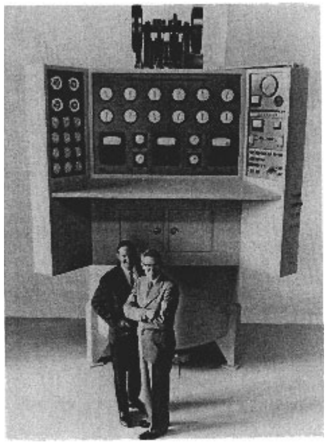
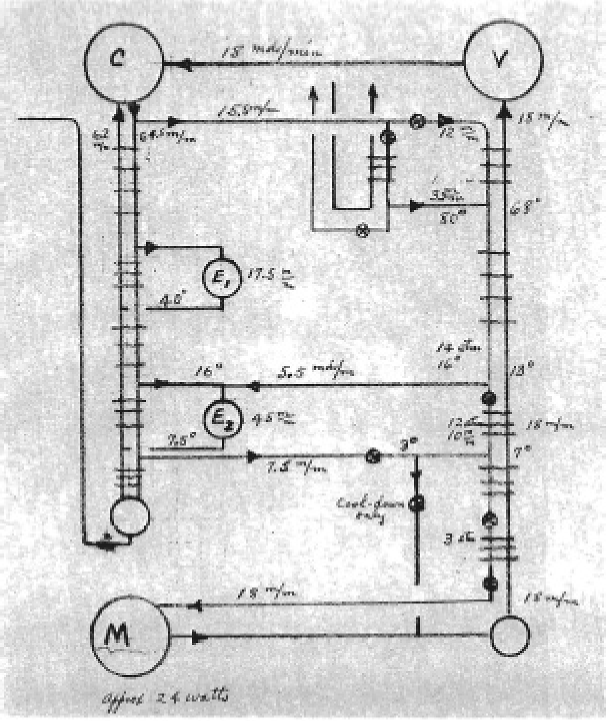
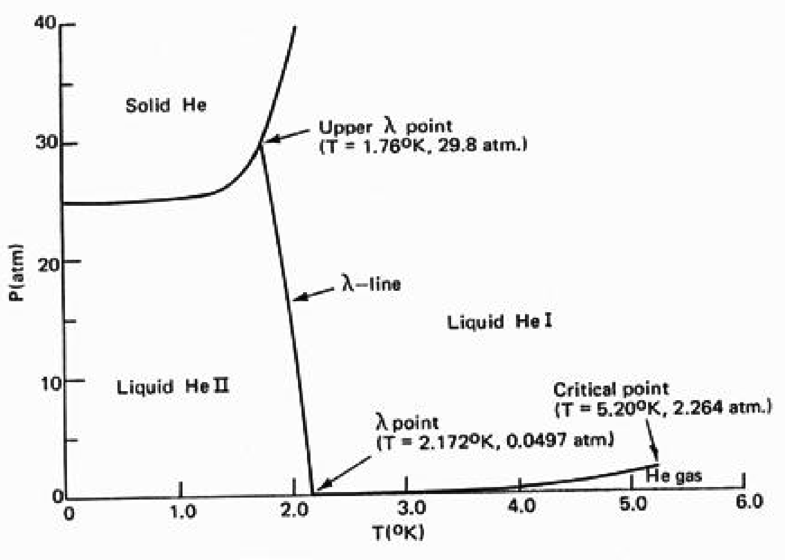
Process Study for the Design of Small Scale 2K Refrigeration System





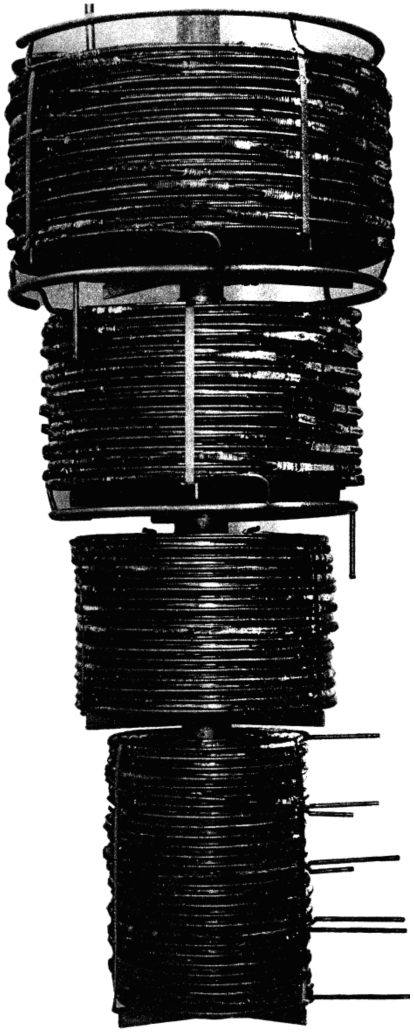


The phase diagram of He^4.

P. Knudsen

Cryogenics Group,

Engineering Division

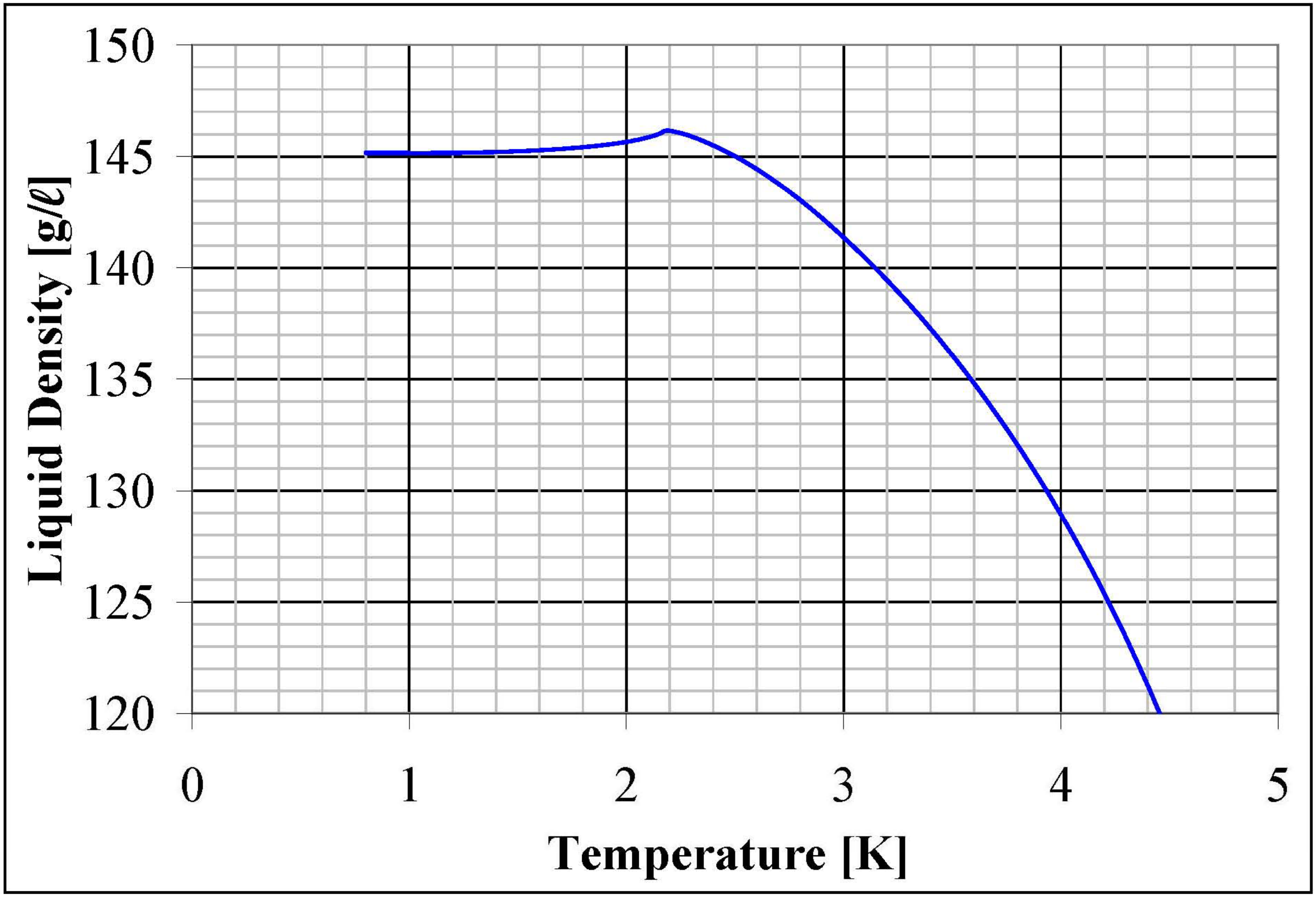


LOW PRESSURE HEAT EXCHANGER

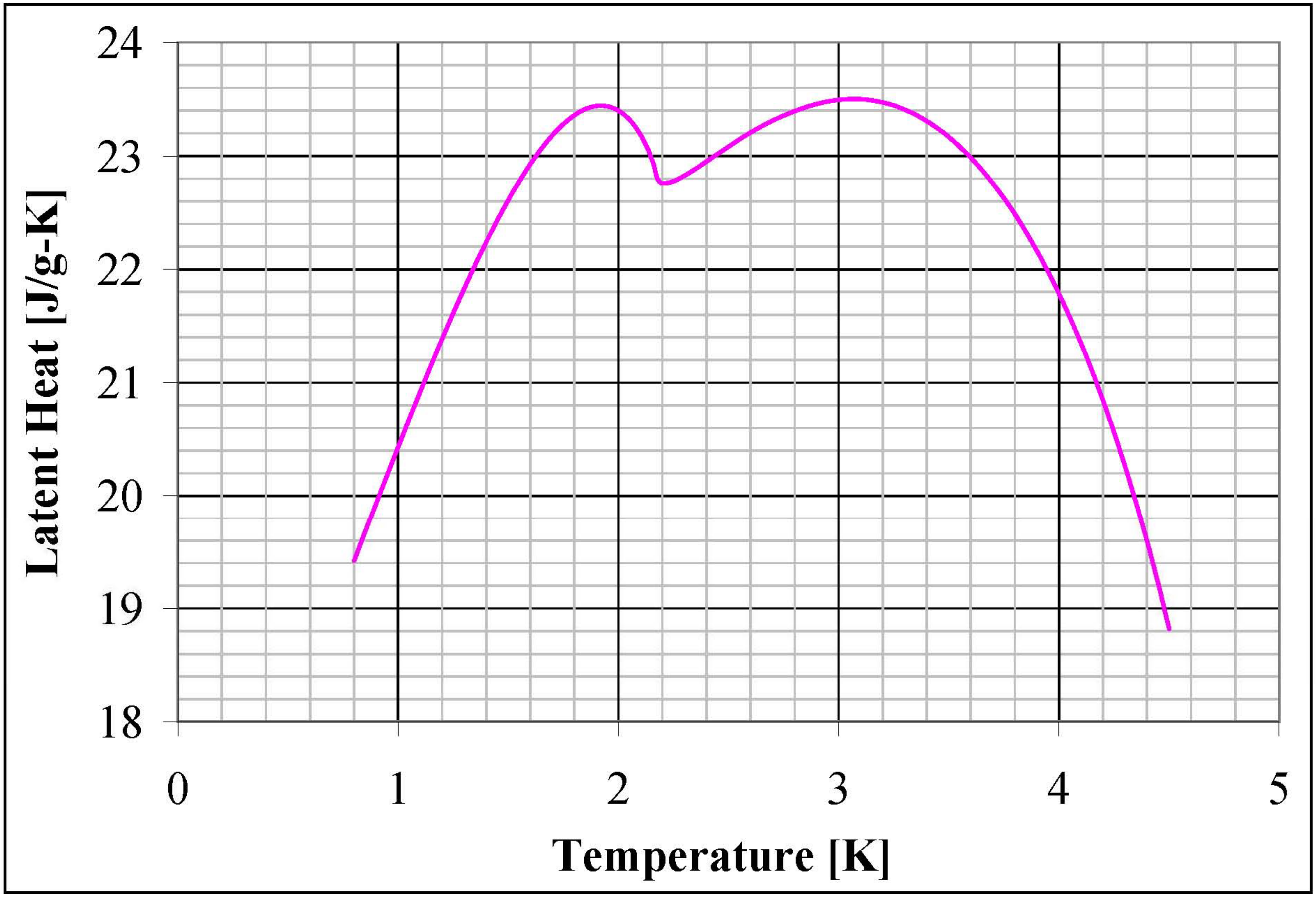
Process Study - Small Scale 2K Refrigeration

- Normal boiling point for Helium (I) at atmospheric pressure (1 atm) is 4.22 K (known in the field as 4.5-K)
- Helium II occurs below 'Lambda' transition temperature (T_λ) at ~2.2 K
  - —Density ~15% greater than Helium I at 4.5-K
  - —Two components are present
    - Normal fluid; ordinary Navier-Stokes fluid
    - Super-fluid (Helium II); has viscosity & entropy = 0
  - —Below 1 K, Helium II is 99% super-fluid
- Typically super-conducting (SC) magnets and SC radio-frequency use helium at 1.8 to 2.1 K (i.e., 0.016 to 0.041 atm)

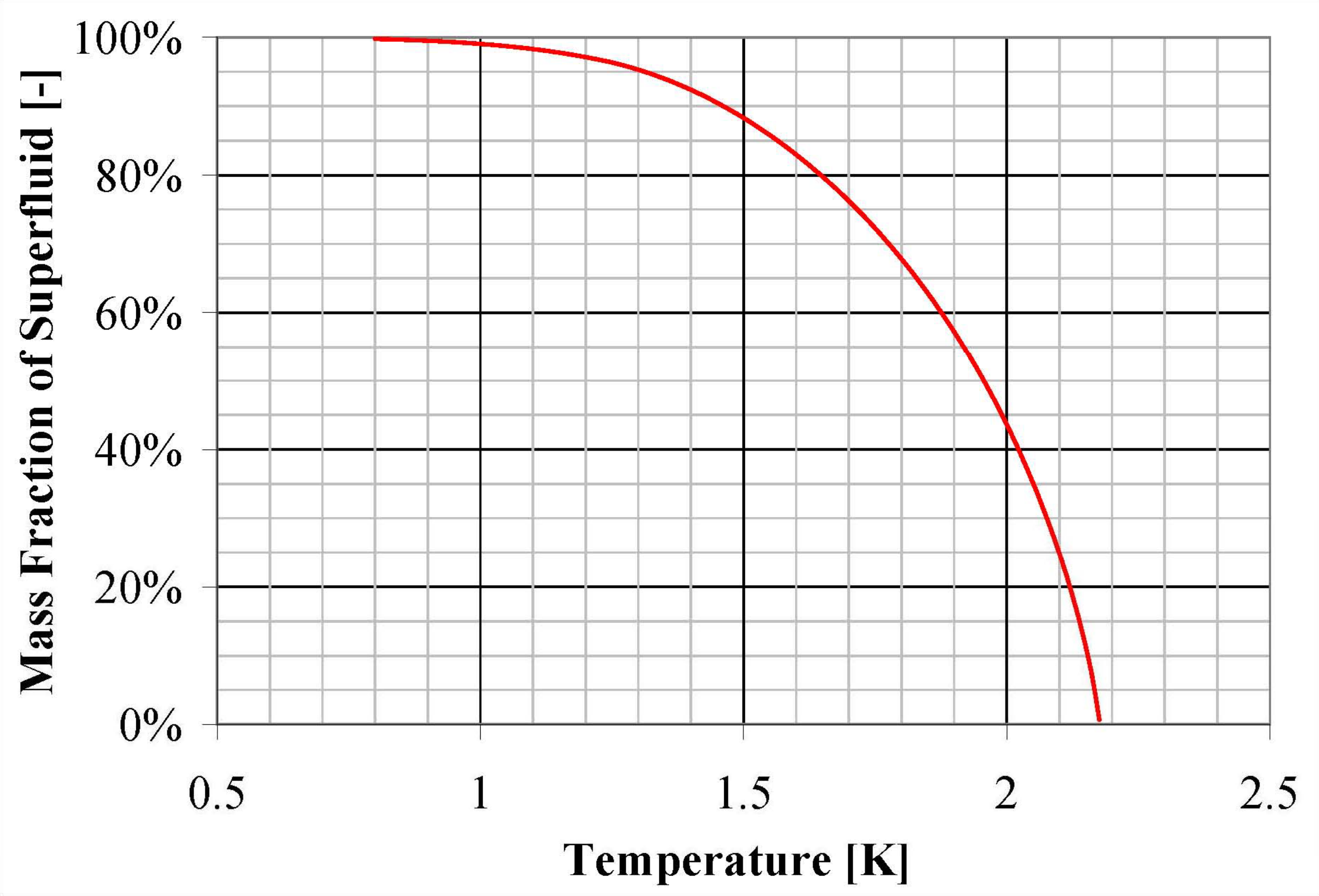
Process Study - Small Scale 2K Refrigeration



Process Study - Small Scale 2K Refrigeration



Process Study - Small Scale 2K Refrigeration



Process Study - Small Scale 2K Refrigeration

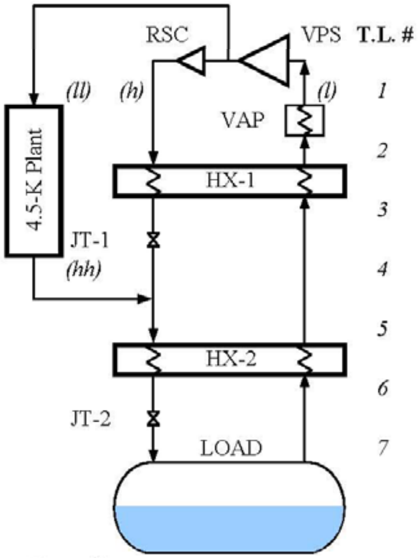
- For helium refrigeration below 4.22 K (but greater than ~0.8 K), typically four methods are used;
  - Direct vacuum pumping – none or very minimal recovery of sub-atmospheric helium sensible refrigeration (known in the field as refrigeration recovery) (ex. Triumf e-Linac, BNL ERL)
  - Refrigeration recovery using (ambient temperature) vacuum pumps (ex. SLAC, DESY TTF, JLab CTF)
  - Cryogenic centrifugal turbo-compressors (known in the field as 'cold compressors') – used to compress sub-atmospheric helium to ~1 atm. in conjunction with sensible refrigeration recovery (ex. CEBAF, SNS)
  - Combination of both cold-compressors and vacuum pumps (or screw compressors) in conjunction with sensible refrigeration recovery (ex. Tore-Supra, ELBE-Rossendorf, SBT CEA-Grenoble, LEP, LHC, MSU FRIB)

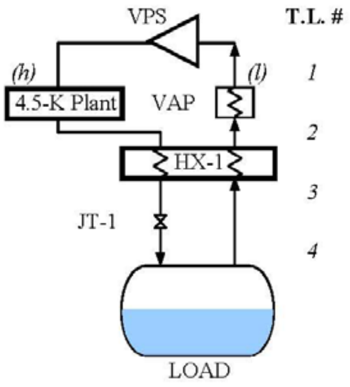
Process Study - Small Scale 2K Refrigeration

- OBJECTIVE: Process study centered around the development small scale (100 Watt Range) 2 Kelvin (K) Refrigerators capable of working in conjunction with a *commercially available* 4.5 K helium liquefaction system
- Major sub-systems of a small scale 2-K refrigeration system
  - Small (2-3 g/s) commercially available 4.5-K liquefier system (also referred to as a '4.5 K plant')
  - Vacuum pumping system (VPS) commercially available (on the order of 10 g/s)
  - Positive compression system (RSC) commercially available (on the order of 10 g/s)
  - 2 K cold box (CBX)

Process Study - Small Scale 2K Refrigeration

- 2-K CBX; consisting of:
  - —NO rotating machinery inside the refrigerator's 2K CBX; i.e., no cold compressors or expanders
  - —only passive components, such as heat exchangers (HX's) and Joule-Thompson (JT; or, throttling) valves
- PURPOSE: Study, the effect of key 2-K CBX process parameters, that yield the best performance; i.e.,
  - —Mass flow imbalance:
    - *(h)* to *(l)* streams
  - —Heat exchanger size (Ntu's)
    - HX-1, HX-2
  - —Supply pressure
    - (h) stream; $p_{h,1}$





Process Study - Small Scale 2K Refrigeration

- Practical issues key to objective but not directly coupled to process study
  - —Commercially available VPS and RSC require some mods to compensate for helium's high heat of compression – these are not typically supplied or known to manufacturers
    - E.g., oil injection and oil cooler sizing
  - —Properly designed oil removal system
    - Although proper design is relatively simple, oil carry-over into CBX is an *unpublished but very common problem* (Fermi, BNL, CERN, SNS Target refrigerator, Triumf and others)

Process Study - Small Scale 2K Refrigeration

- Continued…practical issues key to objective
  - —Proper mechanical design to minimize risk of air leaks into sub-atmospheric stream
    - The use of 'guard vacuum' (as it is known in the field)
    - Proper helium mass-spectrometer leak testing during fabrication
    - Proper selection of joints and seals
    - Usefulness of oil-flooded vacuum pumps (sealing)
  - —Integrated helium purifier to remove air contamination
    - 'ppm' (parts-per-million) level of contamination will occur and be present despite best practices and design
    - Will affect the interval length between warm-ups

Design to minimize possibility of leaks and effect of leaks, but also design as if (i.e., assume) they will be there!

Process Study - Small Scale 2K Refrigeration

- Two comparable (recent) 2-K systems
  - —JLab Cryogenic Test Facility (CTF)
  - —DESY TESLA Test Facility (TTF)
- 'Comparable' – meaning distinct and separate:
  - —4.5-K plant (supplying super-critical helium to 2-K CBX)
  - —VPS and RSC
- Only able to obtain data on JLab CTF

Process Study - Small Scale 2K Refrigeration

	JLab CTF	DESY TTF
Load Temperature	2.0 K	1.8 K
Nominal Load	180 W (9 g/s)	200 W (10 g/s)
4.5-K Plant	Koch Model 2200 588 W at 4.5 K, or 5.35 g/s 4.5 K liquefaction	Linde AG 900 W at 4.5 K and, 2 kW at 70 K
Vacuum Pumps	Kinney Lobe Blower, KMBD-8000 Kinney Liquid Ring Pump, KLRC-2100S	Leybold Lobe Blowers RA16000, RA13000, RA9001 Leybold Rotary Vane Pumps, SV1200

Process Study - Small Scale 2K Refrigeration

- Possible optimization goals
  - —Maximum overall efficiency
    - This objective seeks to minimize input power and utility consumption for a specified load
    - Typically (but not always) used for new designs
  - —Maximum system capacity
    - i.e., for the given equipment, what is the largest load that can be supported, regardless of the input power
    - Typically (but not always) used for existing equipment
- In general, other optimization goals
  - —Maximum reliability
  - —Maximum availability
  - —Minimum maintenance

Process Study - Small Scale 2K Refrigeration

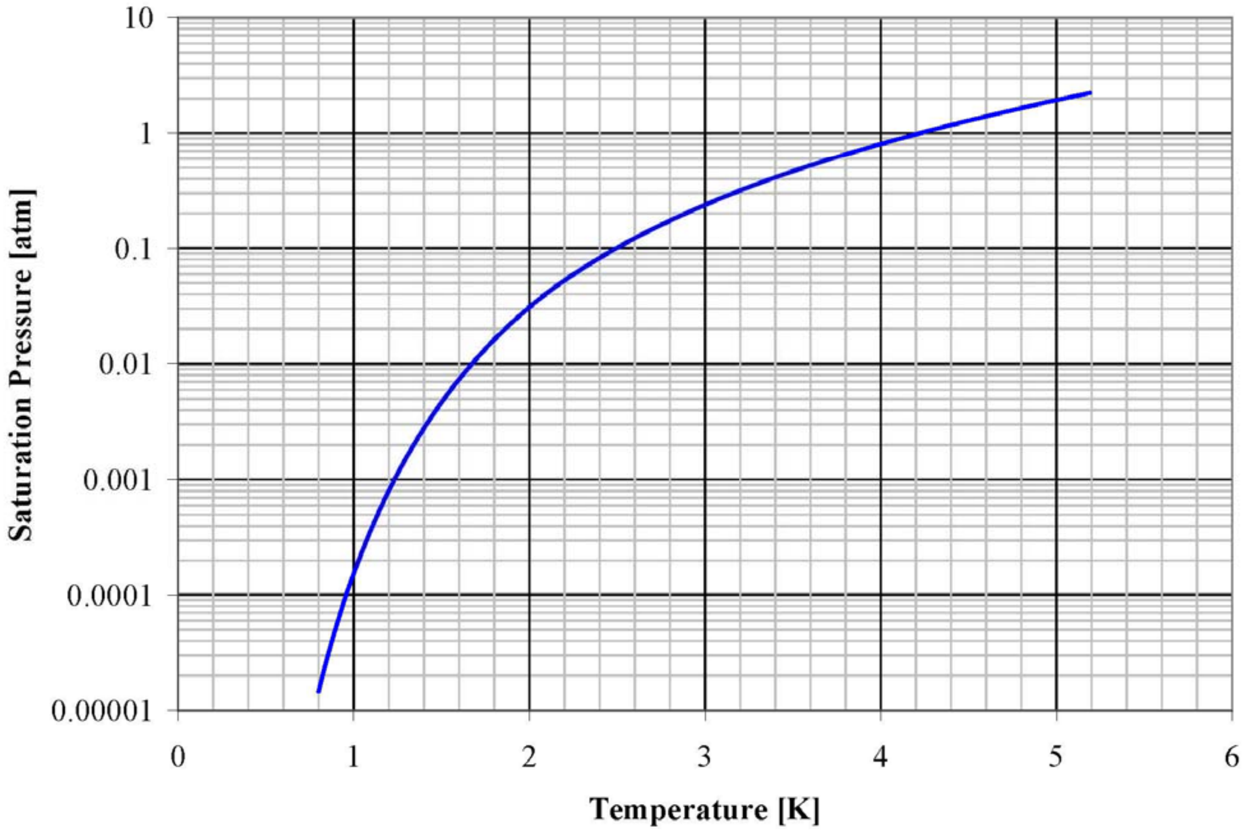
- These optimizations are usually not mutually exclusive
- Usually, optimization for maximum overall efficiency results in a global optimum of the others
- For this study, will seek to maximize overall efficiency using typical realistic performance not specific to any particular manufacturer

Process Study - Small Scale 2K Refrigeration

- Process parameters
  - —Fixed process parameters
    - i.e., either constant values or fixed characteristics
    - E.g., load temperature, 4.5 K system exergetic efficiency, isothermal efficiency of VPS, heat in-leak, sub-atm stream pressure drop
  - —Varied process parameters
    - i.e., varied over a predetermined range or set of proposed configurations
    - E.g., mass flow ratio, total HX Ntu's, supply pressure
  - —Overall efficiency of 2-K system is strongly influenced by both of these types of parameters

Process Study - Small Scale 2K Refrigeration

- Fixed parameters:
  - —Load temperature – for helium II
    - T ~ ***ln***(p), so T ~ isothermal input power



Process Study - Small Scale 2K Refrigeration

- Fixed parameters…continued
  - Overall exergetic efficiency of commercial 4.5-K liquefier system
    - This ‘system’ includes not only the cold box but also the compression and gas management systems.
    - Unpublished data indicated 11-13%
  - Isothermal efficiency of VPS
    - This is a very significant usage of the total input power losses (~40%)
  - Parasitic (non-load) heat in-leak into the process
    - Assumed 55 W, divided proportionally to each HX size
    - Maybe somewhat large but will deter from too optimistic performance

Process Study - Small Scale 2K Refrigeration

	w_L [g/s]	E_L [kW]	P_T [kW]	η_C [-]
GM Cryocooler	0.014	0.0952	19.5	0.5%
Linde 1600	1.97	13.6	124	10.9%
Linde 1600 (Mod)	2.10	14.5	129	11.3%
Linde 2200 (Mod)	3.92	27.1	206	13.2%
CTF (Koch 2200)	5.35	37.0	307	12.0%
CTI/Helix 1500W	11.0	76.0	807	9.4%
SSC ASST-A	34.1	235.9	1582	14.9%

Nomenclature:

w_L - *net helium liquefaction flow [g/s]*

$\Delta\varepsilon_L$ - *specific exergy for 4.5-K liquefaction* = 6.91 [kJ/g]

E_L - *load Carnot (reversible) input power [kW]*, $= w_L * \Delta\varepsilon_L$

w_{LN} - *nitrogen mass flow [g/s]*, 1.3 [gph / (g/s)] *or* 4.9 [ℓph / (g/s)]

η_{LN} - *LN equivalent efficiency [-], = 35% (assumed in this study)*

$\Delta\varepsilon_{LN}$ - *specific exergy for LN cooling*, = 0.70 [kJ/g]

E_{LN} - *LN cooling Carnot input power [kW]*, $= \Delta\varepsilon_{LN} * w_{LN}$

P_{LN} - *equivalent input power for LN [kW]*, $= E_{LN} / \eta_{LN}$

P_m - *total electrical power input [kW]*

P_T - *total power input (incl. LN) [kW]*, $= P_m + P_{LN}$

η_C - *Carnot efficiency*, $= E_L / P_T$

Process Study - Small Scale 2K Refrigeration

- Fixed parameters…continued
  - Sub-atmospheric pressure drop
    - From load to VPS suction
    - Assumed proportional to HX size (Ntu's)
    - Most importantly, this affects the size of the VPS required.
      - i.e., the suction pressure is inversely proportionally to the VPS volumetric capacity requirement

Process Study - Small Scale 2K Refrigeration

- Varied process parameters
  - (Mass) Flow ratio: ratio of high pressure helium flow to sub-atmospheric helium flow in the main HX
    - Varied from 40 to 100% (as solution allows)
    - Also called 'flow imbalance'
  - Total HX Ntu's
    - Varied from 20 to 45 (inc. 5)
    - Greater than 45 not studied due to excessive sub-atmospheric pressure drop
    - Proportional to HX effective length
    - Also, for a fixed return flow, this is proportional to the HX size and total thermal rating (UA)

Process Study - Small Scale 2K Refrigeration

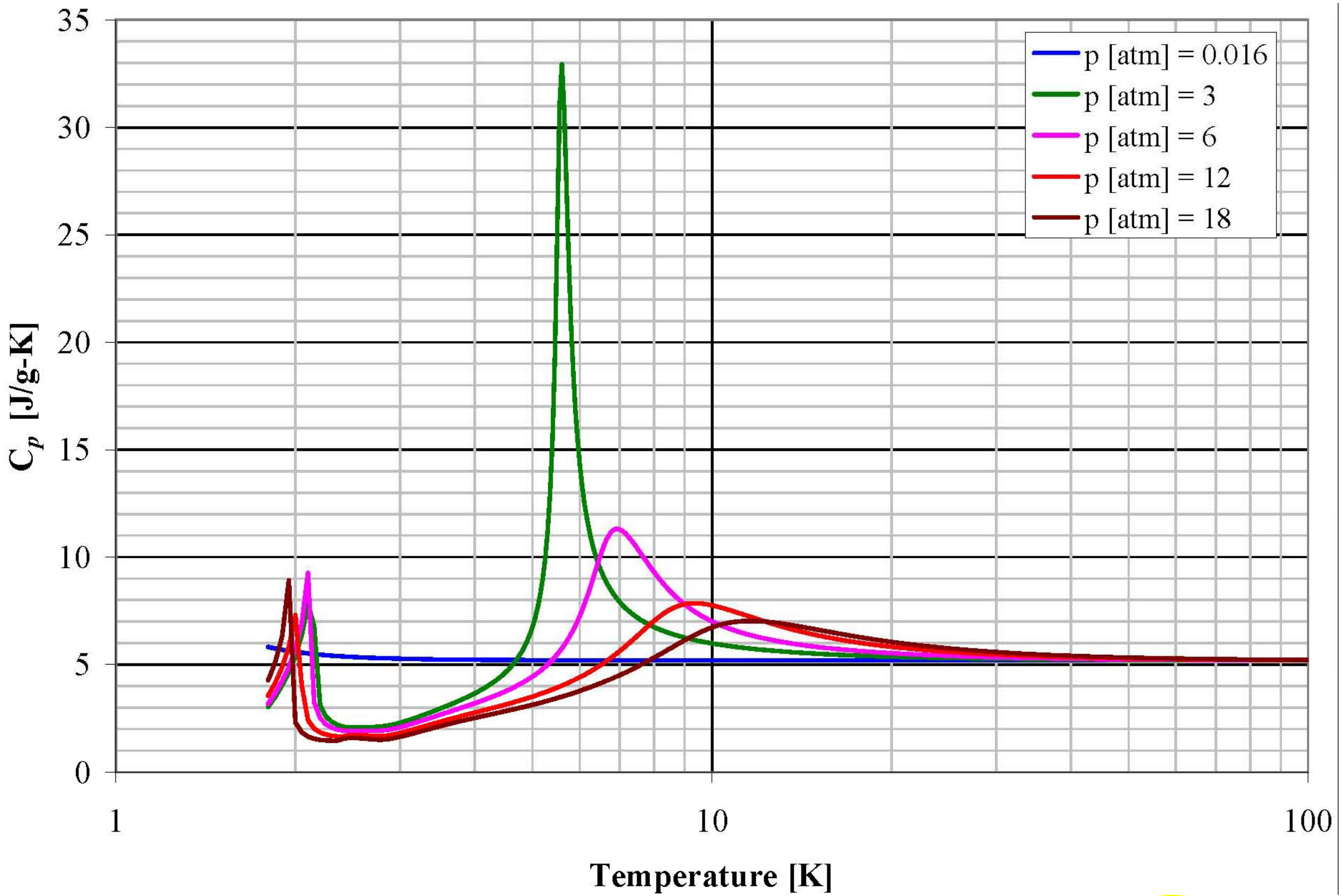
- Varied process parameters…continued
  - Supply pressure to 2-K CBX (from RSC discharge)
    - Varied from 6 to 18 atm (inc. 3)
    - Determines availability (exergy) supplied to 2-K CBX and to a lesser degree the input power to the RSC

Process Study - Small Scale 2K Refrigeration

- Helium's specific heat capacity & HX's
  - Cannot ignore very non-linear C_p [J/g-K] for both real fluid near liquid-vapor dome and for Helium II (i.e., below T_λ)
    - Note: Helium's critical pressure and temperature is 2.245 atm & 5.195 K
    - Helium $C_p \approx 5.2$ J/g-K at 1 atm 300 K
  - Process design must deal with C_p variation in the most reversible manner possible.
  - What is the (theoretically) most reversible stream temperature difference (ΔT_{hl}) distribution in a counter flow HX?

$\Delta T_{hl} / T =$ constant (ref. Grassmann & Kopp)

Process Study - Small Scale 2K Refrigeration



Process Study - Small Scale 2K Refrigeration

- Helium's C_p & HX's…continued
  - —Ideal ΔT_{hl} distribution is quite different from the predicted logarithmic temperature distribution for a constant stream capacity HX
  - —To deal with this, increasing HX Ntu's (i.e., effective length) will,
    - Decrease finite temperature difference losses but,
    - Increase sub-atmospheric stream pressure drop losses
  - —Fortunately in practice, HX exergetic losses are only on the order of 5% of the total equivalent input power
    - These HX losses are composed of losses due to a finite temperature difference, pressure drop and heat in-leak
    - Sub-atm pressure drop in HX's composes almost all of HX pressure drop losses, but is only ~13% of the 5% (i.e., less than 1% of total input power)

Process Study - Small Scale 2K Refrigeration

- Helium's C_p & HX's…continued
  - —So, for HX design, require
    - At least 1 meter of effective length per 10 Ntu's (for aluminum brazed HX's)
    - Sufficient cross-sectional area so that sub-atmospheric pressure drop is no more than 25% of the load saturation pressure

Process Study - Small Scale 2K Refrigeration

- Model component characterizations
  - —Fluid properties: HePak (v3.4) for helium and GasPak (v3.30) for nitrogen
  - —4.5-K liquefaction system exergetic efficiency
    - Large liquefiers ~25% (i.e., 100's g/s)
    - For liquefier systems producing 2-3 g/s, the study will assume 10% (except where liquid nitrogen pre-cooling is employed for the 2-K CBX, where it will be 11%)

    Note: The performance of the 2 K system is primarily dependent on the 4.5 K system exergetic efficiency!

    - Assume supply is super-critical (SC) helium at 3 atm and 4.5 K (i.e., close to liquid enthalpy for easy of flow distribution)

    Note: Many small systems do not use SC helium supply, but rather sub-cooled liquid. This must be examined carefully since two phase flow is possible.

Process Study - Small Scale 2K Refrigeration

Model component characterizations

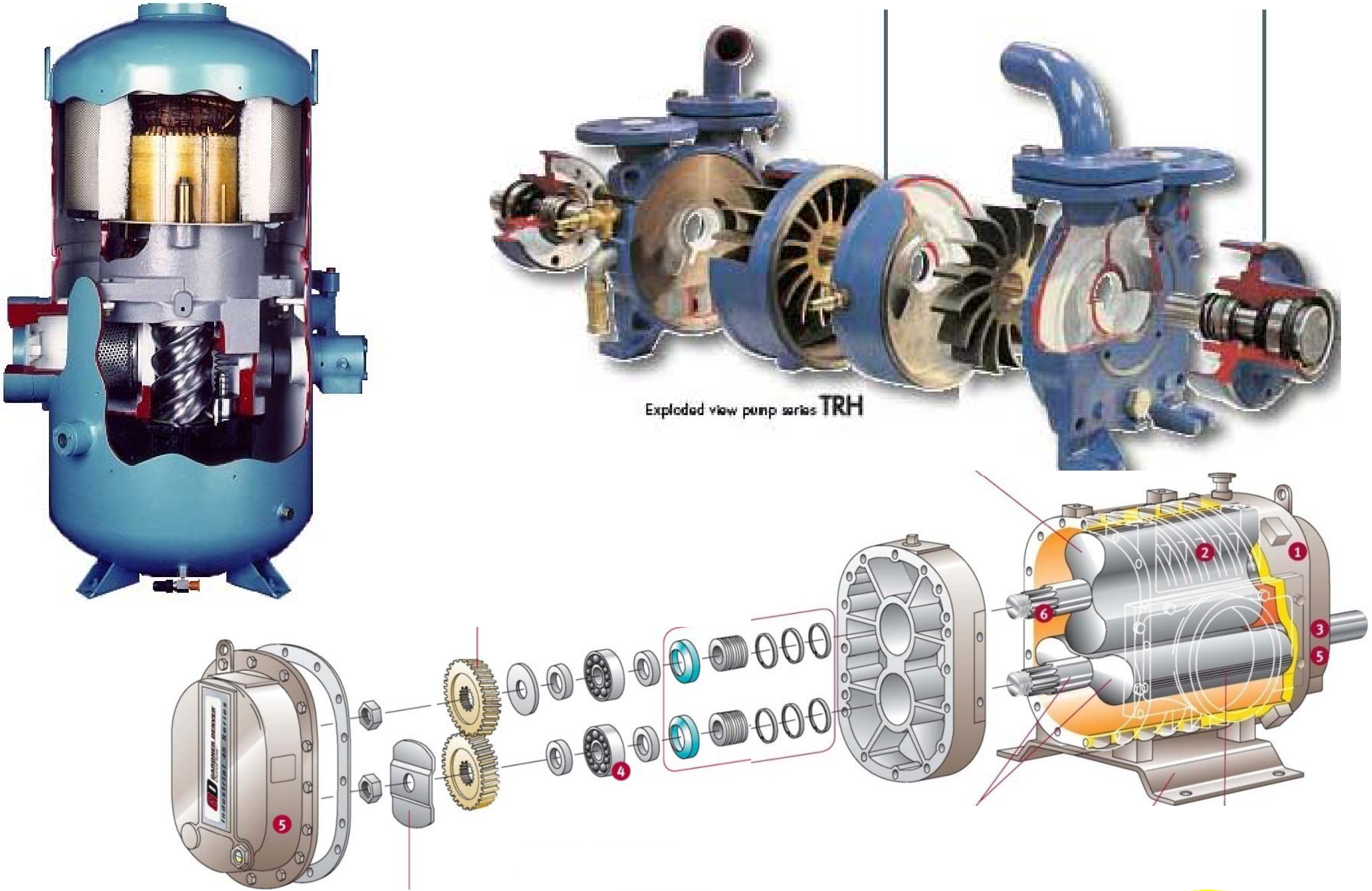
Process Study - Small Scale 2K Refrigeration

- Model component characterizations…cont.
  - —Vacuum pumping system (VPS)
    - Typically consists of (one or several) roots (lobe) blower(s) and either a liquid ring type pump(s) or a rotary vane type pump(s)
    - Isothermal efficiency (η_{iso}) is proportional the logarithm of the pressure ratio; but this is essential constant
    - Based upon JLab's CTF VPS, use $\eta_{iso} = 14.5\%$
    - HX pressure drop for sub-atm stream can contribute significantly to both the displacement (size) required for the VPS and the isothermal efficiency (due to an increased pressure ratio)
  - —Compression system
    - Typically an oil-flooded rotary screw compressor (RSC)
    - Isothermal efficiency is primarily a function of the pressure ratio (for a given stage type and built-in-volume ratio)
    - From published data, use a linear characterization,

$$\eta_{iso} = 0.6 - 0.0177\cdot(p_{r,c} - 3)\text{, valid from 3-18 atm}$$

Process Study - Small Scale 2K Refrigeration

- Model component characterizations…cont.



Process Study - Small Scale 2K Refrigeration

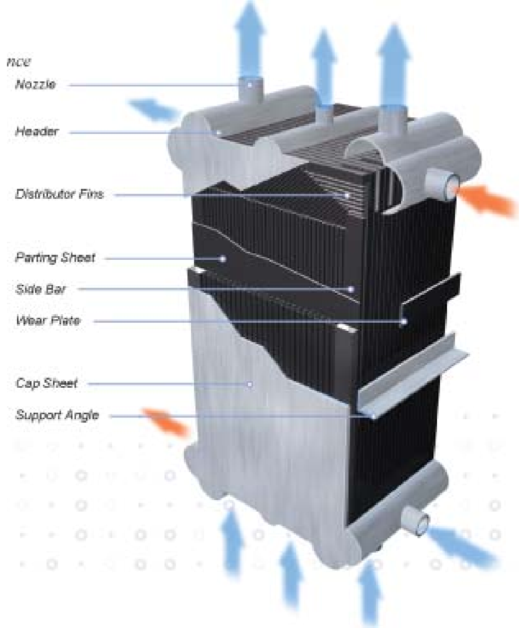
- Heat exchangers
  - —For sub-atmospheric pressure drop use,

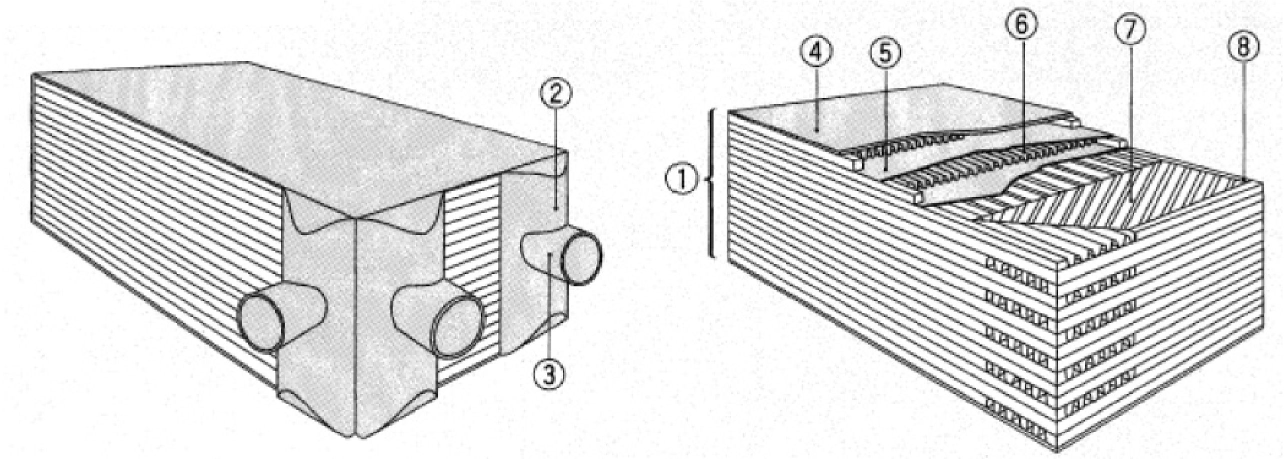
    Δp_l [atm] = $(2x10^{-4})\cdot$Ntu

    i.e., Δp_l = 0.004 to 0.009 atm for 20 to 45 Ntu's
  - —For (UA) and Ntu calculations, use integrated cooling curve since constant (or average) stream capacity is grossly inaccurate
    - i.e., methodology is to sub-divide HX into sufficiently small temperature spans so that constant stream capacity assumption becomes sufficiently precise
    - It is important to preserve sub-division and overall energy balance

Process Study - Small Scale 2K Refrigeration

- Heat exchangers…continued
  - —Calculation of HX thermal effectiveness is more involved since the minimum stream temperature difference (i.e., ‘pinch’) may not occur at the ends
  - —The condition where the ‘pinch’=0 is then the maximum heat transfer possible

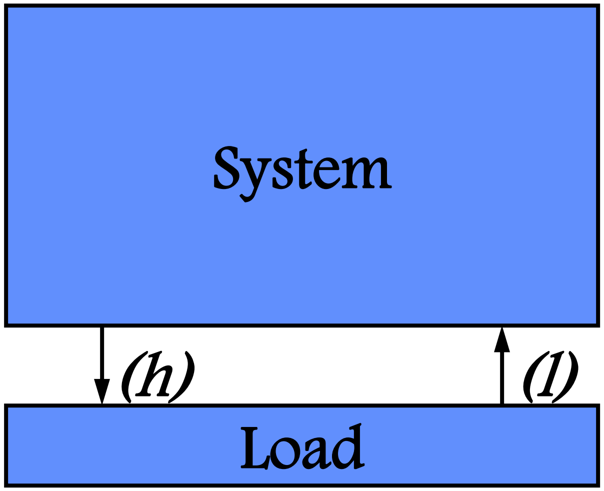




1.Block(Core)
2.Header
3.Nozzle
4.Cap Sheet(Side Plate)
5.Parting Sheet(Tube Plate)
6.Heat Transfer Fin(Corrugated Fin)
7.Distributor Fin
8.Side Bar(Spacer Bar)

Process Study - Small Scale 2K Refrigeration

- Exergy & Its Usage
  - Useful in quantifying how input power is utilized in the process
  - Specific physical exergy, $\varepsilon = h - T_0{}^{*}s$
    - $T_0 = 300$ K (reference temperature of zero availability)
  - Example;



System

(h)

(l)

Load

For steady conditions with
no mass accumulation and,
only one environmental heat sink,
the reversible, or exergetic input power:

$$E = \dot{W}_{rev} = \dot{m}_h \cdot \varepsilon_h - \dot{m}_l \cdot \varepsilon_l$$

Process Study - Small Scale 2K Refrigeration

- Measures of Process Performance
  - —Exergetic efficiency (η_C)
    - Also known as efficiency as compared to Carnot, or (abbreviated) just 'Carnot' efficiency
    - Ratio of reversible input power required by load to actual total input power
    - For cases involving LN pre-cooling, need to account for cooling provided by this utility
      - – Equivalent input power is reversible input power divided by LN system Carnot efficiency
      - – For this study assume $\eta_{C,LN} = 35\%$
      - – Add equivalent input power of LN pre-cooling to input power to obtain total equivalent input power

Process Study - Small Scale 2K Refrigeration

- Measures of Process Performance…continued
  - Inverse of Coefficient of Performance (COP$_{INV}$)
    - Two types used
    - *Real* COP$_{INV}$ – ratio of total (equivalent) input power to the heat into Helium II bath (or 'heat load')

$$COP_{INV} = \frac{P_{tot}}{q_L}$$

    - *Ideal* COP$_{INV}$ – ratio of reversible input power required by CBX & load (i.e., the availability given to the CBX) to the heat into the Helium II bath

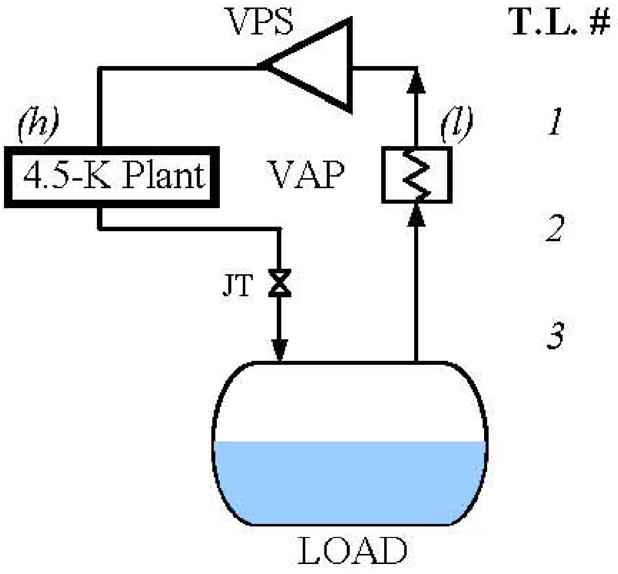
$$COP_{INV} = \frac{E_{cbx}}{q_L}$$

Process Study - Small Scale 2K Refrigeration

- Measures of Process Performance…continued
  - —*Real* & *Ideal* COP_{INV} useful in examining loss effects between active and passive components
  - —Key independent process parameters (flow ratio, total HX Ntu's and 2-K CBX supply pressure) will be studied with respect to these COP_{INV}'s.
  - —Consistency of interface locations and process conditions between 4.5-K liquefier and 2-K CBX important so comparing performance parameters is meaningful
    - 3 atm, 4.5 K supply to 2-K CBX
    - Either 1.05 atm, 300 K or 1.2 atm, 79.4 K from 2-K system to 4.5-K liquefier system

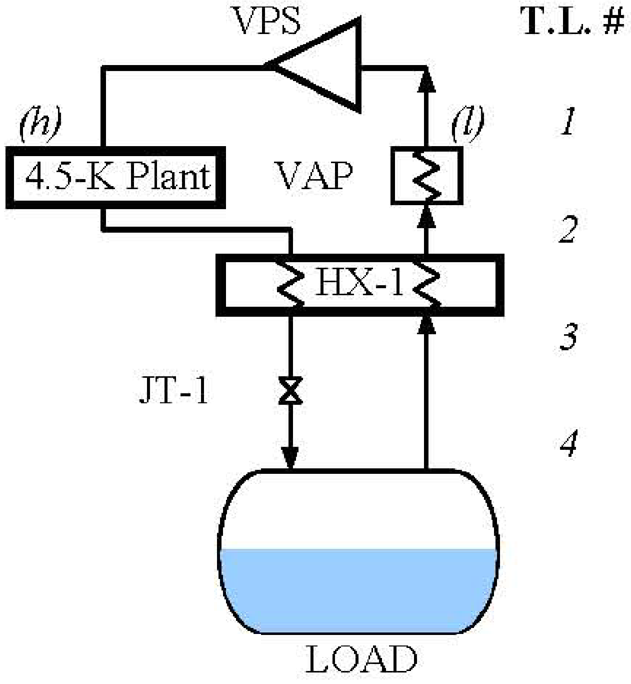
Process Study - Small Scale 2K Refrigeration

- Direct Vacuum Pumping
  - This is a very commonly used method
    - Useful for 2-K loads less than 50 W and for short or very infrequent testing programs
  - No or very little sensible recovery of load refrigeration; sub-atmospheric return flow is warm to ambient temperature using ambient air heat exchanger ('VAP')
  - For 4.5-K plant with η_C = 10%,
  - *Ideal* COP_{INV} ~700 W/W
  - *Real* COP_{INV} ~6500 W/W



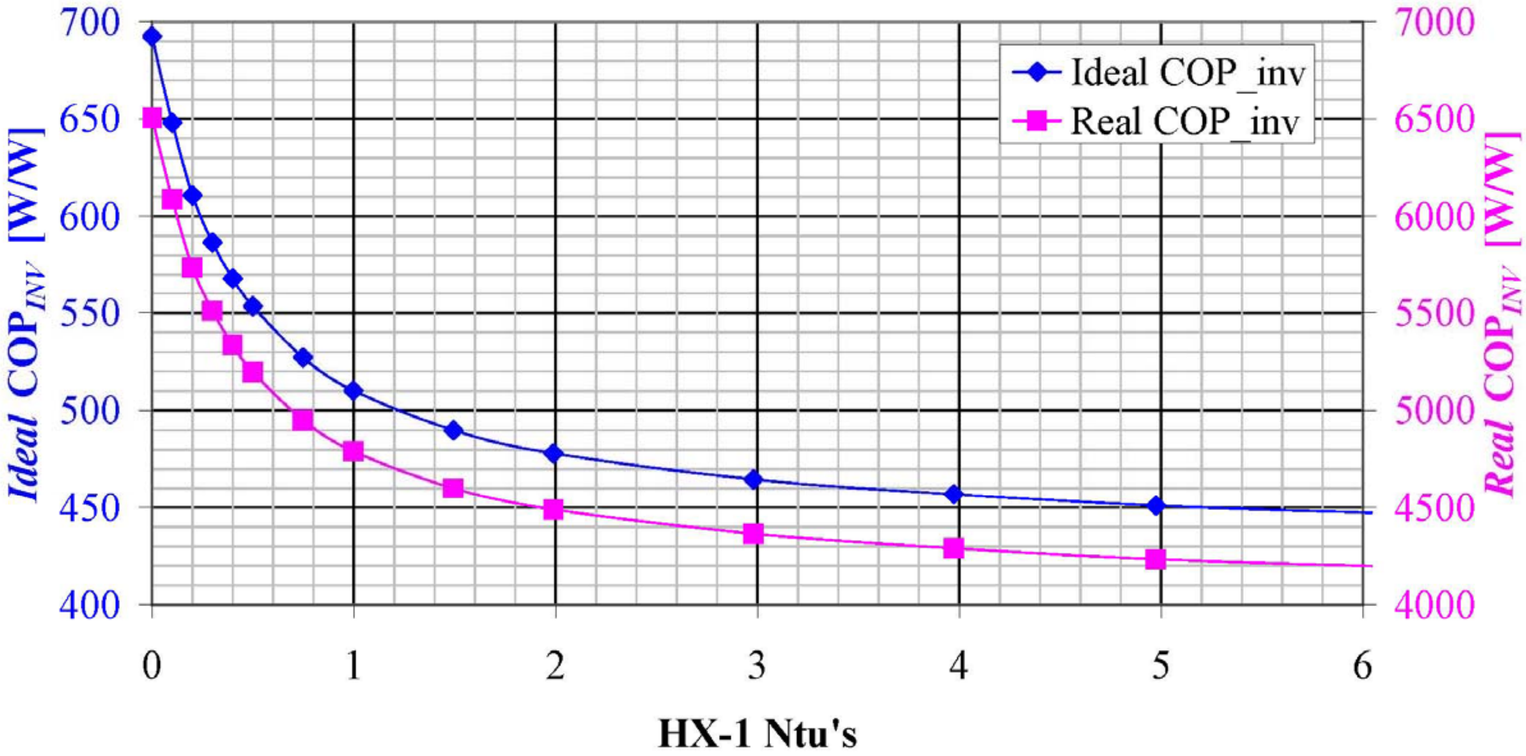
Process Study - Small Scale 2K Refrigeration

- Direct Vacuum Pumping…continued
  - —If a small HX is introduced to recovery a portion of the highly valuable sub-atmospheric stream refrigeration between 2 and 4.5 K…
  - —Reduces COP_{INV}'s by ~30% for 2 Ntu's
  - —Reduces COP_{INV}'s by ~35% for 6 Ntu's



Process Study - Small Scale 2K Refrigeration

- Direct Vacuum Pumping…continued
  - —At 6 Ntu's
    - *Ideal* COP_{INV} ~450 W/W
    - *Real* COP_{INV} ~4200 W/W



Process Study - Small Scale 2K Refrigeration

- Direct vacuum pumping result provides an upper limit (worst case) on COP_{INV} values to expect from process configurations to be studied
- As a lower limit (best case) on expected COP_{INV} values, performance of large 2-K systems using cold-compressors is ~900 W/W (for *real* process) for 4.5-K plant with $\eta_C = 25\%$

Note: Using cold-compressors with small 4.5-K systems (say, $\eta_C \sim 10\%$) may NOT be more efficient than a properly designed 2 K refrigeration recovery system.

Process Study - Small Scale 2K Refrigeration

- Comparable 2-K systems – JLab CTF
  - —Real COP_{INV} ~3400 W/W
- In summary, for process configurations to be studied, real COP_{INV} should be,
  - —Much less than 4200 W/W
  - —Probably less than 3400 W/W
  - —Greater than 900 W/W

2-K Load		
Temperature	2.09	[K]
Pressure	0.040	[atm]
Heat Load	140	[W]
Mass flow	9.0	[g/s]
Effective latent heat	15.5	[J/g]
Exergy	**24.5**	[kW]

4.5-K Liquefier System		
Compressors		
Input power	270	[kW]
LN System		
Mass flow	6.8	[g/s]
Carnot efficiency	35.0%	[-]
Equivalent input power	13.4	[kW]
Sub-Total	**284**	[kW]

Vacuum Pumping System		
Pressure ratio	42.8	[-]
Isothermal efficiency	14.2%	[-]
Input power	**149**	[kW]

2-K Compressor System		
Pressure ratio	13.8	[-]
Isothermal efficiency	38.0%	[-]
Input power	**38.9**	[kW]

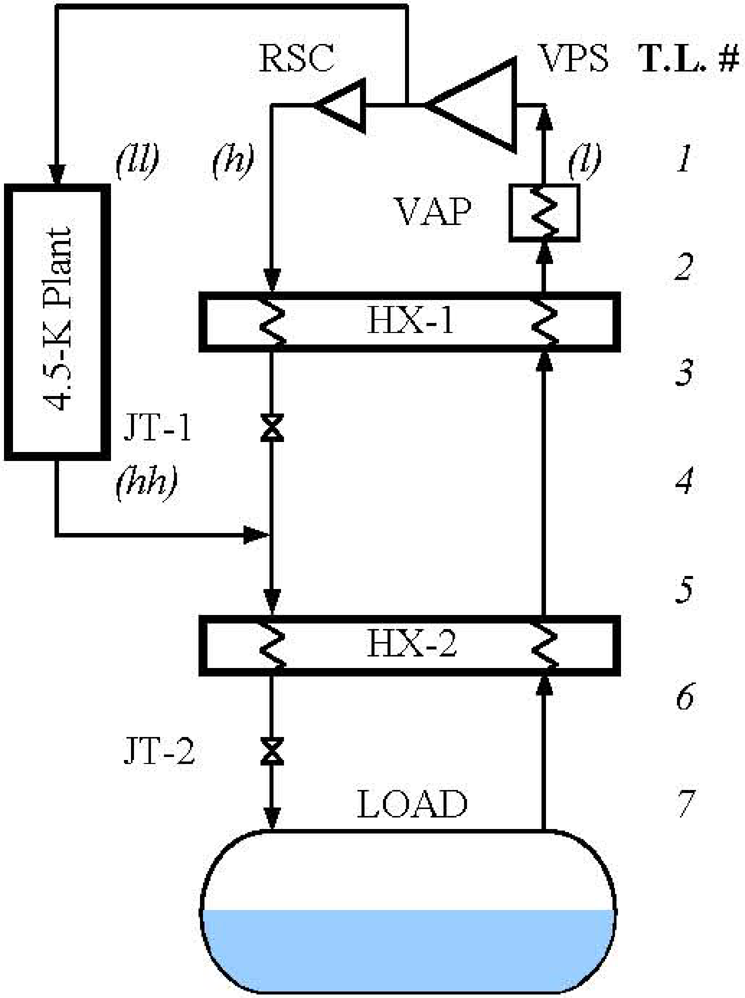
Overall 2-K System		
Total input power	**472**	[kW]
COP_{INV}	3368	[W/W]
Carnot efficiency	5.2%	[-]

Process Study - Small Scale 2K Refrigeration

- Process model simulation
  - Common parameters for each process configuration studied
    - Load temperature of 2 K (i.e., 0.0310 atm saturation pressure)
    - High pressure stream total pressure drop of 0.35 atm (distributed proportionally to HX Ntu's)
    - 2-K system compressor suction pressure of 1.05 atm
    - 2-K system compressor suction/discharge and vacuum pumping system discharge temperature of 300 K
    - 2-K system compressor and vacuum pumping system motor efficiency of 90%
    - Coldest HX size of 5 Ntu's (except for C2-B)
    - LN pre-cooling system Carnot efficiency of 35% (for C2-B)
    - 4.5-K liquefier system Carnot efficiency of 10% (except C2-B which is 11%) and supply to 2-K CBX of 3 atm 4.5 K
    - Total return flow (from 2-K load) of 12 g/s (to be consistent)

Process Study - Small Scale 2K Refrigeration

- Configuration C2-A
  - Refrigeration of sub-atmospheric *(l)* flow from 2-K load recovered to nearly 300 K using HX-1 & HX-2; then warmed to 300 K using ambient vaporizer (VAP)
  - Vacuum pumping system (VPS) compresses to slightly positive pressure of 1.05 atm, where a portion (the make-up) is diverted to the 4.5-K plant {i.e., *(ll)* stream}

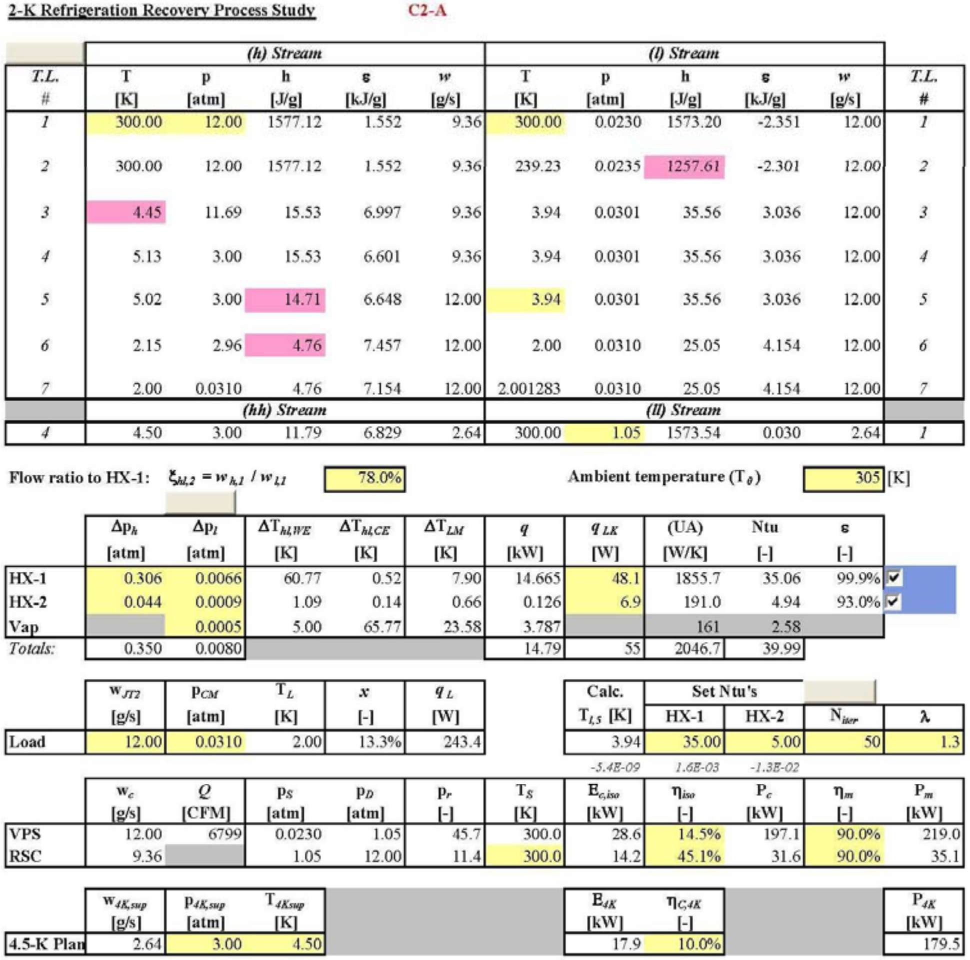


Process Study - Small Scale 2K Refrigeration

- Configuration C2-A…continued
  - —Recall that 4.5-K plant (i.e., commercial 4.5-K liquefier system) has its own compressor system
  - —Flow is compressed by the 2-K compressor system (RSC) to high pressure and fed to 2-K cold box HX-1 {as stream *(h)* } at a supply pressure of $p_{h,1}$
  - —HX-1 is imbalanced; the flow ratio (ξ_{hl}) is the ratio between the *(h)* to *(l)* stream mass flow rates
  - —The *(h)* stream pressure is dropped across the throttling (or Joule-Thompson, 'JT') valve JT-1, then mixed with the 3 atm 4.5K make-up flow from the 4.5-K plant
  - —HX-2 is a balanced HX (with 5 Ntu's) operating between approx. 4.5 and 2 K
  - —Finally JT-2 drops the ~3 atm supply to the load pressure of 0.031 atm, resulting in a two-phase supply into the Helium II bath
  - —The 2-K heat load (q_L) boils-off the helium II…and the entire cycle repeats

Process Study - Small Scale 2K Refrigeration

- Configuration C2~A (example)…continued



2-K Refrigeration Recovery Process Study C2-A

	(h) Stream					*(l) Stream*					
T.L. #	T [K]	p [atm]	h [J/g]	s [kJ/g]	*w* [g/s]	T [K]	p [atm]	h [J/g]	s [kJ/g]	*w* [g/s]	*T.L.* #
1	300.00	12.00	1577.12	1.552	9.36	300.00	0.0230	1573.20	-2.351	12.00	*1*
2	300.00	12.00	1577.12	1.552	9.36	239.23	0.0235	1257.61	-2.301	12.00	*2*
3	4.45	11.69	15.53	6.997	9.36	3.94	0.0301	35.56	3.036	12.00	*3*
4	5.13	3.00	15.53	6.601	9.36	3.94	0.0301	35.56	3.036	12.00	*4*
5	5.02	3.00	14.71	6.648	12.00	3.94	0.0301	35.56	3.036	12.00	*5*
6	2.15	2.96	4.76	7.457	12.00	2.00	0.0310	25.05	4.154	12.00	*6*
7	2.00	0.0310	4.76	7.154	12.00	2.001283	0.0310	25.05	4.154	12.00	*7*
	(hh) Stream					*(ll) Stream*					
4	4.50	3.00	11.79	6.829	2.64	300.00	1.05	1573.54	0.030	2.64	*1*

Flow ratio to HX-1: $\xi_{hl,2} = w_{h,1} / w_{l,1}$ 78.0%

Ambient temperature (T_0) 305 [K]

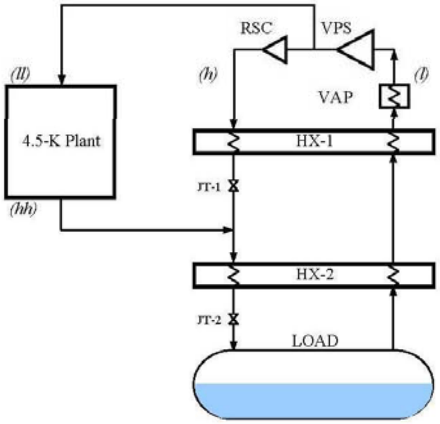
	Δp_h [atm]	Δp_l [atm]	$\Delta T_{hl,WE}$ [K]	$\Delta T_{hl,CE}$ [K]	ΔT_{LM} [K]	*q* [kW]	q_{LK} [W]	(UA) [W/K]	Ntu [-]	s [-]	
HX-1	0.306	0.0066	60.77	0.52	7.90	14.665	48.1	1855.7	35.06	99.9%	☑
HX-2	0.044	0.0009	1.09	0.14	0.66	0.126	6.9	191.0	4.94	93.0%	☑
Vap		0.0005	5.00	65.77	23.58	3.787		161	2.58		
Totals:	0.350	0.0080				14.79	55	2046.7	39.99		

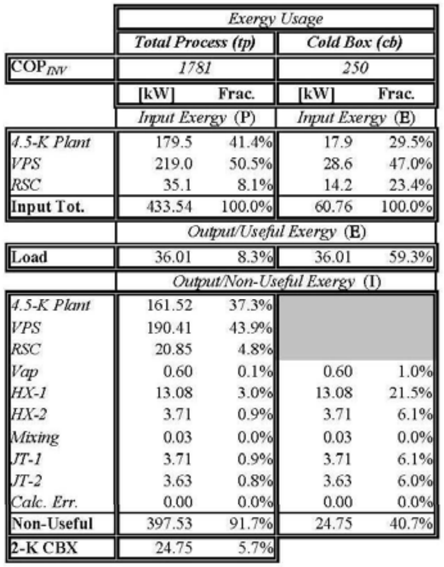
	w_{JT2} [g/s]	p_{CM} [atm]	T_L [K]	*x* [-]	q_L [W]
Load	12.00	0.0310	2.00	13.3%	243.4

Calc. $T_{l,5}$ [K]	Set Ntu's HX-1	Set Ntu's HX-2	N_{iter}	λ
3.94	35.00	5.00	50	1.3
-5.4E-09	*1.6E-03*	*-1.3E-02*		

	w_c [g/s]	*Q* [CFM]	p_S [atm]	p_D [atm]	p_r [-]	T_S [K]	$E_{c,iso}$ [kW]	η_{iso} [-]	P_c [kW]	η_m [-]	P_m [kW]
VPS	12.00	6799	0.0230	1.05	45.7	300.0	28.6	14.5%	197.1	90.0%	219.0
RSC	9.36		1.05	12.00	11.4	300.0	14.2	45.1%	31.6	90.0%	35.1

	$w_{4K,sup}$ [g/s]	$p_{4K,sup}$ [atm]	T_{4Ksup} [K]	E_{4K} [kW]	$\eta_{C,4K}$ [-]	P_{4K} [kW]
4.5-K Plan	2.64	3.00	4.50	17.9	10.0%	179.5

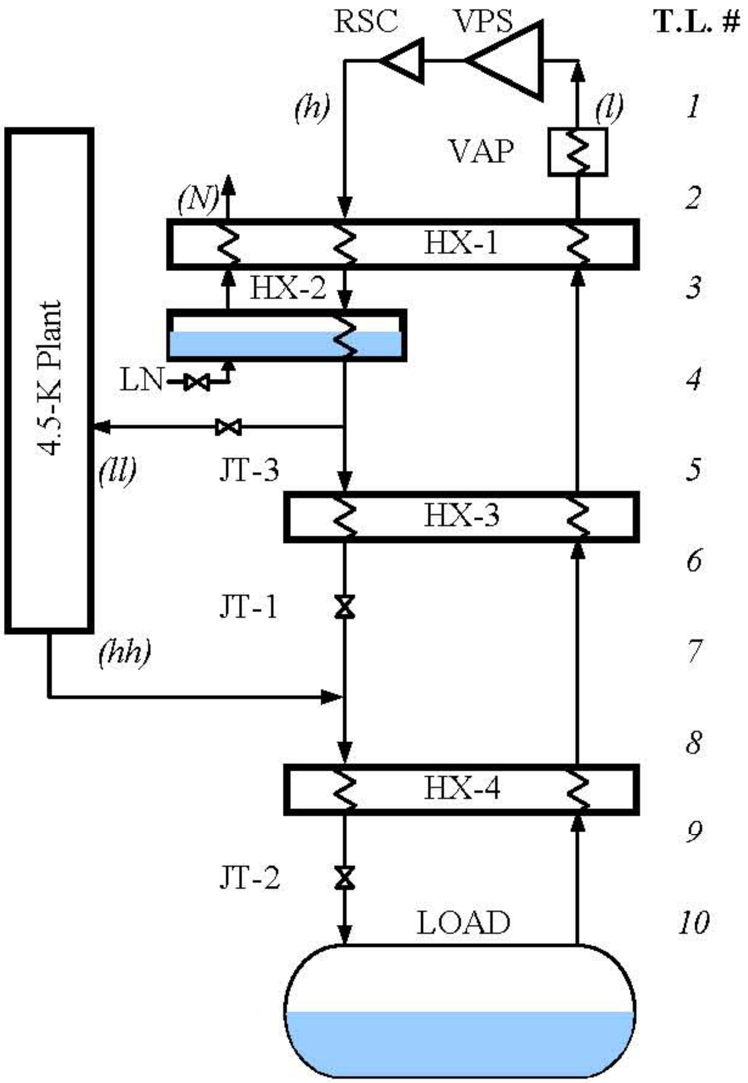




	Exergy Usage			
	Total Process (tp)		***Cold Box (cb)***	
COP$_{INV}$	*1781*		*250*	
	[kW]	**Frac.**	[kW]	**Frac.**
	Input Exergy (P)		*Input Exergy (E)*	
4.5-K Plant	179.5	41.4%	17.9	29.5%
VPS	219.0	50.5%	28.6	47.0%
RSC	35.1	8.1%	14.2	23.4%
Input Tot.	433.54	100.0%	60.76	100.0%
	Output/Useful Exergy (E)			
Load	36.01	8.3%	36.01	59.3%
	Output/Non-Useful Exergy (I)			
4.5-K Plant	161.52	37.3%		
VPS	190.41	43.9%		
RSC	20.85	4.8%		
Vap	0.60	0.1%	0.60	1.0%
HX-1	13.08	3.0%	13.08	21.5%
HX-2	3.71	0.9%	3.71	6.1%
Mixing	0.03	0.0%	0.03	0.0%
JT-1	3.71	0.9%	3.71	6.1%
JT-2	3.63	0.8%	3.63	6.0%
Calc. Err.	0.00	0.0%	0.00	0.0%
Non-Useful	397.53	91.7%	24.75	40.7%
2-K CBX	24.75	5.7%		

Process Study - Small Scale 2K Refrigeration

- Configuration C2-A-p
  - Similar to C2-A, except it uses LN to pre-cool the *(h)* stream to 80 K, then sends a portion (equal to the make-up flow) back to the 4.5-K plant at a reduced pressure of 1.2 atm {i.e., *(ll)* stream} through JT-3

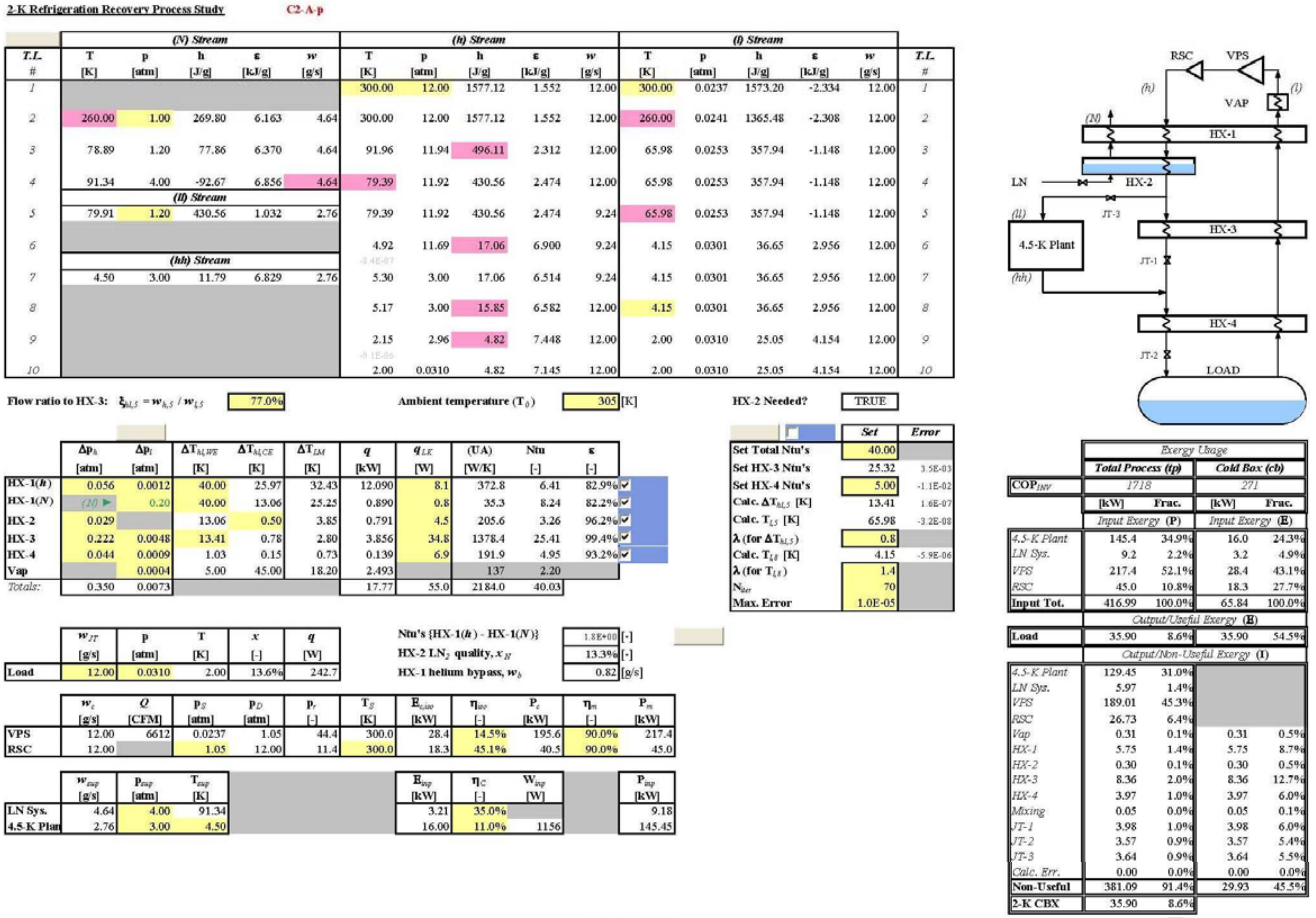


Process Study - Small Scale 2K Refrigeration

- Configuration C2-A-p…continued
  - Need for JT-3 is a practical consequence of matching operating pressures between 4.5-K plant and 2-K system
  - Carnot efficiency of 4.5-K plant is increased by ~1% (from 10% to 11%) as a result of the cooling provided by the 80-K flow from the 2-K CBX
  - So, from HX-3 downward, this configuration looks just like C2-A
  - Note that at some lower flow ratio (in HX-3) the use of LN would not be necessary; so, this configuration's performance below this point was not studied

Process Study - Small Scale 2K Refrigeration

- Configuration C2~A~p (example)…continued



2-K Refrigeration Recovery Process Study C2-A-p

	(N) Stream					(h) Stream					(l) Stream					
T.L. #	T [K]	p [atm]	h [J/g]	ε [kJ/g]	w [g/s]	T [K]	p [atm]	h [J/g]	ε [kJ/g]	w [g/s]	T [K]	p [atm]	h [J/g]	ε [kJ/g]	w [g/s]	T.L. #
1						300.00	12.00	1577.12	1.552	12.00	300.00	0.0237	1573.20	-2.334	12.00	1
2	260.00	1.00	269.80	6.163	4.64	300.00	12.00	1577.12	1.552	12.00	260.00	0.0241	1365.48	-2.308	12.00	2
3	78.89	1.20	77.86	6.370	4.64	91.96	11.94	496.11	2.312	12.00	65.98	0.0253	357.94	-1.148	12.00	3
4	91.34	4.00	-92.67	6.856	4.64	79.39	11.92	430.56	2.474	12.00	65.98	0.0253	357.94	-1.148	12.00	4
	(ll) Stream															
5	79.91	1.20	430.56	1.032	2.76	79.39	11.92	430.56	2.474	9.24	65.98	0.0253	357.94	-1.148	12.00	5
6						4.92	11.69	17.06	6.900	9.24	4.15	0.0301	36.65	2.956	12.00	6
	(hh) Stream					-8.4E-07										
7	4.50	3.00	11.79	6.829	2.76	5.30	3.00	17.06	6.514	9.24	4.15	0.0301	36.65	2.956	12.00	7
8						5.17	3.00	15.85	6.582	12.00	4.15	0.0301	36.65	2.956	12.00	8
9						2.15	2.96	4.82	7.448	12.00	2.00	0.0310	25.05	4.154	12.00	9
						-9.1E-06										
10						2.00	0.0310	4.82	7.145	12.00	2.00	0.0310	25.05	4.154	12.00	10

Flow ratio to HX-3: $\xi_{hl,5} = w_{h,5} / w_{l,5}$ 77.0%

Ambient temperature (T_0) 305 [K]

HX-2 Needed? TRUE

	Δp_h [atm]	Δp_l [atm]	$\Delta T_{hl,WE}$ [K]	$\Delta T_{hl,CE}$ [K]	ΔT_{LM} [K]	q [kW]	q_{LK} [W]	(UA) [W/K]	Ntu [-]	ε [-]	
HX-1(*h*)	0.056	0.0012	40.00	25.97	32.43	12.090	8.1	372.8	6.41	82.9%	☑
HX-1(*N*)	(N) ▶	0.20	40.00	13.06	25.25	0.890	0.8	35.3	8.24	82.2%	☑
HX-2	0.029		13.06	0.50	3.85	0.791	4.5	205.6	3.26	96.2%	☑
HX-3	0.222	0.0048	13.41	0.78	2.80	3.856	34.8	1378.4	25.41	99.4%	☑
HX-4	0.044	0.0009	1.03	0.15	0.73	0.139	6.9	191.9	4.95	93.2%	☑
Vap		0.0004	5.00	45.00	18.20	2.493		137	2.20		
Totals:	0.350	0.0073				17.77	55.0	2184.0	40.03		

☐	Set	Error
Set Total Ntu's	40.00	
Set HX-3 Ntu's	25.32	3.5E-03
Set HX-4 Ntu's	5.00	-1.1E-02
Calc. $\Delta T_{hl,5}$ [K]	13.41	1.6E-07
Calc. $T_{l,5}$ [K]	65.98	-3.2E-08
λ (for $\Delta T_{hl,5}$)	0.8	
Calc. $T_{l,8}$ [K]	4.15	-5.9E-06
λ (for $T_{l,8}$)	1.4	
N_{iter}	70	
Max. Error	1.0E-05	

	w_{JT} [g/s]	p [atm]	T [K]	x [-]	q [W]
Load	12.00	0.0310	2.00	13.6%	242.7

Ntu's {HX-1(*h*) - HX-1(*N*)} 1.8E+00 [-]

HX-2 LN$_2$ quality, x_N 13.3% [-]

HX-1 helium bypass, w_b 0.82 [g/s]

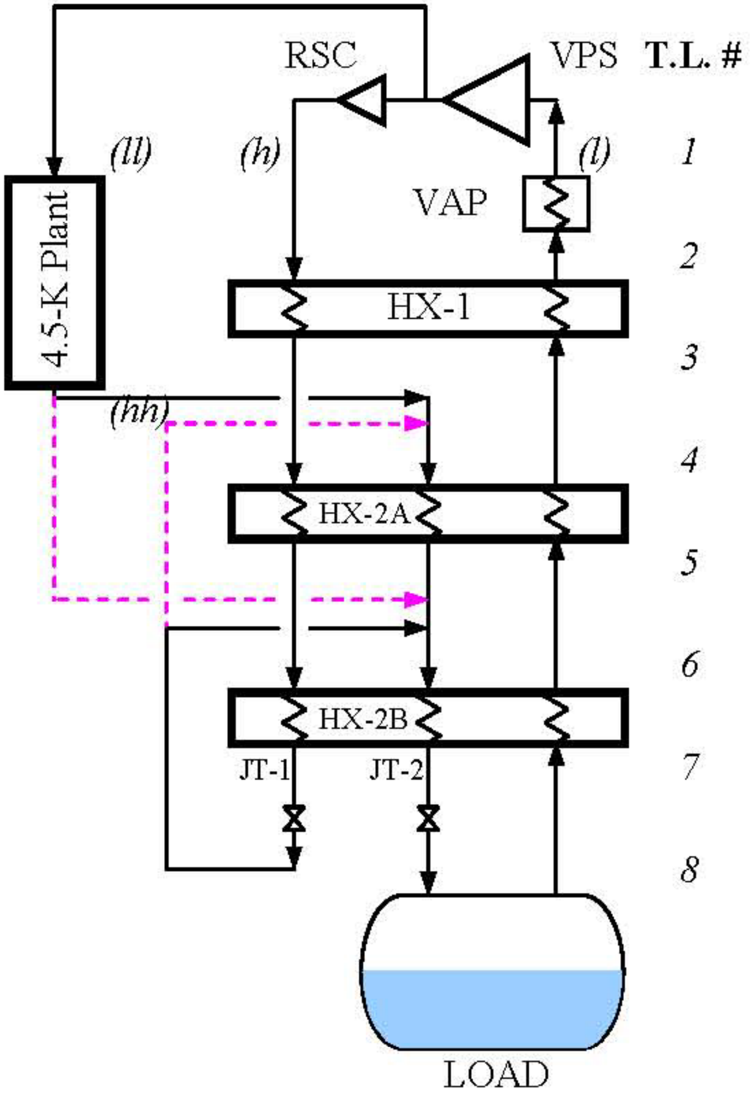
	w_c [g/s]	Q [CFM]	p_S [atm]	p_D [atm]	p_r [-]	T_S [K]	$E_{c,iso}$ [kW]	η_{iso} [-]	P_c [kW]	η_m [-]	P_m [kW]
VPS	12.00	6612	0.0237	1.05	44.4	300.0	28.4	14.5%	195.6	90.0%	217.4
RSC	12.00		1.05	12.00	11.4	300.0	18.3	45.1%	40.5	90.0%	45.0

	w_{sup} [g/s]	p_{sup} [atm]	T_{sup} [K]	E_{inp} [kW]	η_C [-]	W_{inp} [W]	P_{inp} [kW]
LN Sys.	4.64	4.00	91.34	3.21	35.0%		9.18
4.5-K Plan	2.76	3.00	4.50	16.00	11.0%	1156	145.45

	Exergy Usage			
	Total Process (tp)		Cold Box (cb)	
COP$_{INV}$	1718		271	
	[kW]	Frac.	[kW]	Frac.
	Input Exergy (P)		Input Exergy (E)	
4.5-K Plant	145.4	34.9%	16.0	24.3%
LN Sys.	9.2	2.2%	3.2	4.9%
VPS	217.4	52.1%	28.4	43.1%
RSC	45.0	10.8%	18.3	27.7%
Input Tot.	416.99	100.0%	65.84	100.0%
	Output/Useful Exergy (E)			
Load	35.90	8.6%	35.90	54.5%
	Output/Non-Useful Exergy (I)			
4.5-K Plant	129.45	31.0%		
LN Sys.	5.97	1.4%		
VPS	189.01	45.3%		
RSC	26.73	6.4%		
Vap	0.31	0.1%	0.31	0.5%
HX-1	5.75	1.4%	5.75	8.7%
HX-2	0.30	0.1%	0.30	0.5%
HX-3	8.36	2.0%	8.36	12.7%
HX-4	3.97	1.0%	3.97	6.0%
Mixing	0.05	0.0%	0.05	0.1%
JT-1	3.98	1.0%	3.98	6.0%
JT-2	3.57	0.9%	3.57	5.4%
JT-3	3.64	0.9%	3.64	5.5%
Calc. Err.	0.00	0.0%	0.00	0.0%
Non-Useful	381.09	91.4%	29.93	45.5%
2-K CBX	35.90	8.6%		

Process Study - Small Scale 2K Refrigeration

- Configuration C2-B
  - —Similar to C2-A, except that coldest HX (HX-2A/B) has been sub-divided with an additional high pressure stream pass *(hh)*
  - —Re-injection from JT-1 will occur between HX-A & B when (h) stream enthalpy out of HX-2B is less than 4.5-K plant supply enthalpy (11.8 J/g); otherwise these injection points are swapped (i.e., magenta colored lines)

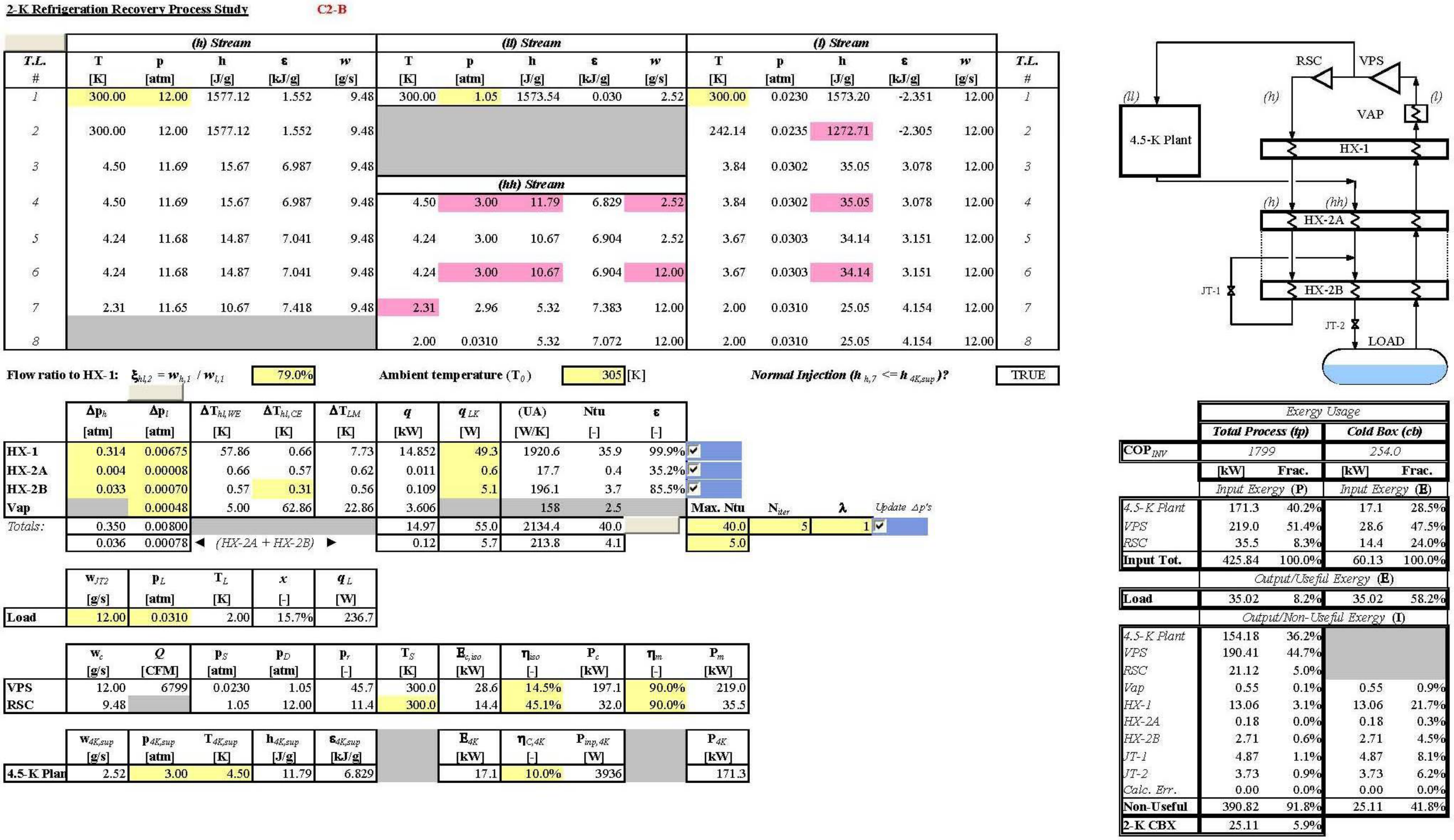


Process Study - Small Scale 2K Refrigeration

- Configuration C2-B…continued
  - —Motivation is centered around the fact that the specific heat of the *(h)* stream is less than the *(l)* stream for a good portion of the HX
  - —Length of HX-2A/B is not fixed at 5 Ntu's for this configuration (since this would result in an over-determined problem); rather;
    - Ntu's for HX-2A & 2B are not allowed to exceed 5, while
    - Total HX Ntu's are constrained as previously specified

Process Study - Small Scale 2K Refrigeration

- Configuration C2~B (example)…continued



2-K Refrigeration Recovery Process Study C2-B

	(h) Stream					*(ll) Stream*					*(l) Stream*					
T.L. *#*	T [K]	p [atm]	h [J/g]	ε [kJ/g]	*w* [g/s]	T [K]	p [atm]	h [J/g]	ε [kJ/g]	*w* [g/s]	T [K]	p [atm]	h [J/g]	ε [kJ/g]	*w* [g/s]	*T.L.* *#*
1	300.00	12.00	1577.12	1.552	9.48	300.00	1.05	1573.54	0.030	2.52	300.00	0.0230	1573.20	-2.351	12.00	*1*
2	300.00	12.00	1577.12	1.552	9.48						242.14	0.0235	1272.71	-2.305	12.00	*2*
3	4.50	11.69	15.67	6.987	9.48						3.84	0.0302	35.05	3.078	12.00	*3*
						(hh) Stream										
4	4.50	11.69	15.67	6.987	9.48	4.50	3.00	11.79	6.829	2.52	3.84	0.0302	35.05	3.078	12.00	*4*
5	4.24	11.68	14.87	7.041	9.48	4.24	3.00	10.67	6.904	2.52	3.67	0.0303	34.14	3.151	12.00	*5*
6	4.24	11.68	14.87	7.041	9.48	4.24	3.00	10.67	6.904	12.00	3.67	0.0303	34.14	3.151	12.00	*6*
7	2.31	11.65	10.67	7.418	9.48	2.31	2.96	5.32	7.383	12.00	2.00	0.0310	25.05	4.154	12.00	*7*
8						2.00	0.0310	5.32	7.072	12.00	2.00	0.0310	25.05	4.154	12.00	*8*

Flow ratio to HX-1: $\xi_{hl,2} = w_{h,1} / w_{l,1}$ 79.0%   **Ambient temperature** (T_0) 305 [K]   ***Normal Injection*** ($h_{h,7} <= h_{4K,sup}$)? TRUE

	Δp_h [atm]	Δp_l [atm]	$\Delta T_{hl,WE}$ [K]	$\Delta T_{hl,CE}$ [K]	ΔT_{LM} [K]	*q* [kW]	q_{LK} [W]	(UA) [W/K]	Ntu [-]	ε [-]				
HX-1	0.314	0.00675	57.86	0.66	7.73	14.852	49.3	1920.6	35.9	99.9%	☑			
HX-2A	0.004	0.00008	0.66	0.57	0.62	0.011	0.6	17.7	0.4	35.2%	☑			
HX-2B	0.033	0.00070	0.57	0.31	0.56	0.109	5.1	196.1	3.7	85.5%	☑			
Vap		0.00048	5.00	62.86	22.86	3.606		158	2.5		**Max. Ntu**	N_{iter}	λ	*Update Δp's*
Totals:	0.350	0.00800				14.97	55.0	2134.4	40.0		40.0	5	1	☑
	0.036	0.00078	◄	*(HX-2A + HX-2B)*	►	0.12	5.7	213.8	4.1		5.0			

	w_{JT2} [g/s]	p_L [atm]	T_L [K]	*x* [-]	q_L [W]
Load	12.00	0.0310	2.00	15.7%	236.7

	w_c [g/s]	*Q* [CFM]	p_S [atm]	p_D [atm]	p_r [-]	T_S [K]	$E_{c,iso}$ [kW]	η_{iso} [-]	P_c [kW]	η_m [-]	P_m [kW]
VPS	12.00	6799	0.0230	1.05	45.7	300.0	28.6	14.5%	197.1	90.0%	219.0
RSC	9.48		1.05	12.00	11.4	300.0	14.4	45.1%	32.0	90.0%	35.5

	$w_{4K,sup}$ [g/s]	$p_{4K,sup}$ [atm]	$T_{4K,sup}$ [K]	$h_{4K,sup}$ [J/g]	$\varepsilon_{4K,sup}$ [kJ/g]		E_{4K} [kW]	$\eta_{C,4K}$ [-]	$P_{inp,4K}$ [W]		P_{4K} [kW]
4.5-K Plan	2.52	3.00	4.50	11.79	6.829		17.1	10.0%	3936		171.3

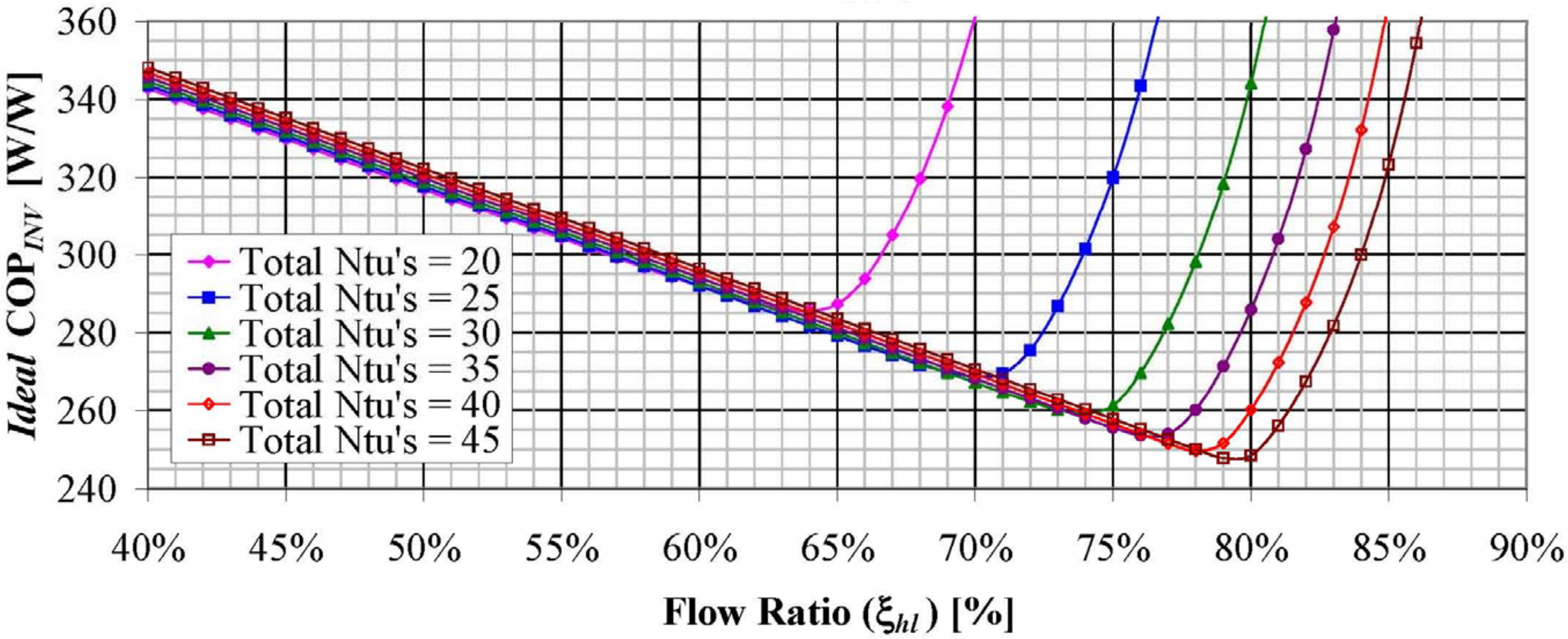
	Exergy Usage			
	Total Process (tp)		***Cold Box (cb)***	
COP_{INV}	*1799*		*254.0*	
	[kW]	**Frac.**	**[kW]**	**Frac.**
	Input Exergy **(P)**		*Input Exergy* **(E)**	
4.5-K Plant	171.3	40.2%	17.1	28.5%
VPS	219.0	51.4%	28.6	47.5%
RSC	35.5	8.3%	14.4	24.0%
Input Tot.	425.84	100.0%	60.13	100.0%
	Output/Useful Exergy **(E)**			
Load	35.02	8.2%	35.02	58.2%
	Output/Non-Useful Exergy **(I)**			
4.5-K Plant	154.18	36.2%		
VPS	190.41	44.7%		
RSC	21.12	5.0%		
Vap	0.55	0.1%	0.55	0.9%
HX-1	13.06	3.1%	13.06	21.7%
HX-2A	0.18	0.0%	0.18	0.3%
HX-2B	2.71	0.6%	2.71	4.5%
JT-1	4.87	1.1%	4.87	8.1%
JT-2	3.73	0.9%	3.73	6.2%
Calc. Err.	0.00	0.0%	0.00	0.0%
Non-Useful	390.82	91.8%	25.11	41.8%
2-K CBX	25.11	5.9%		

Process Study - Small Scale 2K Refrigeration

- Process Model Results
  - —At 12 atm supply pressure ($p_{h,1}$) to 2-K CBX, *ideal* and *real* COP_{INV}'s for three configurations vs.
    - Flow ratio (ξ_{hl}): 40 to 100% (as solution allows)
    - Total HX Ntu's (Ntu_{tot}): 20 to 45
  - —Results at other supply pressures ($p_{h,1}$ = 6, 9, 15, 18 atm) similar in trend and nature, i.e.,
    - There exists a optimum (minimum) COP_{INV} at a particular $\xi_{hl,opt}$ for each $p_{h,1}$ & Ntu_{tot} combination
    - At $\xi_{hl} < \xi_{hl,opt}$, COP_{INV} increases ~linearly
    - At $\xi_{hl} > \xi_{hl,\mathrm{opt}}$, COP_{INV} increase quickly
  - —Note 'knee' of the (constant Ntu_{tot}) curves are sharper for C2-A and C2-A-p than for C2-B

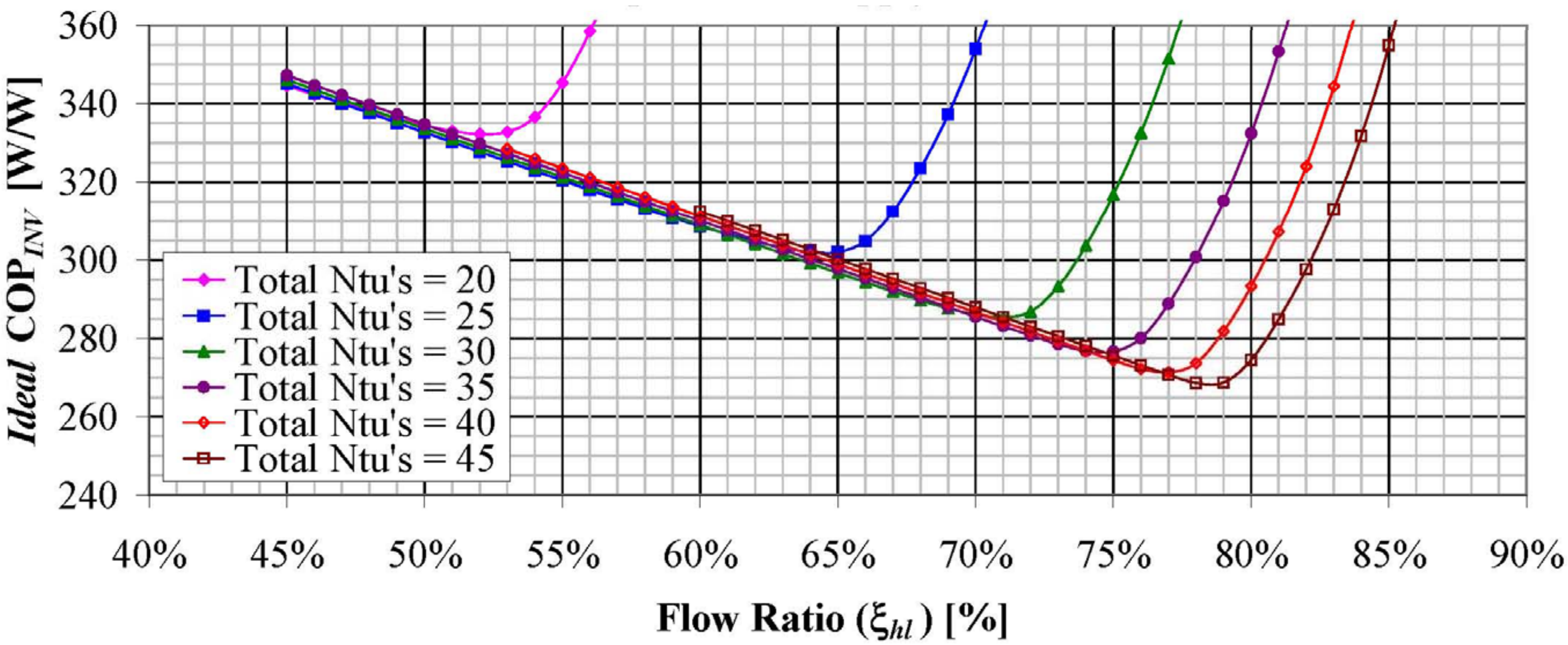
Process Study - Small Scale 2K Refrigeration

- *Ideal* COP_{INV} for configuration C2-A at 12 atm



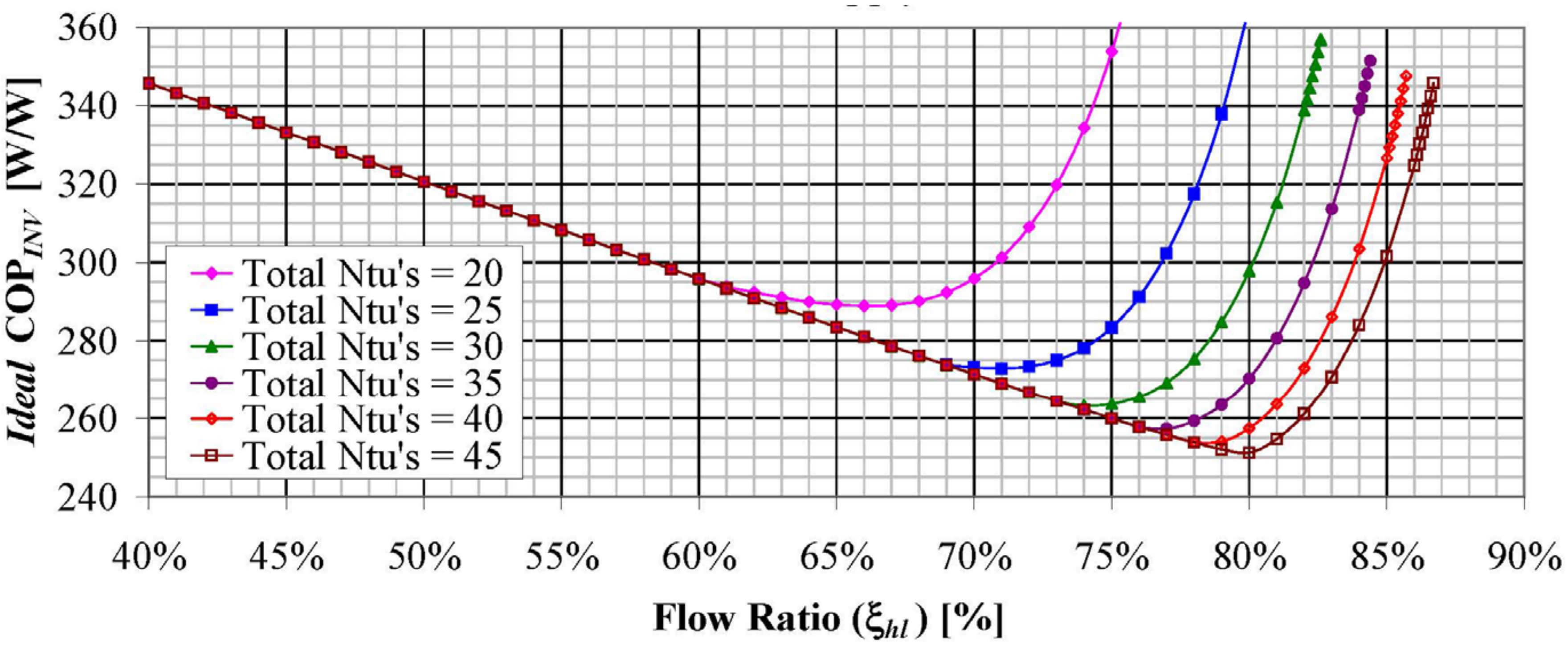
Process Study - Small Scale 2K Refrigeration

- *Ideal* COP$_{INV}$ for configuration C2~A~p at 12 atm



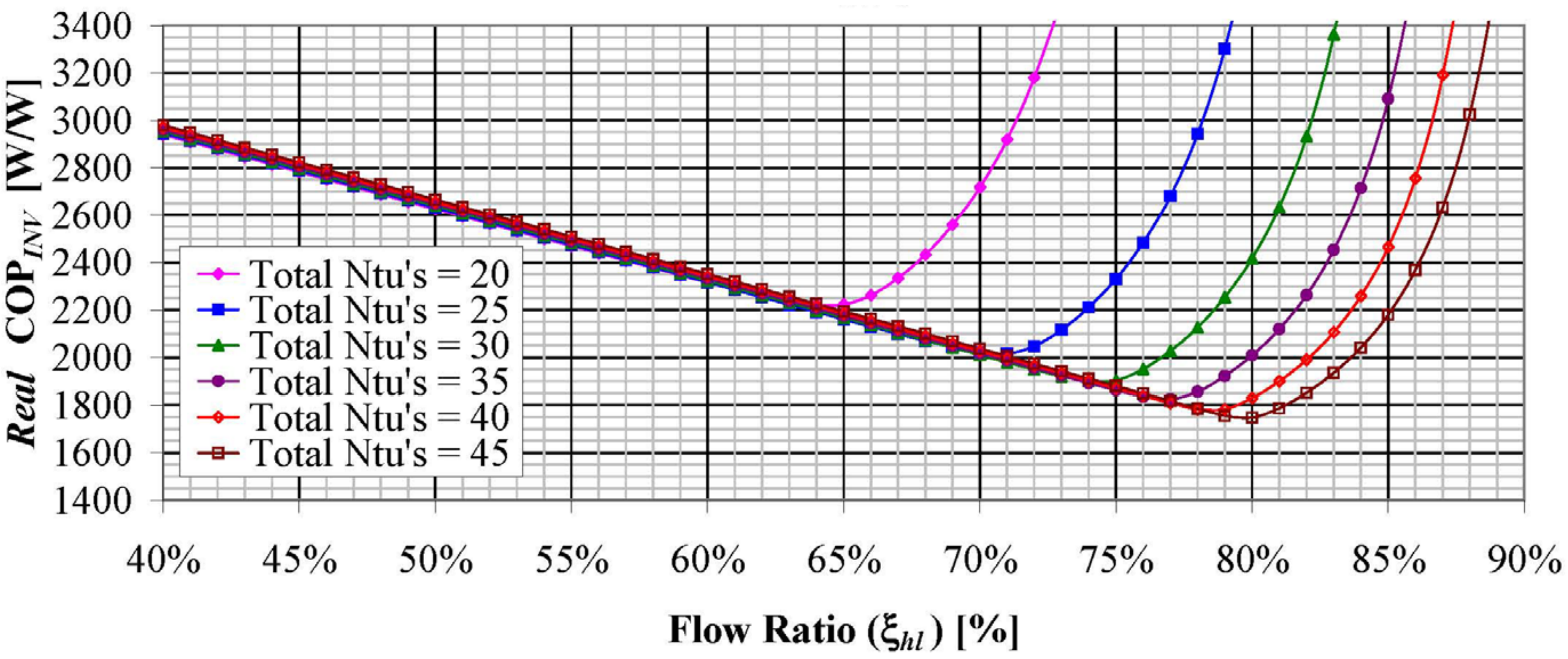
Process Study - Small Scale 2K Refrigeration

- *Ideal* COP$_{INV}$ for configuration C2-B at 12 atm



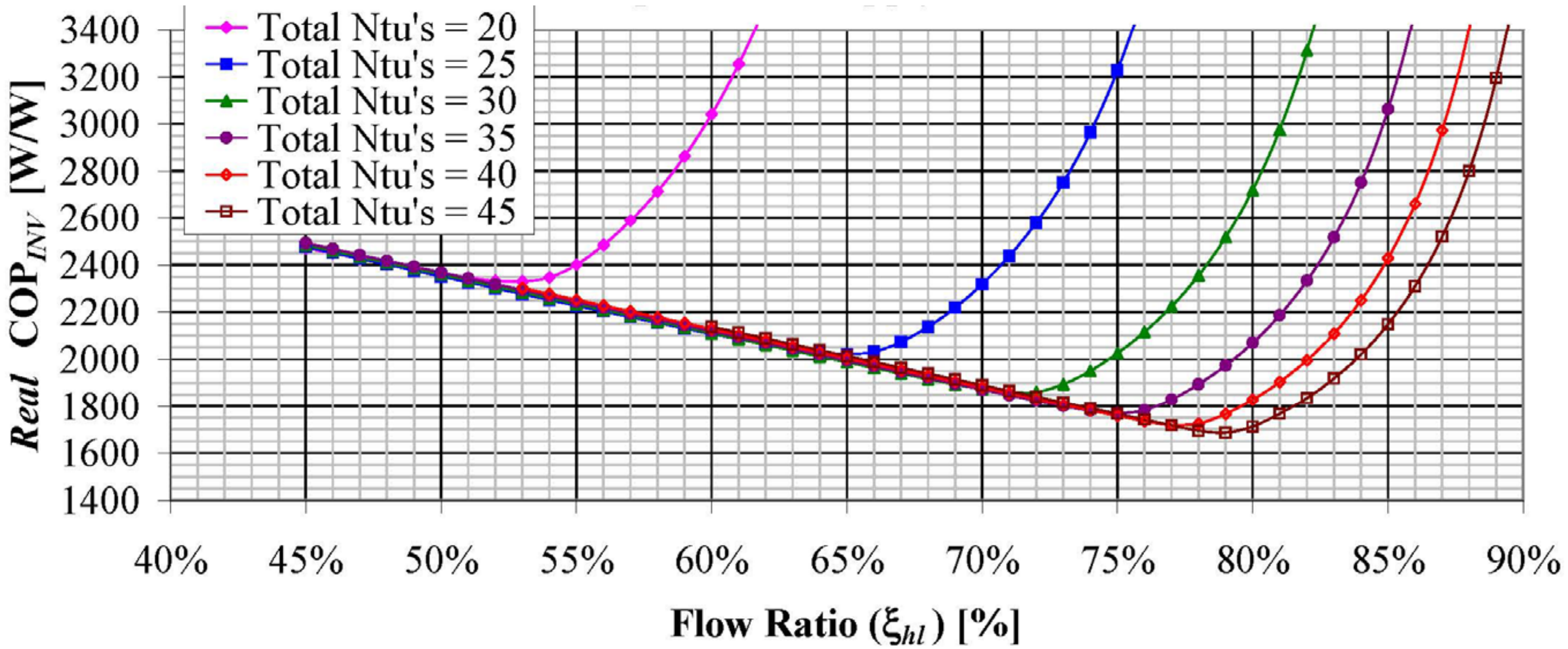
Process Study - Small Scale 2K Refrigeration

- *Real* COP_{INV} for configuration C2-A at 12 atm



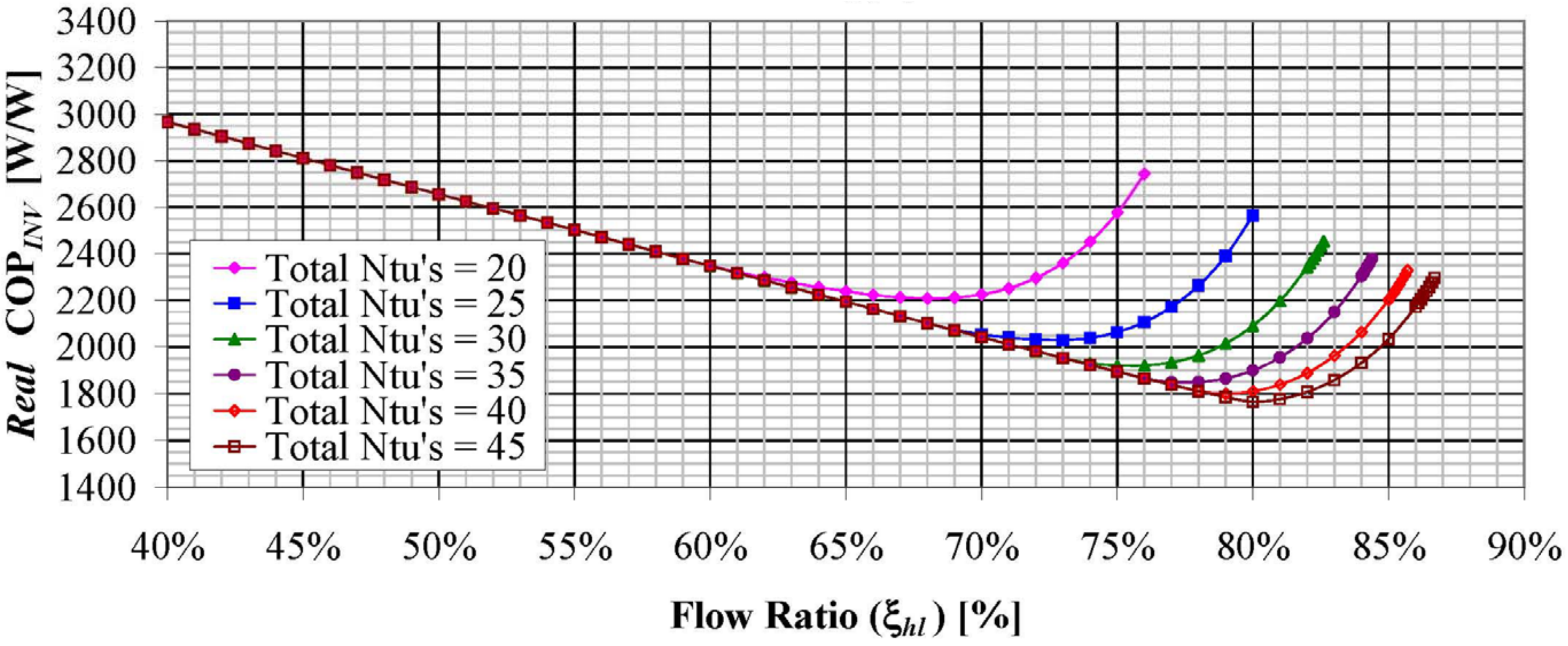
Process Study - Small Scale 2K Refrigeration

- *Real* COP_{INV} for configuration C2~A~p at 12 atm



Process Study - Small Scale 2K Refrigeration

- *Real* COP_{INV} for configuration C2-B at 12 atm

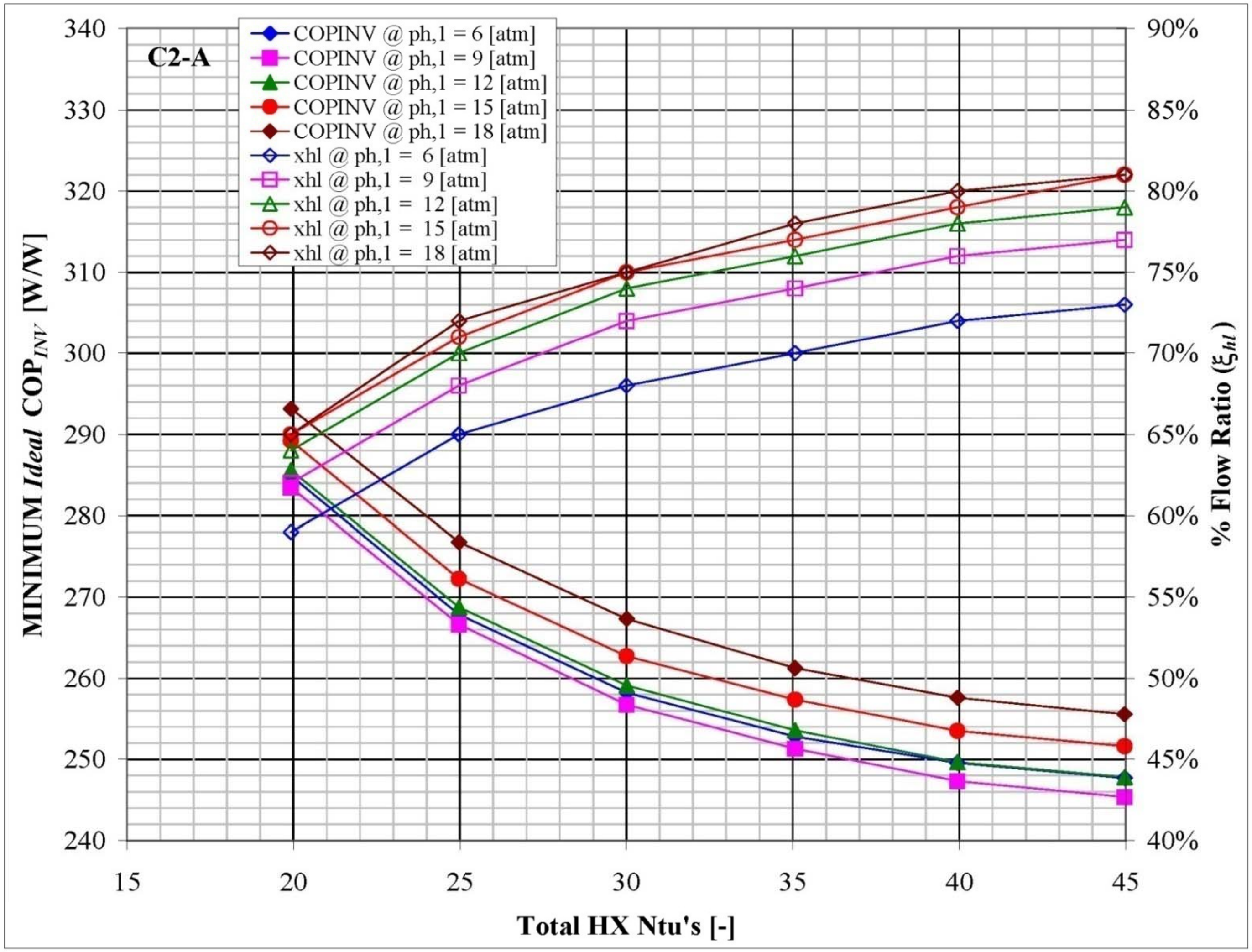


Process Study - Small Scale 2K Refrigeration

- Process Model Results…continued
  - —Optimum (minimum) *ideal* and *real* COP_{INV}'s and their associated $\xi_{hl,opt}$ vs. Ntu_{tot} at each $p_{h,1}$
  - —Overall behavior of optimums are similar in trend and nature
    - Ntu_{tot} is most influential parameter for performance and as it increases so the performance always increases

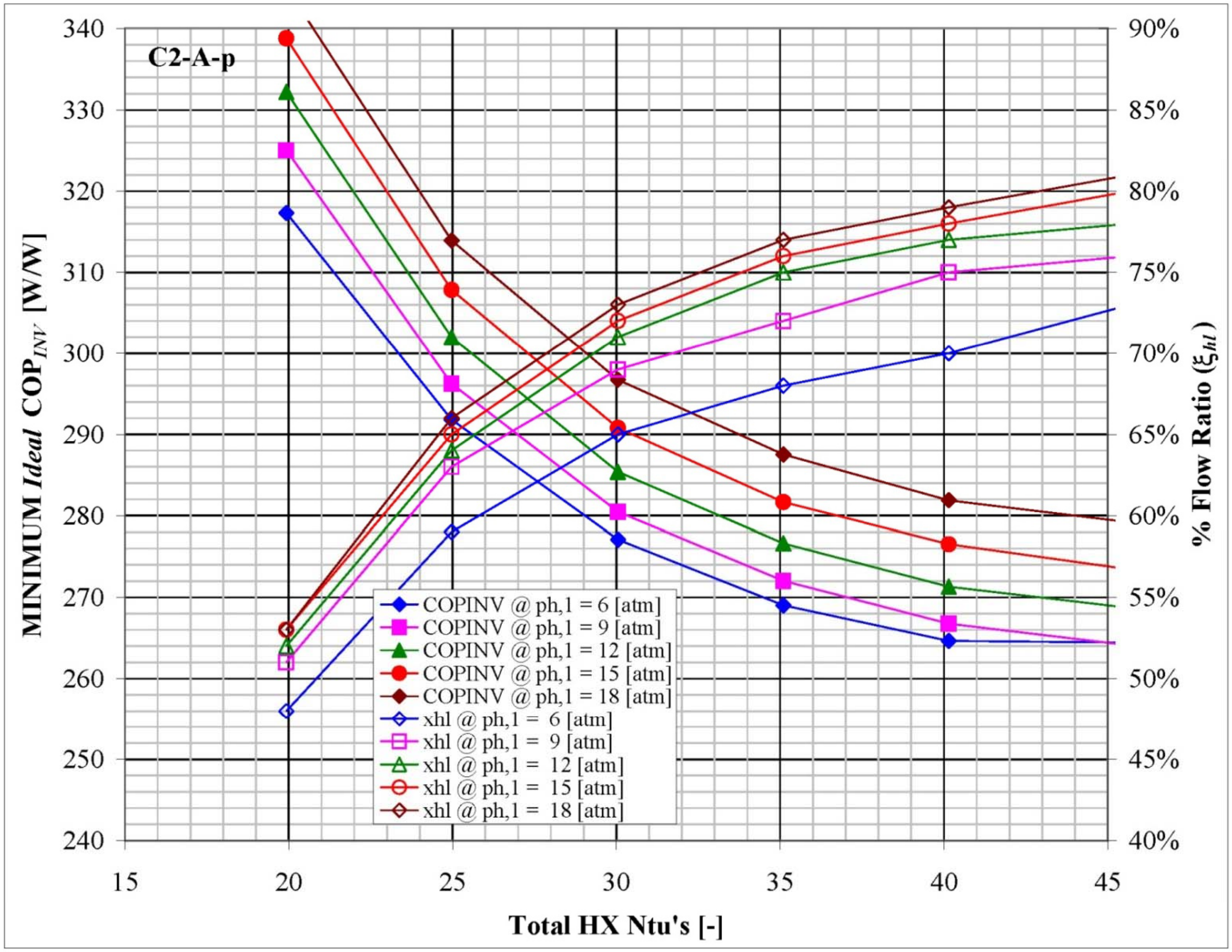
Process Study - Small Scale 2K Refrigeration

- Minimum *ideal* COP$_{INV}$ for C2-A



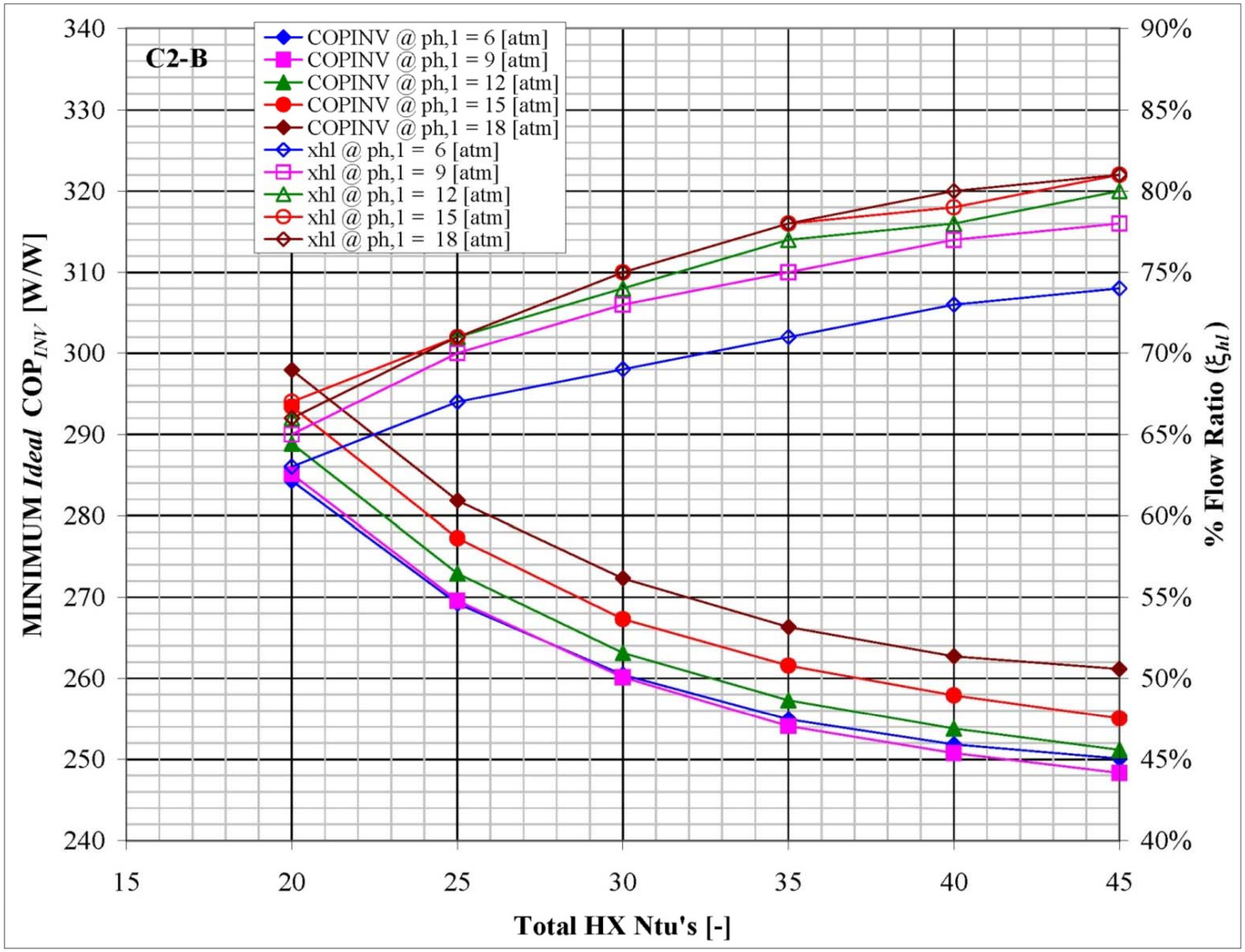
Process Study - Small Scale 2K Refrigeration

- Minimum *ideal* COP$_{INV}$ for C2-A-p



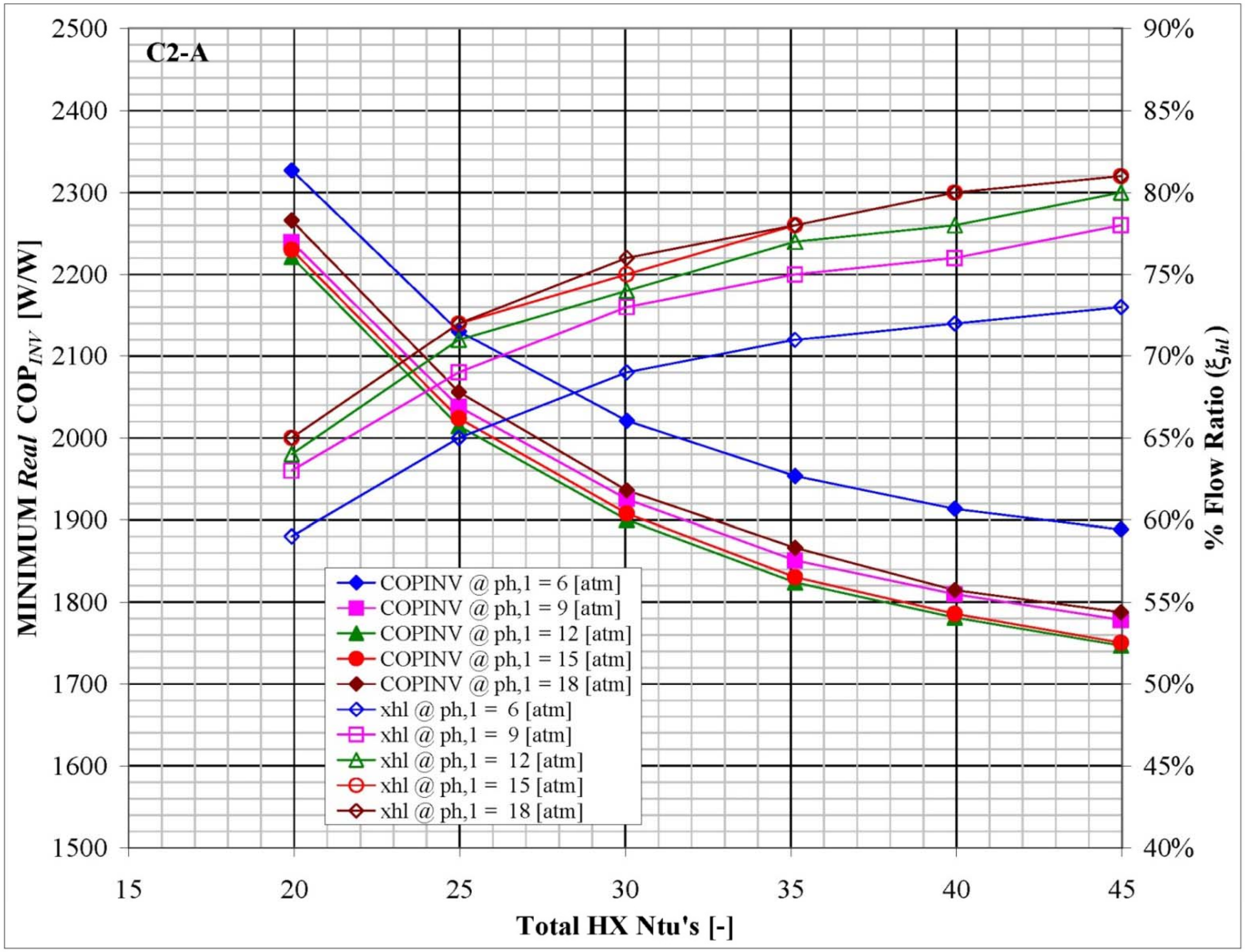
Process Study - Small Scale 2K Refrigeration

- Minimum *ideal* COP$_{INV}$ for C2~B



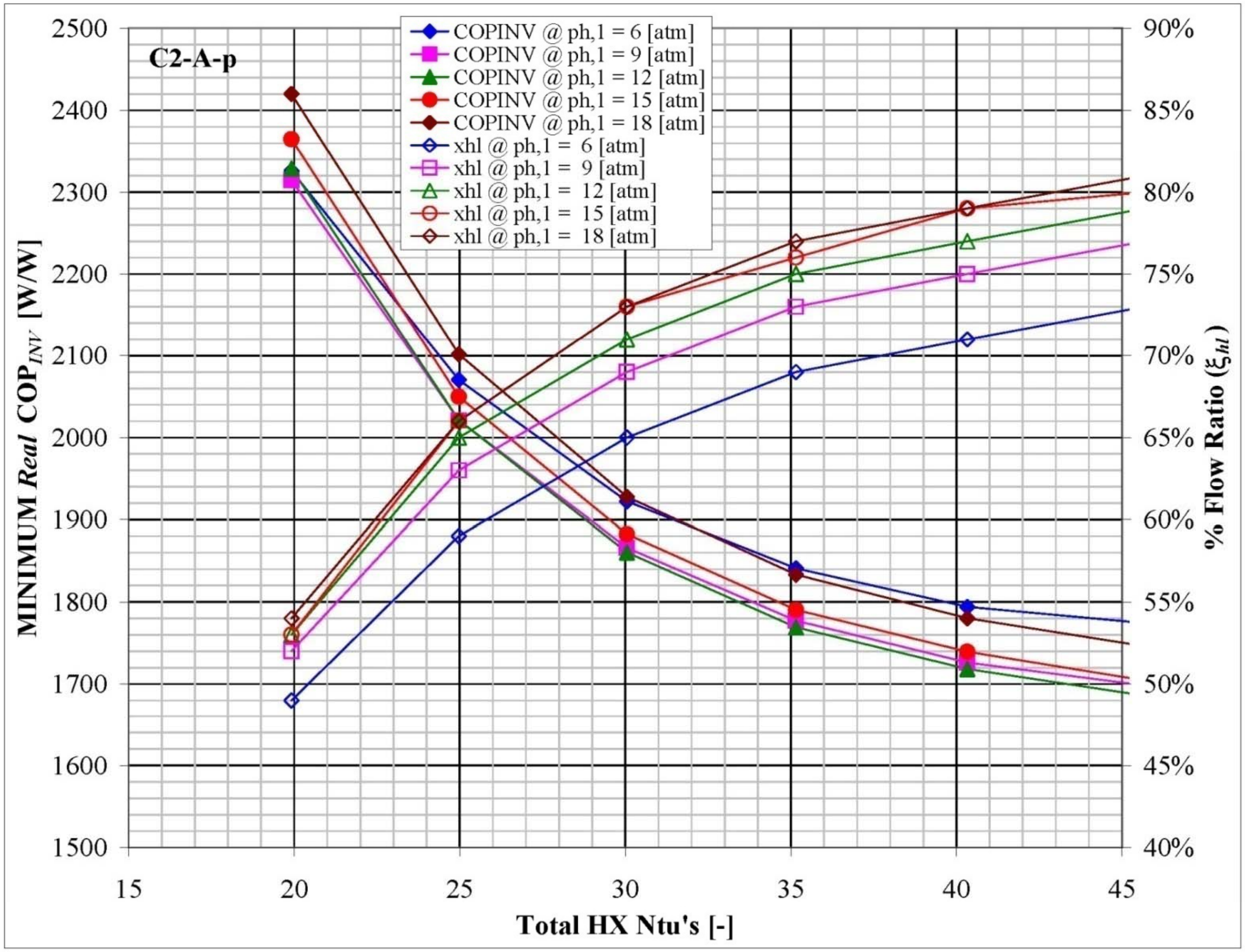
Process Study - Small Scale 2K Refrigeration

- Minimum *real* COP_{INV} for C2~A



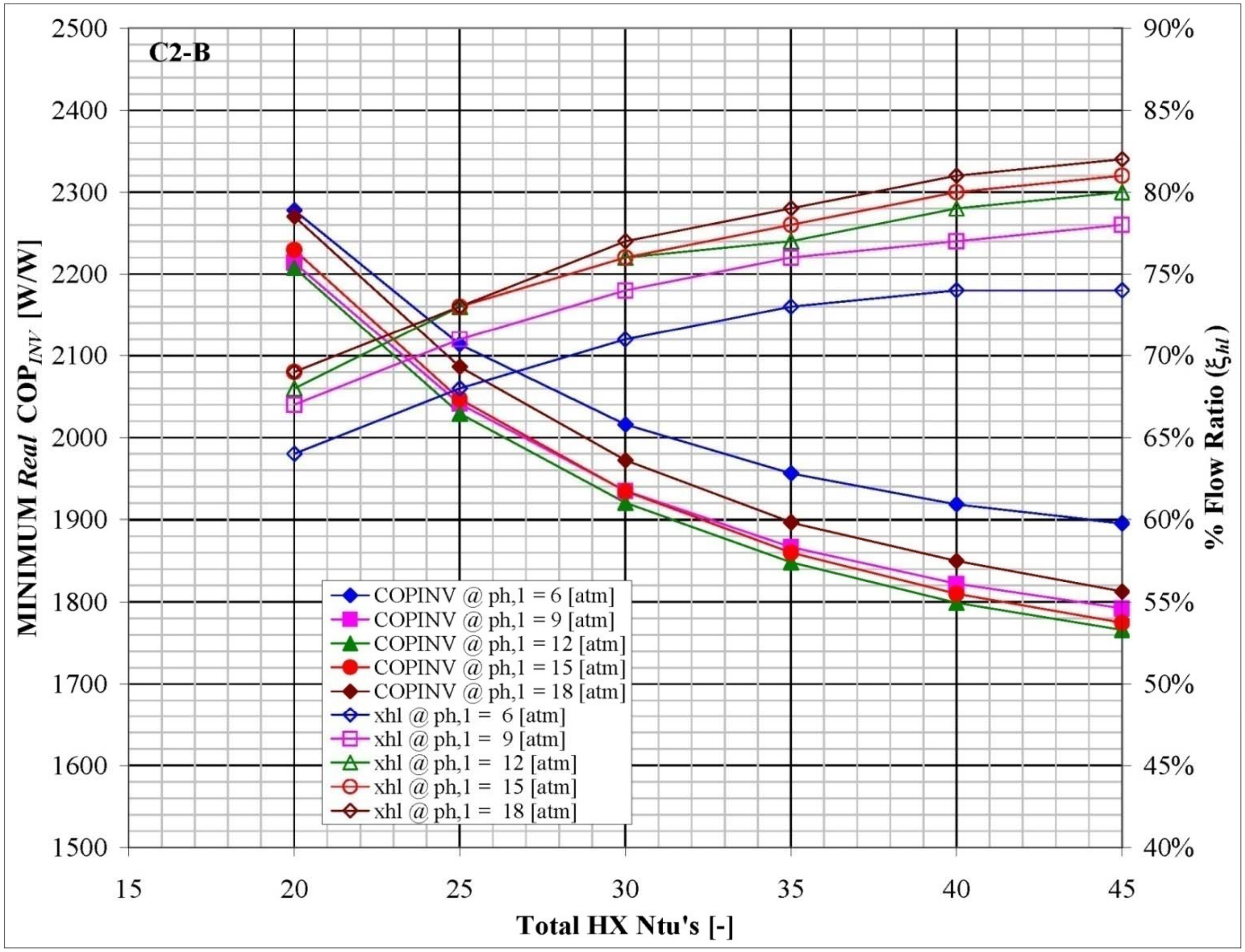
Process Study - Small Scale 2K Refrigeration

- Minimum *real* COP$_{INV}$ for C2~A~p



Process Study - Small Scale 2K Refrigeration

- Minimum *real* COP$_{INV}$ for C2~B



Process Study - Small Scale 2K Refrigeration

—Process Model Results…continued

- Optimum *real* COP_{INV}'s for C2-A-p are less than C2-A (and C2-B), but the optimum *ideal* COP_{INV}'s for C2-A are less than C2-A-p (and C2-B)
  - Recall 4.5-K plant Carnot efficiency is 11% for C2-A-p (rather than 10% for C2-A and C2-B), resulting in a higher real performance, but
  - throttling loss of JT-3 (i.e., 80-K high pressure stream to 4.5-K plant) is detrimental to ideal performance
- *Ideal* and *real* optimum flow ratios are close, but in general, not equal
- $p_{h,1}$ = 12 atm always yielded a superior *real* COP_{INV}, but the $p_{h,1}$ = 9 or 6 atm yielded a slightly better (lower) *ideal* COP_{INV}
  - A higher ξ_{hl} is more influential on *real* process and,
  - Lower $p_{h,1}$ is more influential on *ideal* process

Process Study - Small Scale 2K Refrigeration

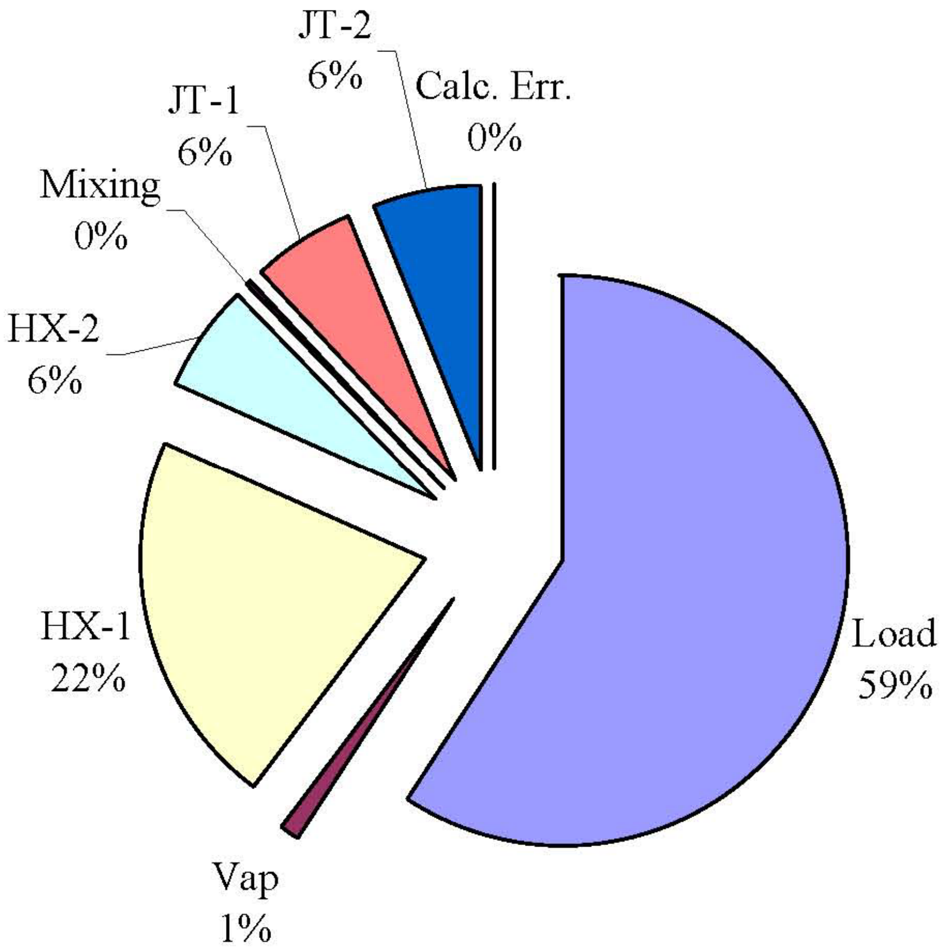
- Process Model Results…continued
  - —So, for reasonable HX sizes (Ntu$_{tot}$ > 30 Ntu's) and a supply pressure ($p_{h,1}$) > 9 atm
    - Optimum flow ratio (ξ_{hl}) is roughly 70 to 80%, with
    - *Ideal* COP$_{INV}$ of 250 to 300 W/W, and
    - *Real* COP$_{INV}$ of 1750 to 1950 W/W
  - —Best *real* process performance occurred at Ntu$_{tot}$ = 45 and $p_{h,1}$ = 12 atm,
    - C2-A and C2-B: COP$_{INV}$ of ~1750 W/W
    - C2-A-p: COP$_{INV}$ of ~1690 W/W

Process Study - Small Scale 2K Refrigeration

- Process Model Results…continued
  - Distribution of 2-K CBX availability
    - Unsurprisingly, major loss component is warm(er) HX
    - For C2-A & C2-B: 2-K load ~60% of total availability (i.e., exergy flux) given to 2-K CBX
    - For C2-A-p: 2-K load ~55% of total availability

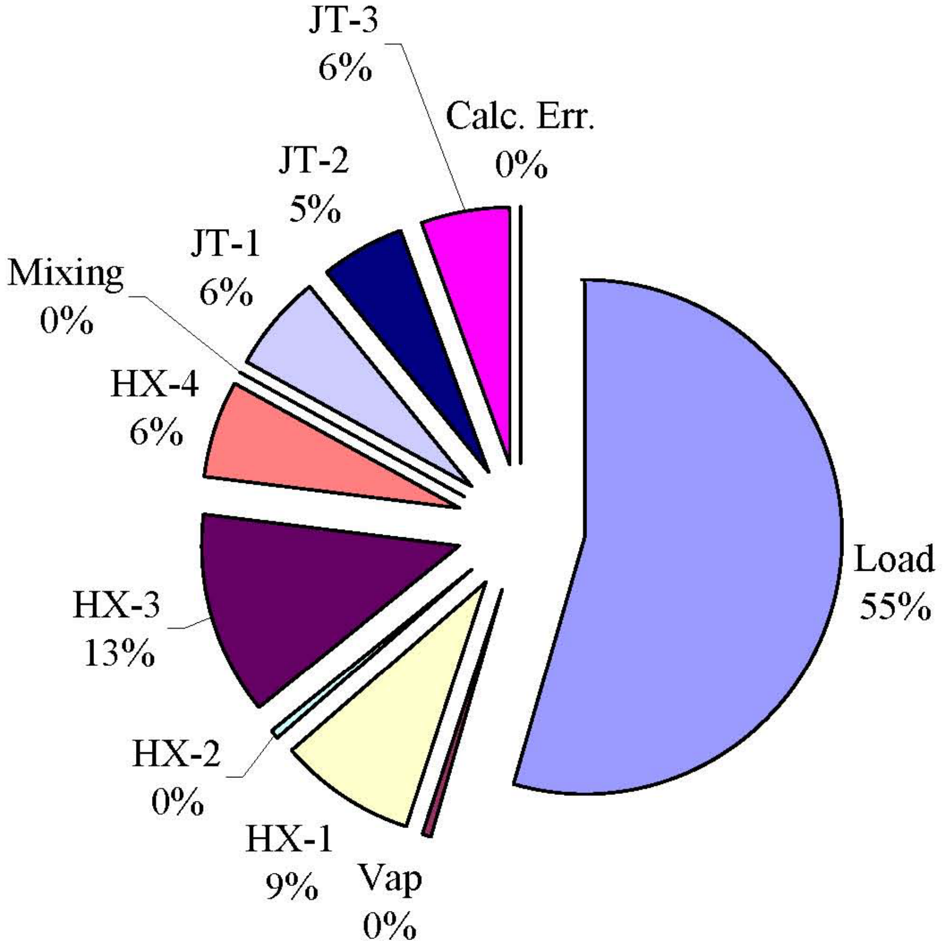
Process Study - Small Scale 2K Refrigeration

- Availability distribution of C2-A at optimum *ideal* COP_{INV} (ξ_{hl} = 78%, $p_{h,1}$ = 12 atm) for Ntu_{tot} = 40



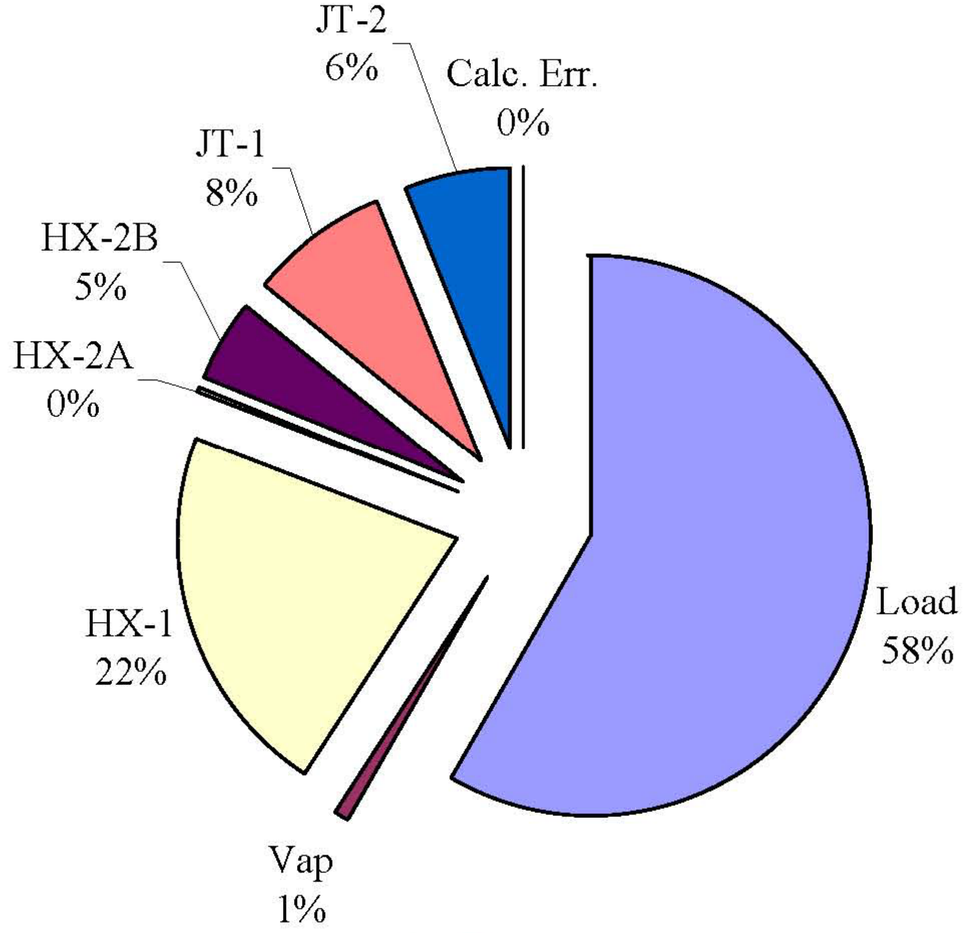
Process Study - Small Scale 2K Refrigeration

- Availability distribution of C2-A-p at optimum *ideal* COP_{INV} (ξ_{hl} = 77%, $p_{h,1}$ = 12 atm) for Ntu_{tot} = 40



Process Study - Small Scale 2K Refrigeration

- Availability distribution of C2-B at optimum *ideal* COP_{INV} ($\xi_{hl} = 79\%$, $p_{h,1} = 12$ atm) for $Ntu_{tot} = 40$

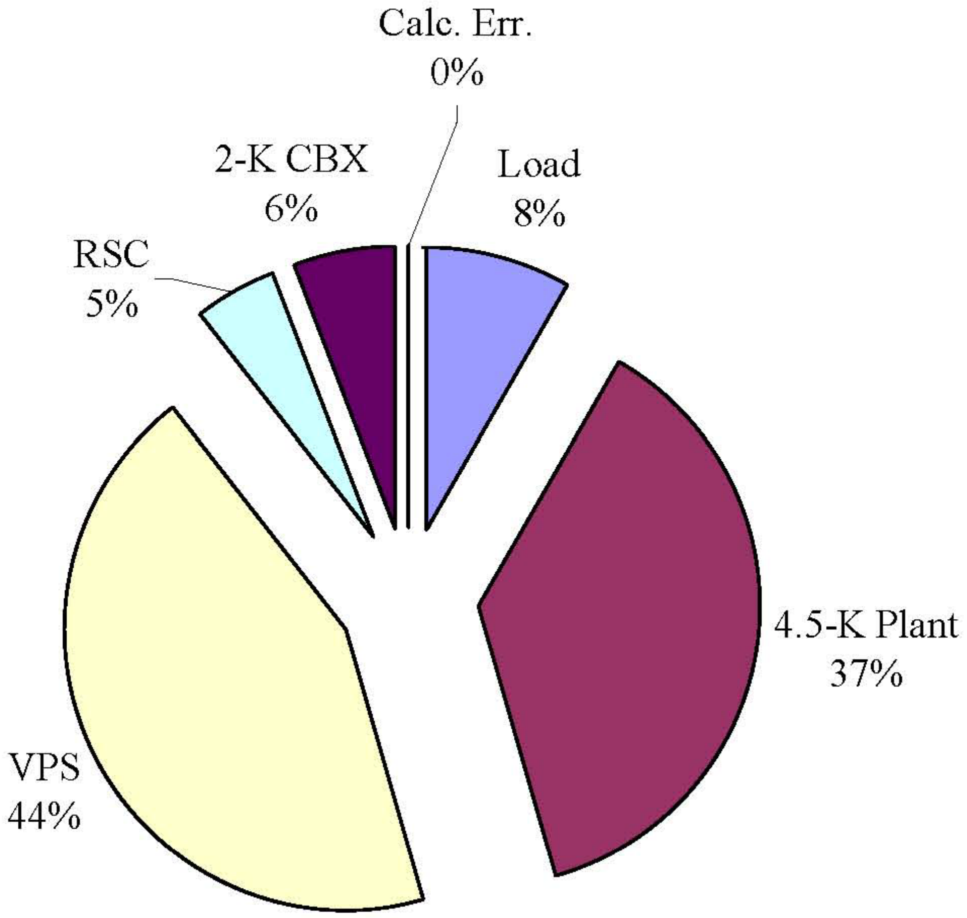


Process Study - Small Scale 2K Refrigeration

- Process Model Results…continued
  - Distribution of *real* process input power usage (useful and non-useful)
    - Only ~8% of input power used (usefully) by 2-K load
    - For C2-A, major loss components are:
      - ~44% for VPS
      - ~37% for 4.5-K plant
      - ~5% for RSC
      - ~6% for 2-K CBX (losses)
    - C2-B similar to C2-A
    - For C2-A-p,
      - 2-K CBX losses higher (~9% vs. ~6%) due to LN system and JT-3 losses

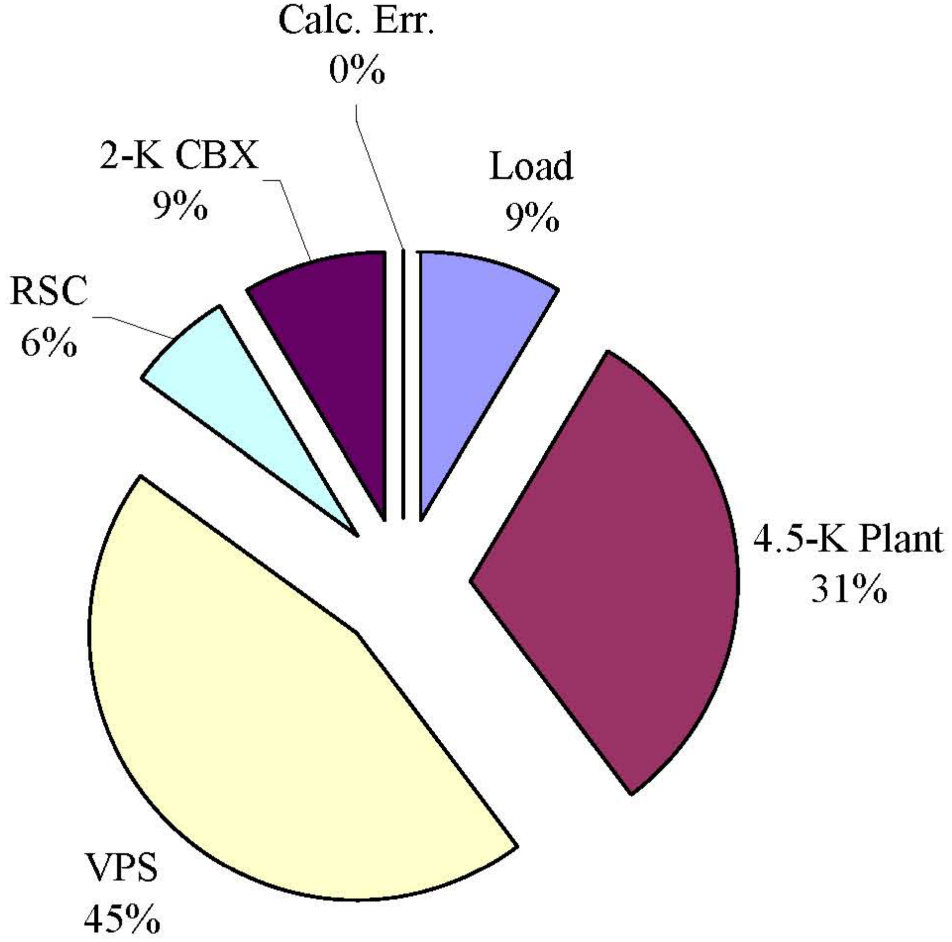
Process Study - Small Scale 2K Refrigeration

- Input power distribution of C2-A at optimum *real* COP_{INV} (ξ_{hl} = 78%, $p_{h,1}$ = 12 atm) for Ntu_{tot} = 40



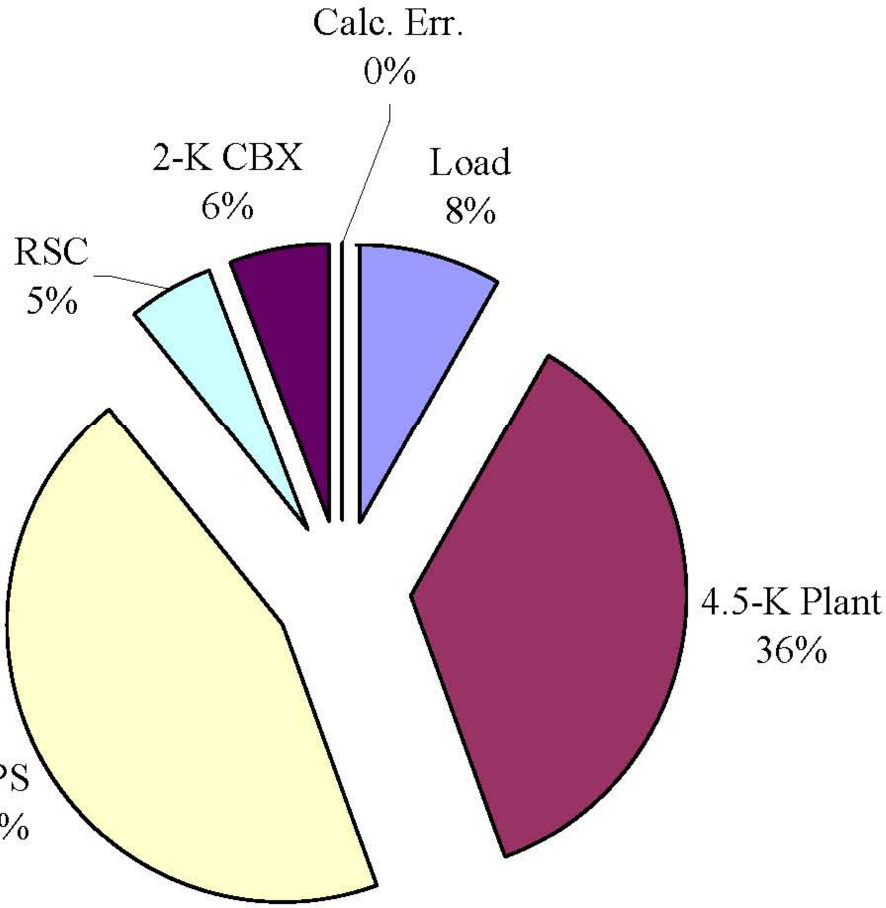
Process Study - Small Scale 2K Refrigeration

- Input power distribution of C2-A-p at optimum *real* COP_{INV} (ξ_{hl} = 77%, $p_{h,1}$ = 12 atm) for Ntu_{tot} = 40



Process Study - Small Scale 2K Refrigeration

- Input power distribution of C2-B at optimum *real* COP_{INV} ($\xi_{hl} = 79\%$, $p_{h,1} = 12$ atm) for $Ntu_{tot} = 40$



Process Study - Small Scale 2K Refrigeration

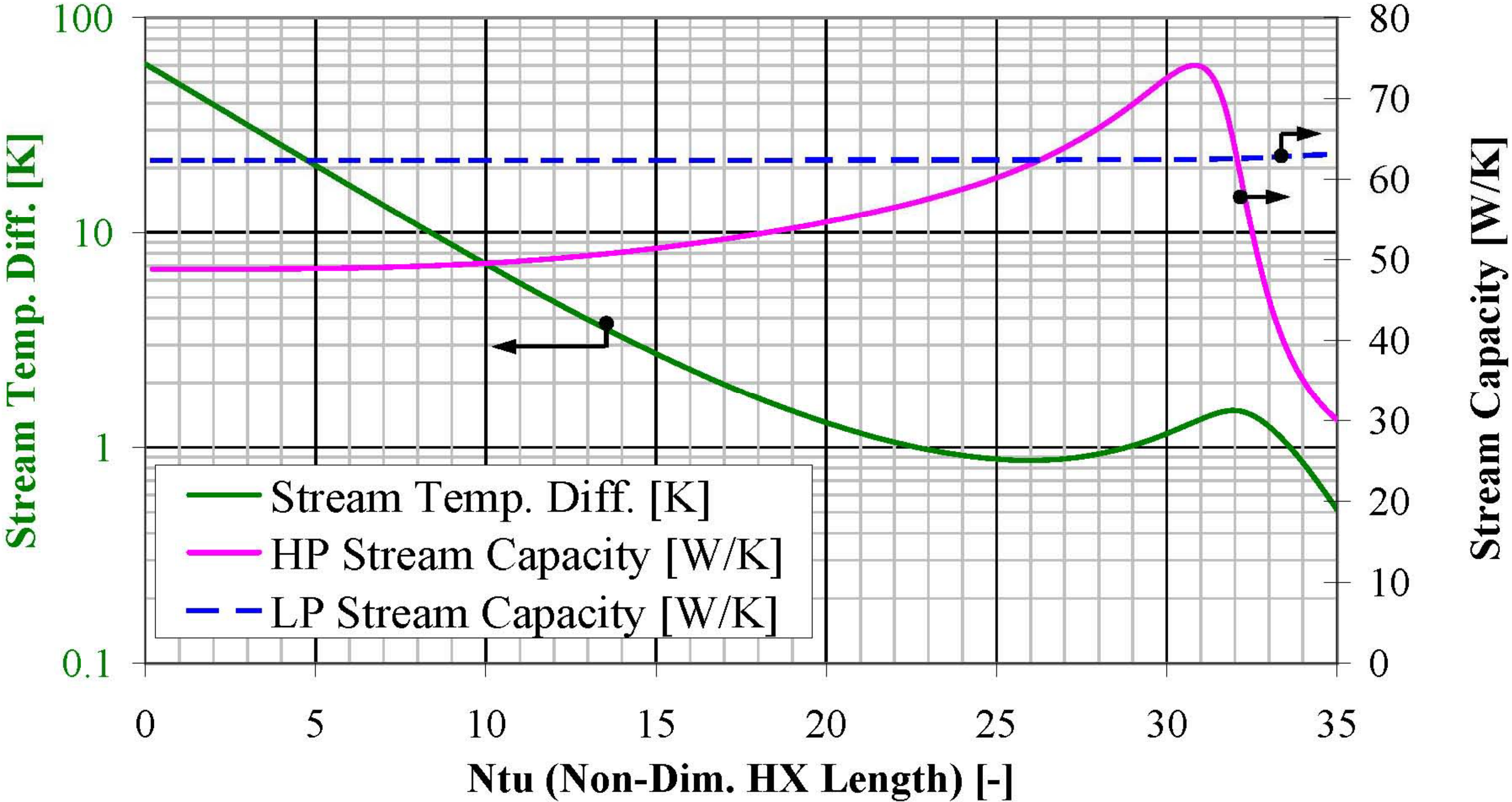
- Process Model Results…continued
  - —Cooling curves for C2-A HX-1 and HX-2 at minimum *real* COP$_{INV}$ (ξ_{hl} = 78%, $p_{h,1}$ = 12 atm) for Ntu$_{tot}$ = 40
  - —Exergy loss distribution

		HX-1	**HX-2**
Total Exergy Loss	[kW]	13.08	3.71
Loss Due to Temperature Difference	[-]	50.8%	66.3%
Loss Due to Pressure Drop	[-]	14.4%	6.1%
Loss Due to Heat In-Leak	[-]	34.9%	27.2%

  - —The following plots clearly show the (very) non-constant specific heat behavior of the real fluid

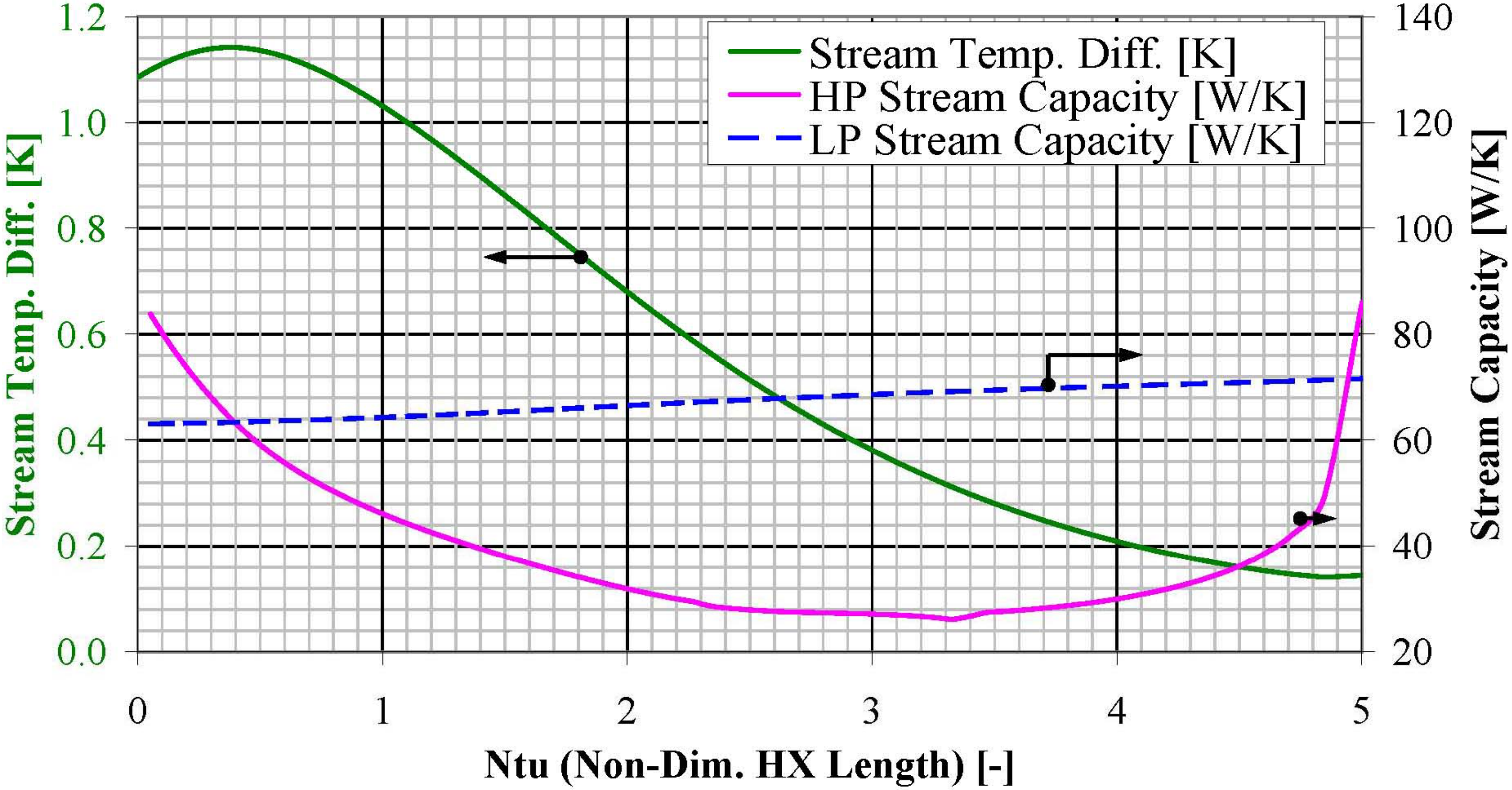
Process Study - Small Scale 2K Refrigeration

- C2-A HX-1 Cooling Curve (ξ_{hl} = 78%, $p_{h,1}$ = 12 atm, Ntu_{tot} = 40)



Process Study - Small Scale 2K Refrigeration

- C2-A HX-2 Cooling Curve (ξ_{hl} = 78%, $p_{h,1}$ = 12 atm, Ntu_{tot} = 40)



Process Study - Small Scale 2K Refrigeration

- Process Model Results…continued
  - C2-A HX-1 cooling curve
    - Imbalanced HX (flow-wise)
    - *(h)* stream capacity > *(l)* stream capacity only between ~13 to 7.5 K {for *(h)* stream}, with peak ~9 K
    - *(l)* stream capacity is nearly constant (as expected for a low pressure gas)
  - C2-A HX-2 cooling curve
    - Balanced HX (flow-wise)
    - *(h)* stream capacity < *(l)* stream capacity except at ends
    - This eludes to motivation for studying C2-B
    - Note that recycling high-pressure flow through JT-1 and back-through HX-2 reduces HX-2 losses (by increasing high pressure stream capacity), but the throttling loss of JT-1 costs more than was saved

Process Study - Small Scale 2K Refrigeration

- Process Model Results…continued
  - —Note that in both HX's there are (2) stationary points & (1) inflection point in ΔT_{hl} vs. Ntu (length) plot
  - —Temperature of sub-atmospheric stream exiting warmest HX is still quite cold (~240 K)
    - Ambient vaporizer (VAP) duty is ~25% of HX-1 (for C2-A)
    - But, the real process input loss is ~0.1% (~1% for the ideal process) as compared to HX-1 real process input power loss of ~3% (~22% for ideal process)
    - Thermal 'value' (exergy) of fluid becomes much less as the temperature approaches the zero reference temperature (T_0 = 300 K for this study)
    - This is a consequence of the 2nd law of thermodynamics on the ideal gas behavior of helium (i.e., not a 'real' fluid effect)
    - Note: the requirement for the ambient vaporizer is to protect the VPS from low suction temperatures (and provide consistency for the process study)

Process Study - Small Scale 2K Refrigeration

- Conclusions
  - For a 2-K process employing a distinctly separate and commercially available 4.5-K liquefier system, vacuum pumping system and (2-K) compressor system, the following appear achievable,
    - An *ideal* COP_{INV} of ~250 W/W
    - A *real* COP_{INV} of ~1800 W/W
    - This is 3.6 times better than a direct vacuum pumping process (using no cold HX), 1.9 times better than JLab's CTF

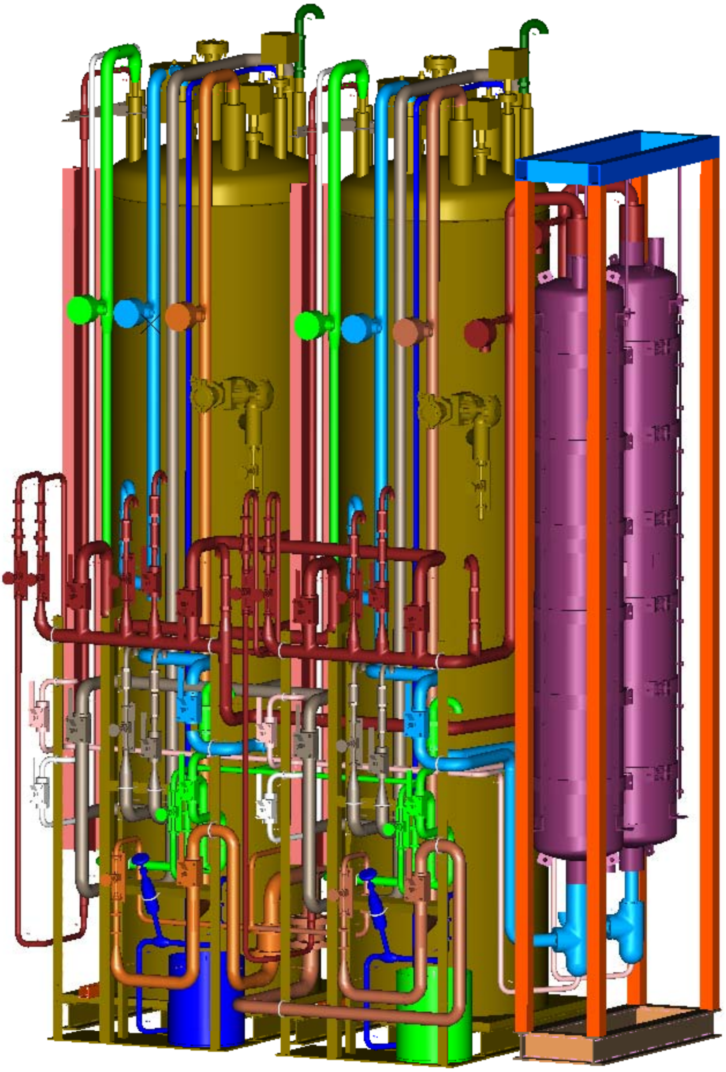
Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - —As mentioned previously, some sort of purification is highly desirable to remove air (leak) contamination
    - C2-A and C2-B would require separate purification units to process either full flow or make-up flow to 4.5-K plant
    - Purification capability built into 4.5-K liquefiers are typically either inadequate or will seriously reduce its capacity during purification
    - C2-A-p most readily lends itself to a simple integration of a ***full flow*** purifier by adding carbon beds in the high pressure stream just after the flow leaves the LN boiler (HX-2)
    - The slightly superior performance of C2-A-p (for $Ntu_{tot} \geq 30$) should be given low weighting in consideration as compared to the importance of flow purification

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued

(Separate) Dual 60 g/s Helium Purifier



Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - Additional advantages of LN pre-cooling
    - Flow mal-distribution in HX's is a rather under-published but very common problem – it's effect is quite significant on HX performance
    - As such, under performance in HX-1 (for C2-A-p) can be eliminated or greatly reduced in exchange for additional LN usage
    - Also, additional LN usage is generally much less costly than allowing the warm-end HX (i.e., HX-1 in C2-A-p) under-performance to be 'carried' to below 80 K

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - —Despite its greater complexity, as indicated by C2-B's blunter 'knee' (ξ_{hl} vs. COP_{INV} curves); it may offer a more stable process for designs having a lower total HX Ntu's (say, $Ntu_{tot} \leq 20$)
  - —LN system exergetic efficiency is site/project specific (depending on the cost and availability of the LN, as well as, the availability required of the 2 K system)
  - —Remember that the exergetic efficiency used for the 4.5-K liquefier system is the most important parameter for any 2 K system!

Process Study - Small Scale 2K Refrigeration

Conclusions…continued

Configuration	*Ideal* COP_{INV} [W/W]	*Real* COP_{INV} [W/W]	Notes
C1	**693**	**6500**	**No cold-end HX**
C1-A	**478** [(a)] **447** [(b)]	**4490** [(a)] **4200** [(b)]	***(a)*** **Cold-end HX = 2 NTU's** ***(b)*** **Cold-end HX = 6 NTU's**
C2-A	**250**	**1780**	$\mathbf{Ntu}_{tot} = 40$; $p_{h,1} = 12$ atm; $\xi_{hl,opt} = 78\%$
C2-A-p	**271**	**1720**	$\mathbf{Ntu}_{tot} = 40$; $p_{h,1} = 12$ atm; $\xi_{hl,opt} = 77\%$
C2-B	**254** [(c)]	**1800** [(d)]	$\mathbf{Ntu}_{tot} = 40$; $p_{h,1} = 12$ atm *(c)* $\xi_{hl,opt} = 78\%$; *(d)* $\xi_{hl,opt} = 79\%$
JLab CTF	**N/A**	**3400**	
CC System	**N/A**	**900**	**4.5 K System,** $\eta_{C,} = 25\%$

Note: CC (cold-compressor) system – performance possible using Floating Pressure cycle with well matched cold box and compressor system

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - Example using results presented:
    - Specified: 2-K load of (q_L =) 174 W
    - Select configuration C2-A-p
    - Select $p_{h,1}$ = 12 atm and Ntu_{tot} = 40
    - From plots read, at 40 Ntu's, $\xi_{hl,opt}$ = 77% and (minimum) *real* COP_{INV} = 1720 W/W
    - For all cases assume enthalpy difference supplied to the 2-K load is (Δh =) 20 J/g (this is conservative: assumes 4.5 to 2 K HX with 1.75 Ntu's for liquid supply and 3.5 Ntu's for SC supply)
    - So, the total refrigeration flow (from the 2-K load to VPS) is = 174 [W] / 20 [J/g] = 8.7 g/s
    - Required make-up flow from commercial 4.5-K liquefier system is = (1 – 0.77)·8.7 [g/s] = 2.0 g/s
    - Total equivalent input power required is = 1720 [W/W] · 174 [W] / 1000 [W/kW] = 300 kW

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - As a note of caution for this previously worked example – this study has assumed that the equipment used (i.e., 4.5-K plant, VPS and RSC) is available in a continuum of capacities. Of course, this is not the case, as equipment is only available in specific sizes
  - So, really…why not use direct vacuum pumping?
  - What might a cost comparison look like?

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - Case–1: direct vacuum pumping with,
    - 4.5-K LHe supplied by dewar (say, 1.3 atm)
    - No cold-end HX
  - Case–2: same as Case–1 except use,
    - Cold-end HX (6 Ntu's)
  - Case–3: same as Case–1 except use,
    - 4.5-K helium supplied by 10% Carnot liquefier, and
  - Case–4: same as Case–1 except use,
    - 4.5-K helium supplied by 10% Carnot liquefier
    - Cold-end HX (6 Ntu's)
  - Case–5: Like JLab CTF (*ideally*)
  - Case–6: Use one of configurations studied with,
    - 4.5-K helium supplied by 10% Carnot liquefier
    - Cold-end HX (6 Ntu's)

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued

2-K Load	**180**	[W]
Specific 4.5-K Liquefier Cost	300	[K$/(g/s)]
Specific Vacuum Sys. Cost	60	[K$/(g/s)]

	Case-1	**Case-2**	**Case-3**	**Case -4**	**Case-5**	**Case-6**	
4.5-K Mass Flow	16.7	10.2	13.6	8.7	5.4	2.2	[g/s]
2-K Mass Flow	13.5	8.3	13.6	8.7	9.7	8.7	[g/s]
4.5-K Liquefier System	-	-	4,072	2,620	1,605	655	[K$]
Vaccum Pumping System	811	497	814	524	582	524	[K$]
Compressor System	-	-	-	-	250	200	[K$]
Misc. Equipment	100	150	200	200	250	250	[K$]
Engineering	10	10	58	58	58	58	[K$]
Installation	19	19	154	154	154	154	[K$]
Commisioning	-	-	38	38	38	38	[K$]
Total Capital	**940**	**676**	**5,336**	**3,594**	**2,937**	**1,879**	[K$]

Cost of Electricity	0.055	[$/kW-h]
4.5-K Helium Unit Cost	3.40	[$/l]

	Case-1	**Case-2**	**Case-3**	**Case -4**	**Case-5**	**Case-5**	
COP_{INV}	1.3	0.81	4.8	3.1	3.4	1.8	[kW/W]
Operating Power	239	147	864	558	606	324	[kW]
1/4 Year Operating Cost	**3,602**	**2,209**	**104**	**67**	**73**	**39**	[K$/3 mo.]
Yearly Operating Cost	**14,407**	**8,835**	**416**	**269**	**292**	**156**	[K$/yr]

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - Quarter year operating cost for direct vacuum pumping using a LHe dewar is approx. 2 times more than the capital cost required for the proposed 2-K configurations
  - Capital cost for direct vacuum pumping using a 4.5-K liquefier is approx. 1.9 to 2.8 times the capital cost required for the proposed 2-K configurations; and roughly the same for operating costs (1.7 to 2.7)

Process Study - Small Scale 2K Refrigeration

- Conclusions…continued
  - —Recommendations for further study
    - Characterization of the isothermal efficiency for various VPS – to lead to a classification for use over various flow ranges and methods to improve the efficiency of these systems
    - Testing of alternate HX designs that are less expensive than brazed-aluminum plate-fin HX's but that are easier to manufacture and have less sub-atmospheric pressure drop than spiral-wound finned tubing type

- Questions? Thank you!