



OPTIMAL DESIGN AND OPERATION of Helium Refrigeration Systems

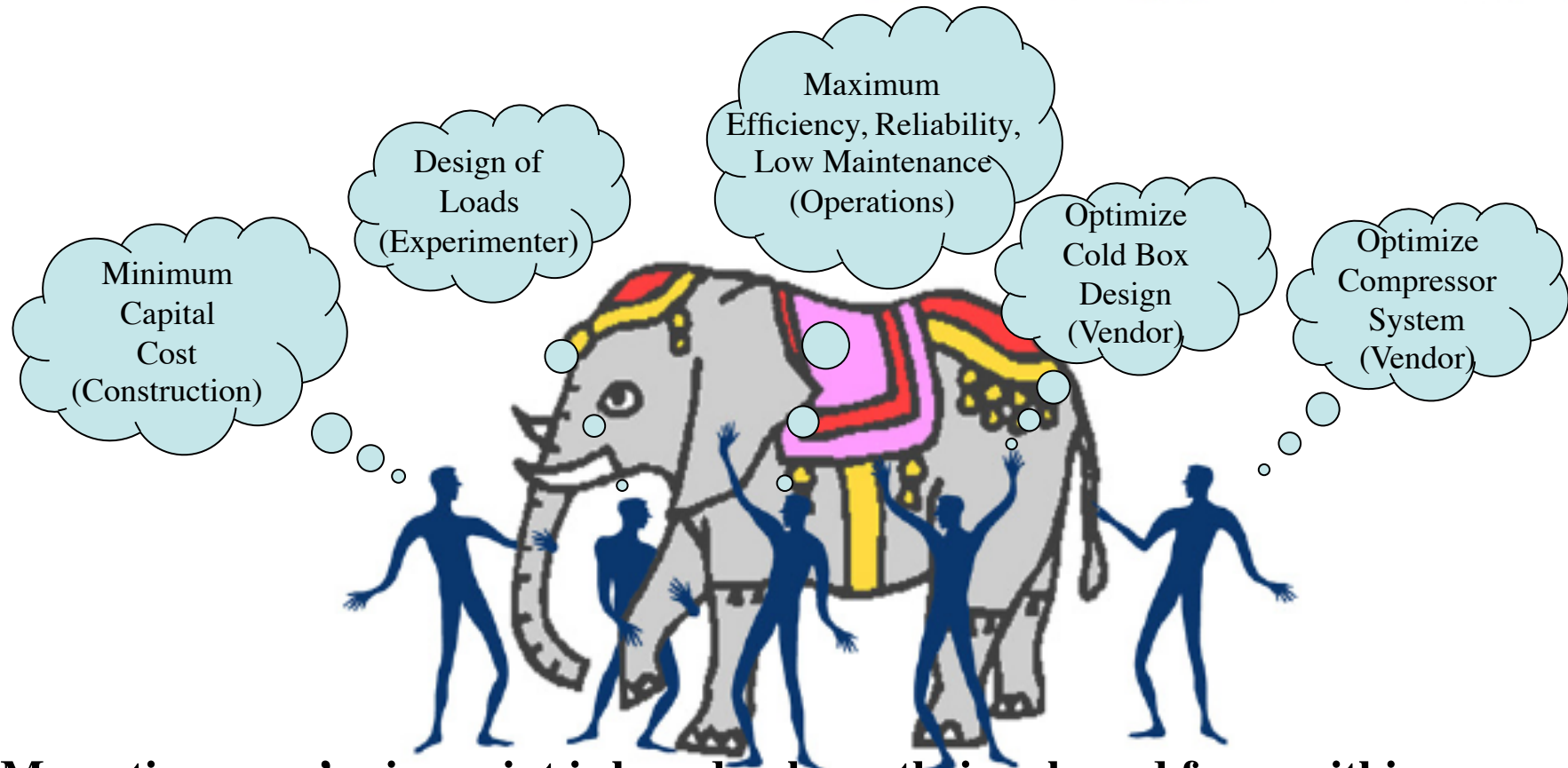
PAC09

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Foreword

- This presentation is intended to,
 - Briefly discuss some very fundamental concepts and ideas
 - Introduce some non-traditional ideas to the ‘**mature**’ technology of **helium cryogenics!**

What is an “Optimal” System



- Many times one's viewpoint is based only on their role and focus within a project
- Many incorrectly believe that their goals compete with others and are not achievable together
- Many believe that maximum system efficiency occurs only at one set of fixed operating conditions



Issues for Thought

- **Cost of Energy**
 - Could ignore inefficiencies in the past, but not anymore!
 - Was it right to ignore it in the past?
- **Accumulation of system inefficiencies, due to,**
 - **Scaling up of the systems**
 - There was a rapid change in system refrigeration capacity needs
 - 200 W in late 1960's to more than 25kW by early 1980's
 - This formed 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**
 - What are the correct pressure ratio choices to match cold box and compression systems (does it matter)?
 - How much margin should be added to loads, on top of margins on cold box, on compressors, etc?
 - Are system efficiencies affected by the amount of the actual refrigeration loads imposed on the machine?

Issues for Thought

- **Lack of component development** (*some questions!*)
 - What are the pros & cons of LN cooling of cold compressors?
 - Is a screw compressor in the present form the right choice and especially for a large plant?
 - What development has been done on the helium compression systems?
 - *It accounts for ~ 2/3 of the energy losses!*
- **Control system philosophies**
 - Are the dependent or independent parameters being controlled
 - *it matters for efficiency & stability!*
- **Is helium cryogenics a 'mature technology'?**
 - Is JLab 2K a 'mature technology' (Operating for ~15 years)
 - Model-T and IBM 286 were mature technologies at one time!
 - Does 'mature' mean that it is OK to say *'give me another one of those'*
 - The term *'mature technology'* **should not be used lightly**
especially professionals involved with the system level of the technology!

Helium Refrigeration Systems are Very Energy Intensive

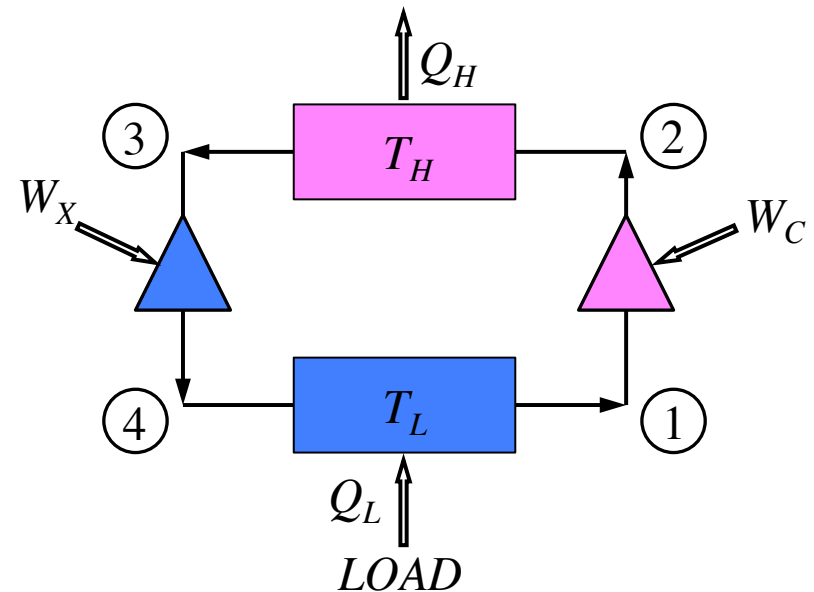
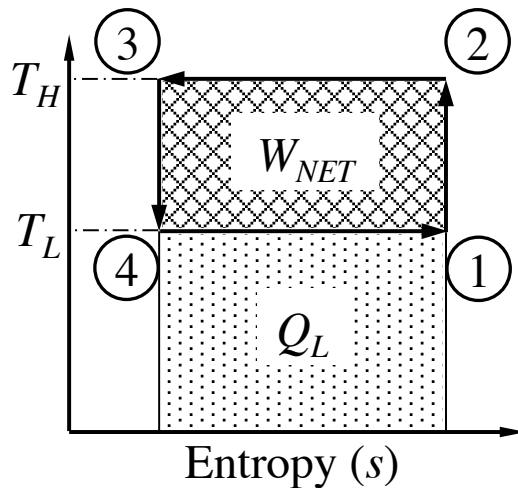
To design and/or to operate a system efficiently, need to understand,

- **The quality of energy**
 - A load at 2K is very different than a load at 4K!
 - Concepts of reversible (Carnot) work, availability and irreversibilities
 - Virtually all the electrical input power is rejected as heat into the environment!
- **The process and the Carnot Step(s) selection**
 - Differences between refrigerator & liquefier design
 - Proper selection of temperature and pressure levels
- **The efficiency and characteristics of the major components**
 - e.g., compressor, expanders, heat exchangers
- **What are the optimization goals?**
- **How do the real components match to the process requirements?**
- **How should the system be controlled? Does it matter?**

What is a Refrigeration System?

- The helium refrigeration and liquefaction systems are an extension of the traditional household refrigeration systems.
- The refrigeration system transfers heat energy from low temperature to high temperature.
- Normally, the term refrigeration is used for absorbing heat energy at a constant temperature, but this does not have to be the case.

Carnot Vapor Compression Refrigeration Cycle



- | | |
|----------------------|---|
| #1 to #2: Compressor | • Fluid is compressed isentropically (requiring W_C) |
| #2 to #3: Condenser | • Heat, Q_H , is rejected isothermally (at T_H) |
| #3 to #4: Expander | • Fluid is expanded isentropically (extracting W_X) |
| #4 to #1: Evaporator | • Heat, Q_L , is absorbed isothermally (at T_L) |

Net input work (W_{NET}) = $W_C - W_X = Q_H - Q_L$

Cooling provided (Q_L)

Coefficient of Performance (COP) = Q_L / W_{NET}

Inverse COP (COP_{INV}) = $1 / COP$

Input Power and Energy Transfer

Inverse of the Coefficient of Performance,

$$COP_{INV} = \frac{\text{Required Net Input Work}}{\text{Useful Refrigeration}} = \frac{W_{NET}}{Q_L}$$

For a Carnot (reversible) refrigerator,

$$COP_{INV,C} = \frac{W_{NET}}{Q_L} = \frac{Q_H - Q_L}{Q_L} = \frac{T_H}{T_L} - 1$$

So, for an ordinary refrigerator operating between,

$$T_L = -10^\circ C \quad \text{and,} \quad T_H = +50^\circ C$$

$$COP_{INV,C} = \frac{(273.15 + 50)}{(273.15 - 10)} - 1 = 0.23 \text{ W/W}$$

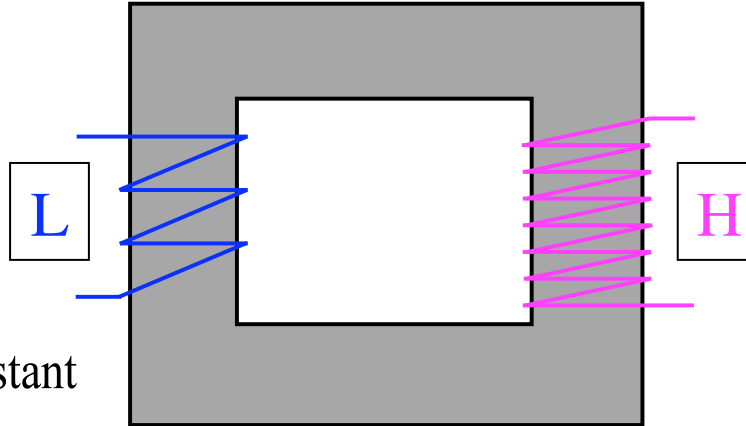
That is, it takes 0.23 kW of input power to transfer 1 kW of heat energy from the low temperature (-10 °C) to the higher temperature (+50 °C).

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

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

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

- Why is any input energy required to transfer heat energy from a cold to a hot temperature reservoir?
- A thermal transformer that permits the heat energy transfer from cold temperature to hot temperature, with no input work does not exist.
- This is quite unlike an ideal electrical transformer, which will permit the transfer between voltage and current with no additional input power.
- 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)

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

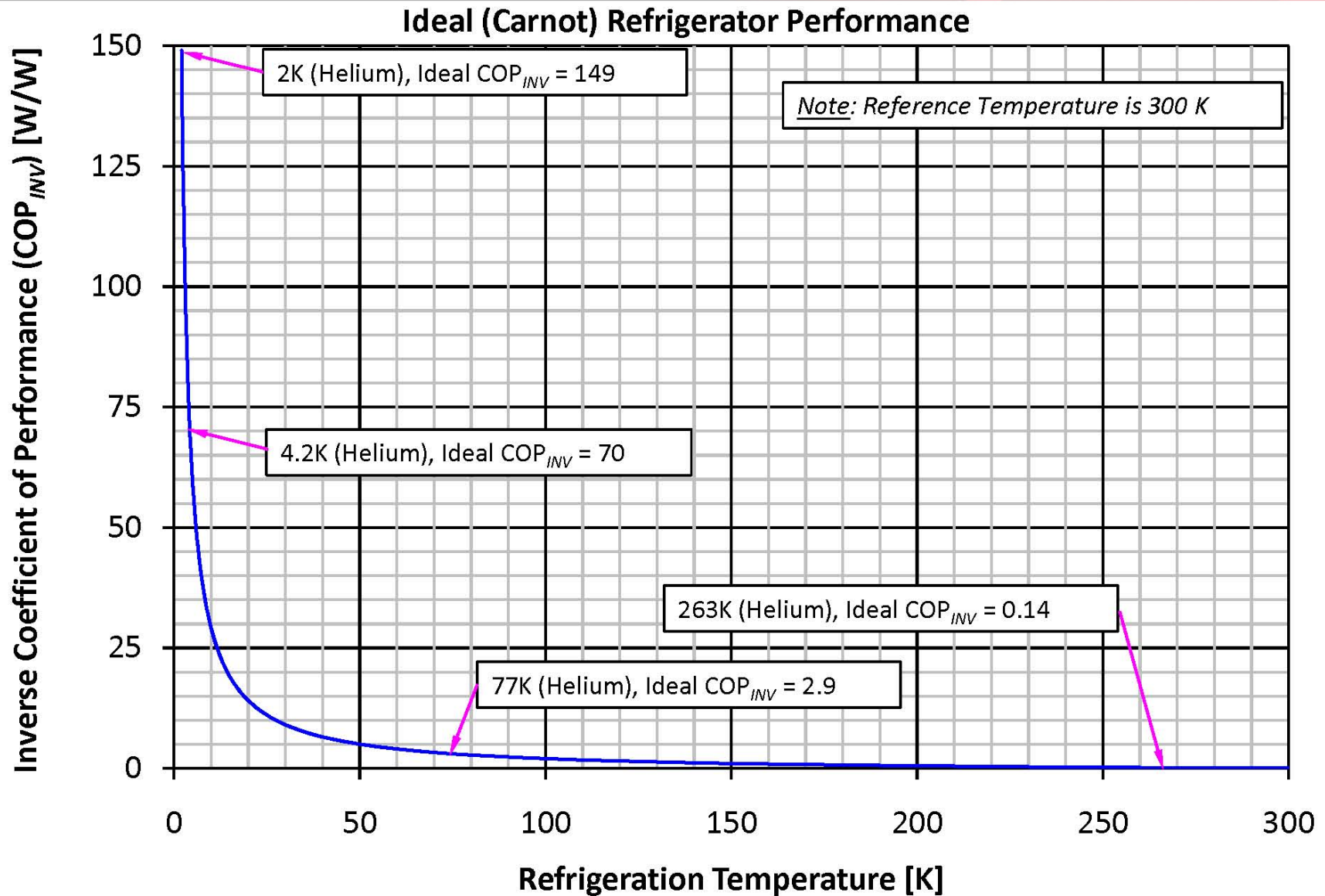
*This equation is a statement of
thermal energy quality equivalence*

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!*

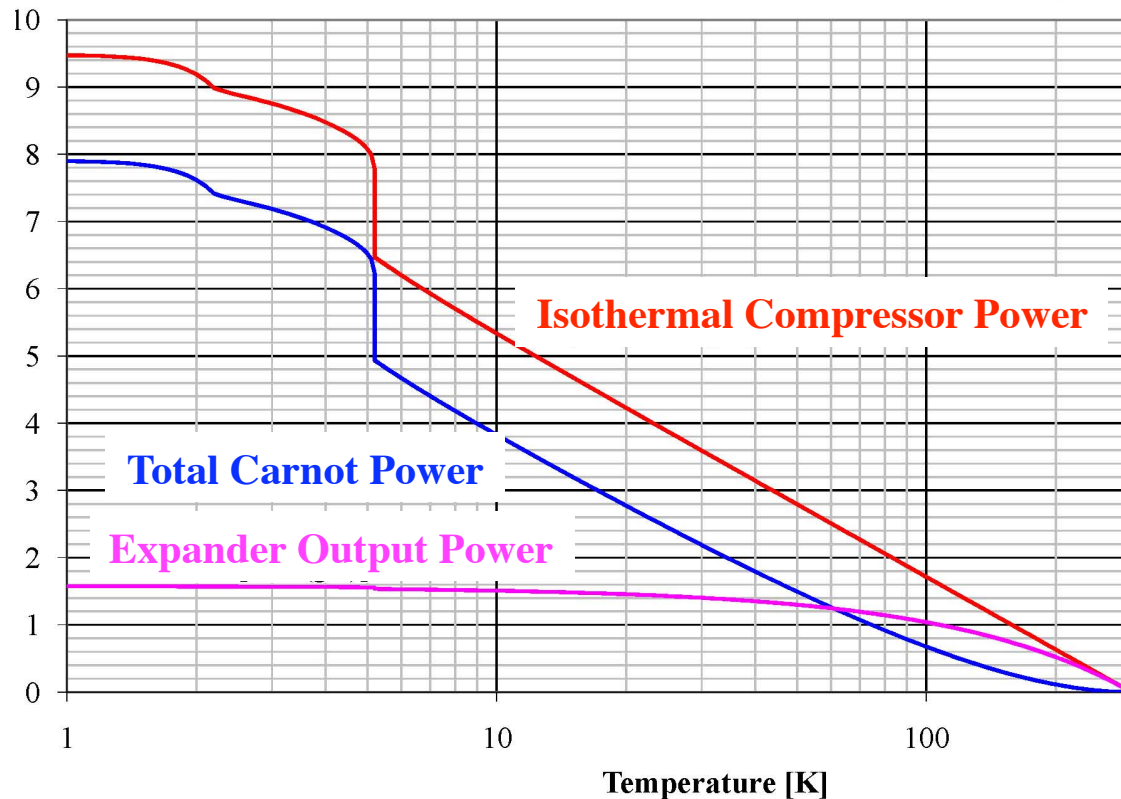
Quality of Energy (Cont.)



Carnot Helium Refrigeration and Liquefaction Systems

- As mentioned previously, normally, the term refrigeration is used for absorbing heat energy at a constant temperature, but this does not have to be the case
- In a 4.5K liquefier, the liquefaction load is cooled by absorbing heat energy at a temperature varying continuously from 300 K to 4.5K
- For a liquefier, would like to examine the ideal,
 - Net Carnot power required
 - Isothermal (i.e., ideal) compression power
 - Expander output power

Carnot Helium Refrigeration and Liquefaction Systems (Cont)



For a liquefaction load,
look at the mass specific

1. Total Carnot Power
2. Isothermal Compressor Power
3. Expander Output Power

to cool 1 g/s of helium
from 1 atm & 300 K to
a temperature 'T'

1. Total Carnot Power $= (T_0 \cdot \Delta s - \Delta h)$
2. Isothermal Compressor Power $= T_0 \cdot \Delta s$
3. Expander Output Power $= \Delta h$

Carnot Helium Refrigeration and Liquefaction Systems (Cont)

Temperature Range Summary for Liquefaction Load:

1. Carnot Power Required $(T_0 \cdot \Delta s - \Delta h)$
2. Isothermal Compressor Power $(T_0 \cdot \Delta s)$
3. Expander Power Output (Δh) , and

As compared to (1 atm & 300K) to 4.22K (100%)

Temperature		$T_0 \cdot \Delta s$	%		Δh	%	$T_0 \cdot \Delta s - \Delta h$	%
Range (K)		[W/ (g/s)]			[W/ (g/s)]		[W/ (g/s)]	
300 - 80		2058	24.5%		1143	73.0%	915	13.4%
80 - 4.22		6329	75.5%		421	27.0%	5908	86.6%
300 - 4.22		8387	100.0%		1564	100.0%	6823	100.0%
4.22 Latent		1469	17.5%		20.7	1.3%	1448	21.2%

Carnot Helium Refrigeration and Liquefaction Systems (Cont)

Carnot Power for Different Fluids

Fluid	Tsat,0	Liquefaction	Refrigeration
	[K]	(W/(g/s))	(W/W)
Helium	4.22	6823	70
Hydrogen	20.28	12573	13.8
Neon	27.09	1336	10.1
Nitrogen	77.31	770	2.9
Argon	87.28	477	2.4
Oxygen	90.19	635	2.3
Methane	111.69	1092	1.7

Note that the Carnot work for Helium is high!

*Constituents in air separation are an order of magnitude less
Carnot power than helium!*

Helium Liquefaction & Refrigeration Systems and the “Carnot Step”

Typically in helium (refrigerator) systems, there are, multiples of certain similar non-simple process steps to accomplish a given process

e.g., warm screw compressor stages,
expansion stages in a cold box, etc..

The **Carnot Step** is defined (*by the author*) as the arrangement (or “spacing”, “distribution”) of a given number of the same type of process step which yield the minimum irreversibility.

Helium Liquefaction & Refrigeration Systems and the Carnot Step

So, the Carnot step,

- Is the arrangement (or spacing) of similar process steps that result in the minimum irreversibility**
- Is applicable for both reversible and irreversible (ideal and real) systems**
- Should result in an efficient (or even optimum) system when used as a design basis for a system constructed with real components**

Load System Carnot Step

The Load:

- A helium refrigeration system typically design to support:
 - Refrigeration load – characterized by a ‘balanced’ flow; can be either isothermal or non-isothermal
 - Liquefaction load – characterized by an ‘unbalanced’ flow; it is non-isothermal
 - Usually a combination of both of these is required
- **VERY IMPORTANT** to minimize the entropy increase of the helium at the load level (temperature) while satisfying the load requirements.

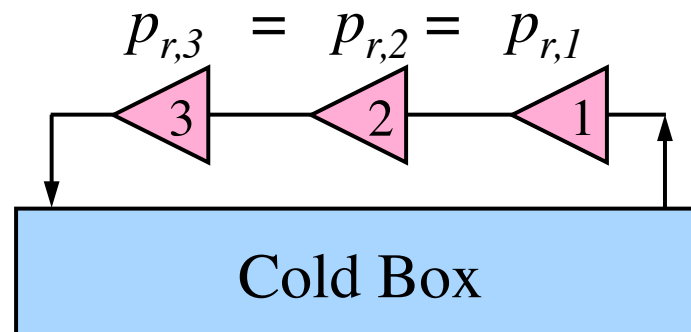
Examples of poor practices:

 - Targets returning 20K helium, but not recovering the refrigeration between this temperature and 300K
 - Distribution systems (transfer lines) with excessive heat leak
 - Loads designed with excessive pressure drop
- Application: *Thermal shield temperature selection between 300 and 4.2K* - assuming equal conductance on both sides of the shield, the idealized choice for the shield temperate to minimize the total reversible input power (i.e., the load Carnot Step spacing) is same as the *equal temperature ratios and is 35K*.

Compressor System Carnot Step

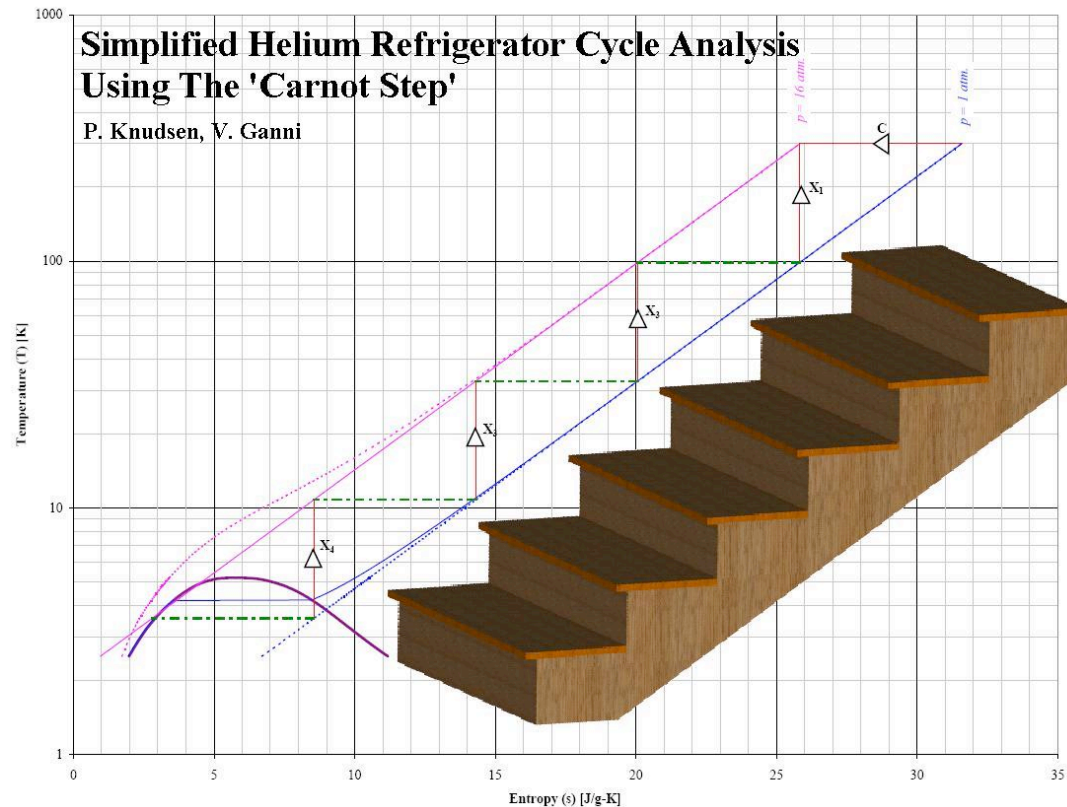
The Compressor System:

- *The compressor system uses the input (usually electrical) energy to increase the availability (e.g., exergy) of the helium gas being supplied to the cold box.*
- *For a multistage polytropic compression process, an equal pressure ratio among each of the equal efficiency stages yields the minimum mass specific input work. This is the compressor Carnot step.*



- *The compressor Carnot step provides a means for evaluating a given compressor system design (efficiency).*

Cold Box Carnot Step



- For a given number of expansion stages, what is the optimum temperature level spacing? Or,
- What is the ideal number of expansion stages for a given high to low pressure stream ratio (i.e., pressure ratio)?

Cold Box Carnot Step (Cont.)

The Cold Box:

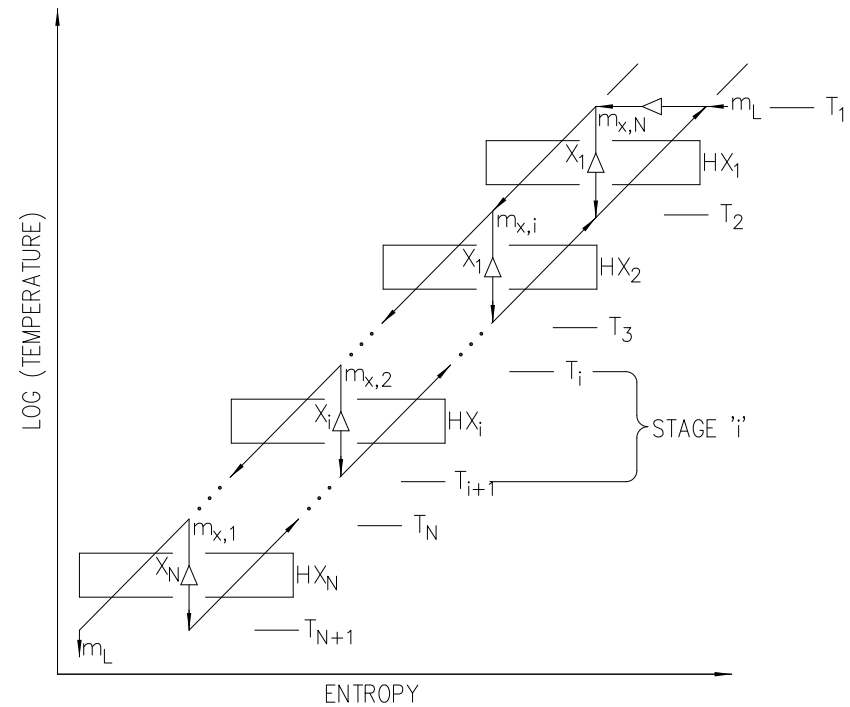
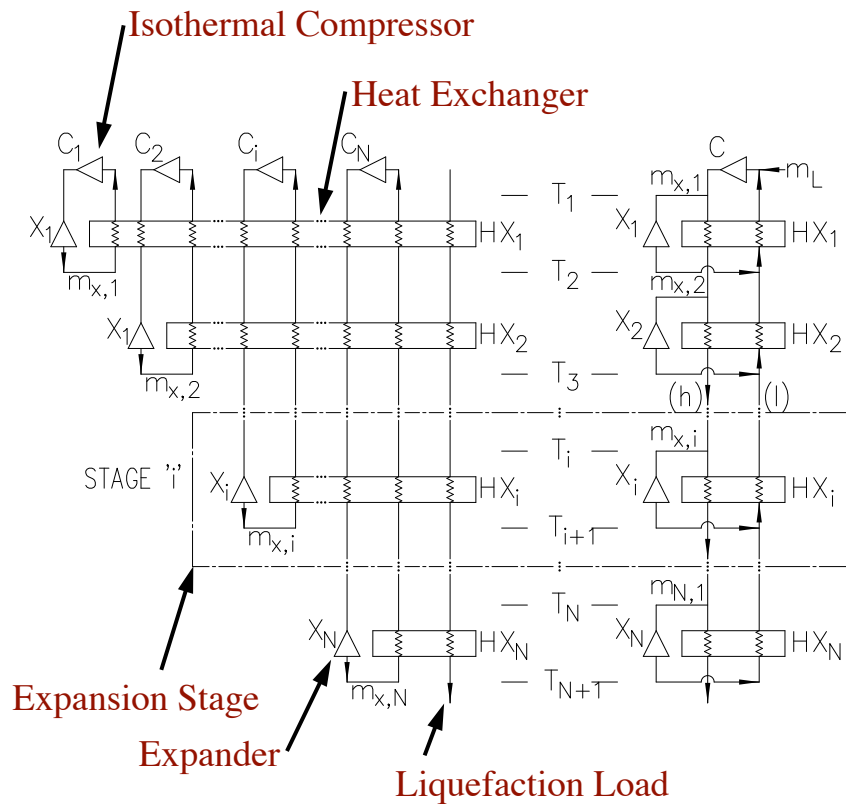
The cold box bridges the temperature difference from the load to ambient conditions, transferring the entropy increase at the load to the ambient utilizing compressor(s).

The cold box has no input power and can only utilize the availability (i.e., exergy) supplied to it by the compressor(s).

It is critically important for the cold box to transfer the exergy to the load with minimum losses along the way.

The cold box provides a process path analogous to transferring a load from a deep basement floor (4.2K) and/or along the path to the ground floor (300K) by walking up the stairs. So, given the 'height' between the 'floors' (4.2K to 300K), we would like to know the optimal spacing of a given number of steps that will yield a minimum irreversibility.

Liquefier - Cold Box Carnot Step (Cont.)



Ideal Claude Liquefier (ICL)

Ts Diagram for the Ideal Claude Liquefier (ICL)

Liquefier - Cold Box Carnot Step (Cont.)

Nomenclature:

P_r – pressure ratio across expanders = p_h / p_l

T_1 – ambient temperature [K]

T_i – temperature at level 'i' [K]

T_{N+1} – load temperature [K]

$T_{r,T}$ – total temperature ratio (ambient to load temperature) = T_1 / T_{N+1}

$T_{r,i}$ – temperature ratio of stage 'i' = T_i / T_{i+1}

N – total number of (ideal) expansion stages

$i = 1$ to $(N + 1)$

γ – ratio of specific heats

$\phi = (\gamma - 1) / \gamma$

Optimum spacing, or Carnot Step is, $T_r = T_{r,i} = \text{constant}$

So, $T_{r,T} = T_1 / T_{N+1} = (T_r)^N$

Also, for isentropic expanders, $T_r = P_r^\phi = \text{constant}$

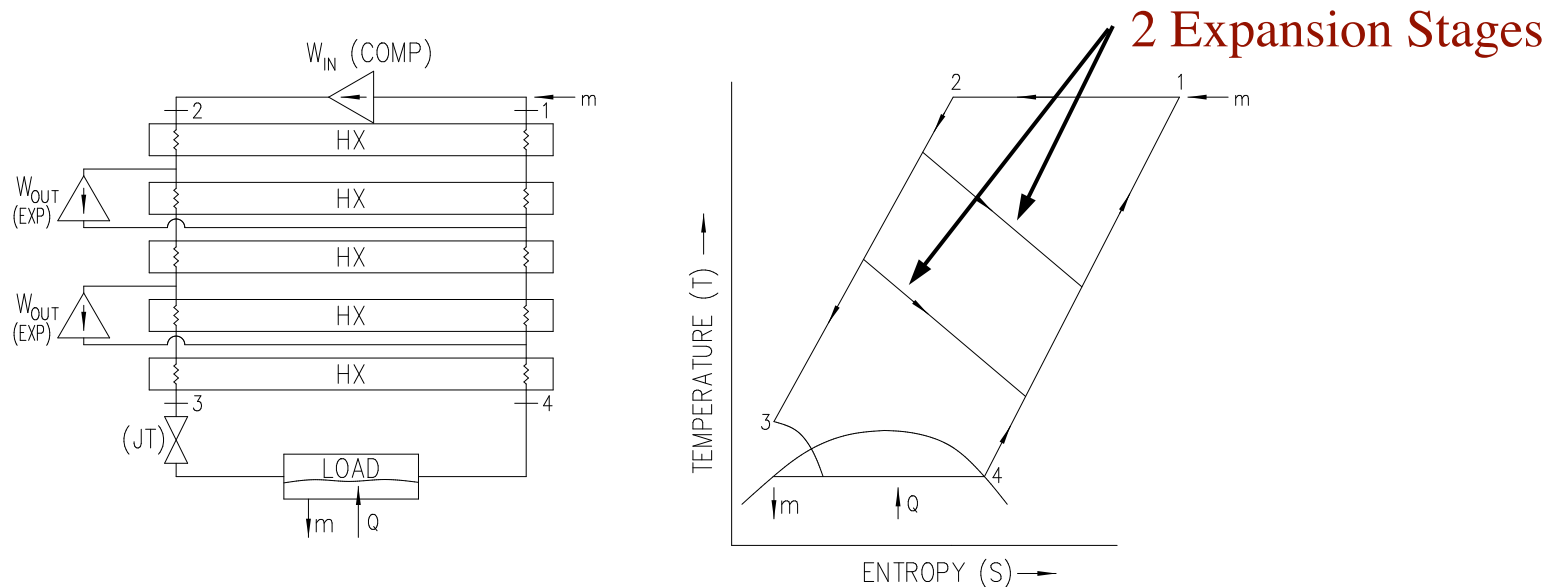
So, the minimum number of expansion stages is,
$$N = \frac{\ln(T_{r,T})}{\phi \cdot \ln(P_r)} = \frac{\ln(T_{r,T})}{\ln(T_r)}$$

Liquefier - Cold Box Carnot Step (Cont.)

- So, the Carnot step, or optimum temperature level spacing, is,
 - the temperature ratio for each expansion stage and,
 - is the same for each expander stage 'i' and,
 - for the ICL, is equal to the expander temperature ratio (which is set by the pressure ratio, p_r) and,
 - results in equal expander mass flows
- For example, a 300K to 4.2K liquefier; e.g., $T_1 = 300\text{K}$, $T_{N+1} = 4.2\text{K}$ with an expander pressure ratio of 16 (e.g., $p_r = 16$)
total temperature ratio is, $T_r = 300 / 4.2 = 71$
temperature ratio for each expander stage is, $T_r = (16)^{0.4} = 3.03$.
- Or, given the expansion stage temperature ratio, the ideal number of expander stages required for the ICL is,
$$N = \ln(71) / \ln(3.03) = 3.85 \approx 4$$

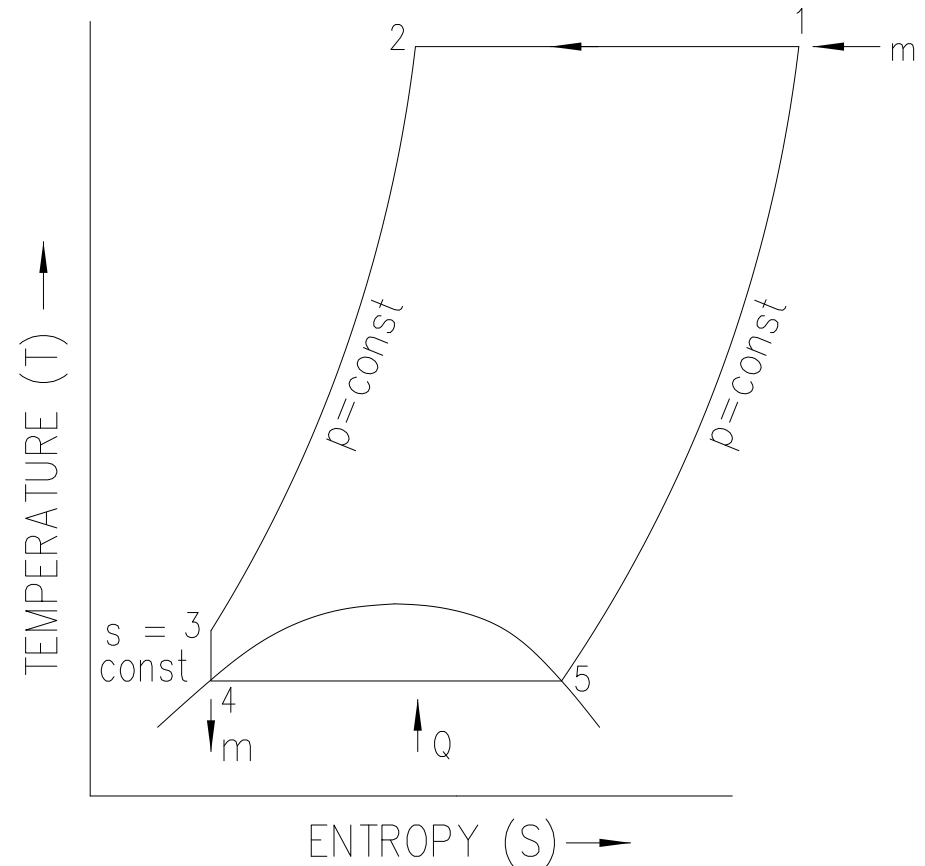
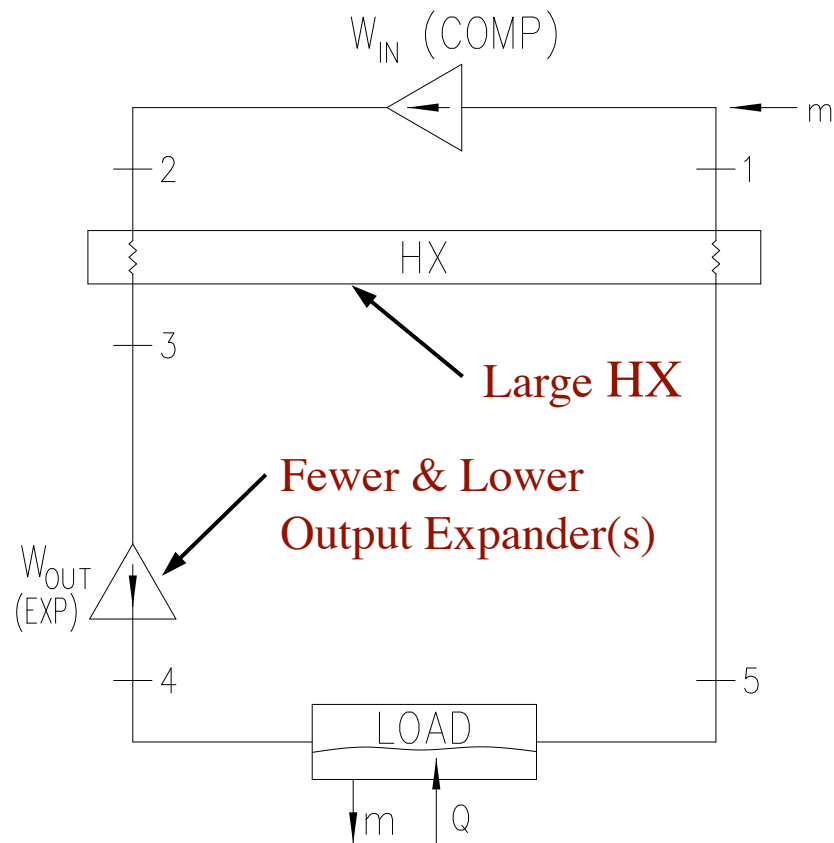
Collins 4.5K Liquefier

- Collins helium liquefaction process



- This is the process developed by Sam Collins at MIT and is an extension of the Claude process.
- Supports lower temperature load operations more efficiently than the Claude process.
- The widely used helium liquefiers originally known as CTI-1400's were based on this process.

Idealized Helium Refrigeration System



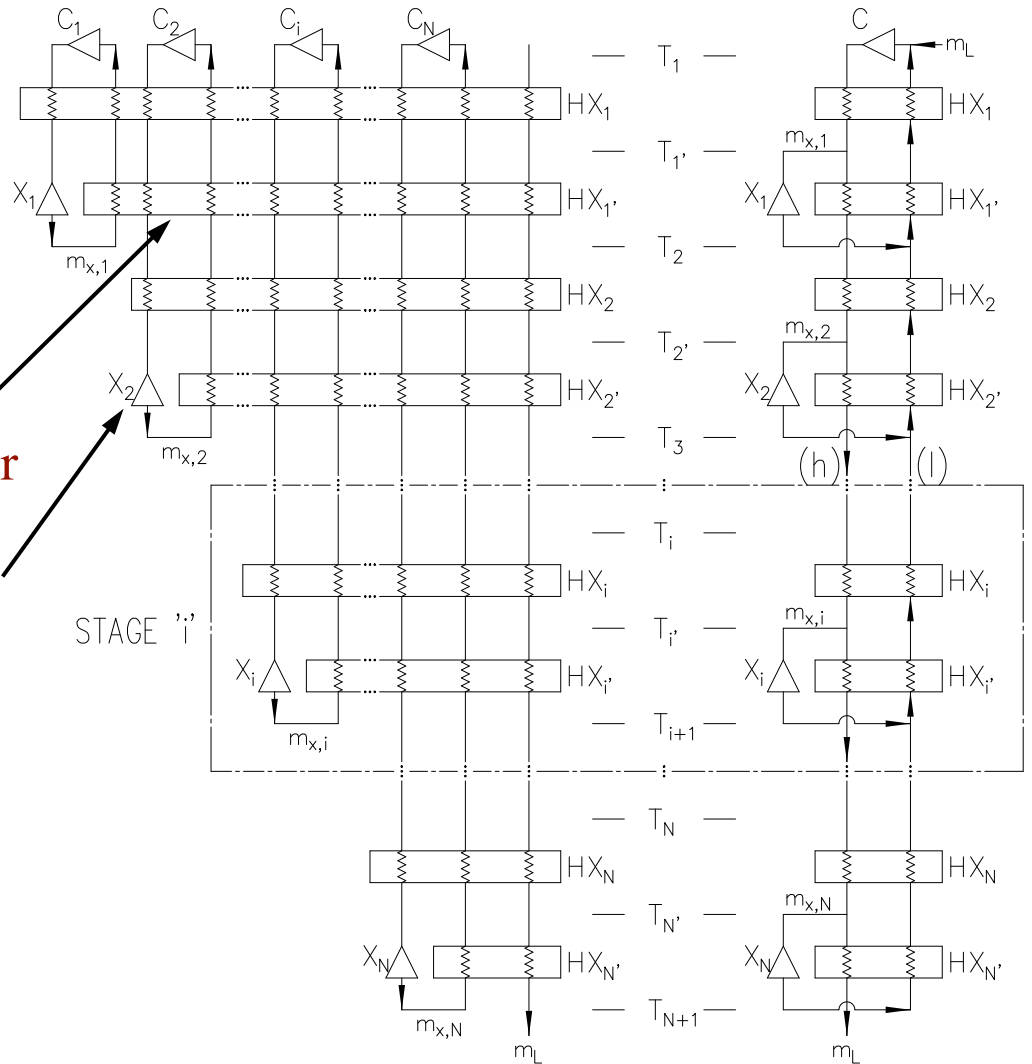
An efficient refrigerator has fewer and lower output expanders, but much larger HX's and larger total HX size

An efficient liquefier has,
Many high output expanders
but generally smaller HX's and
less total HX size due to
imbalanced flow.

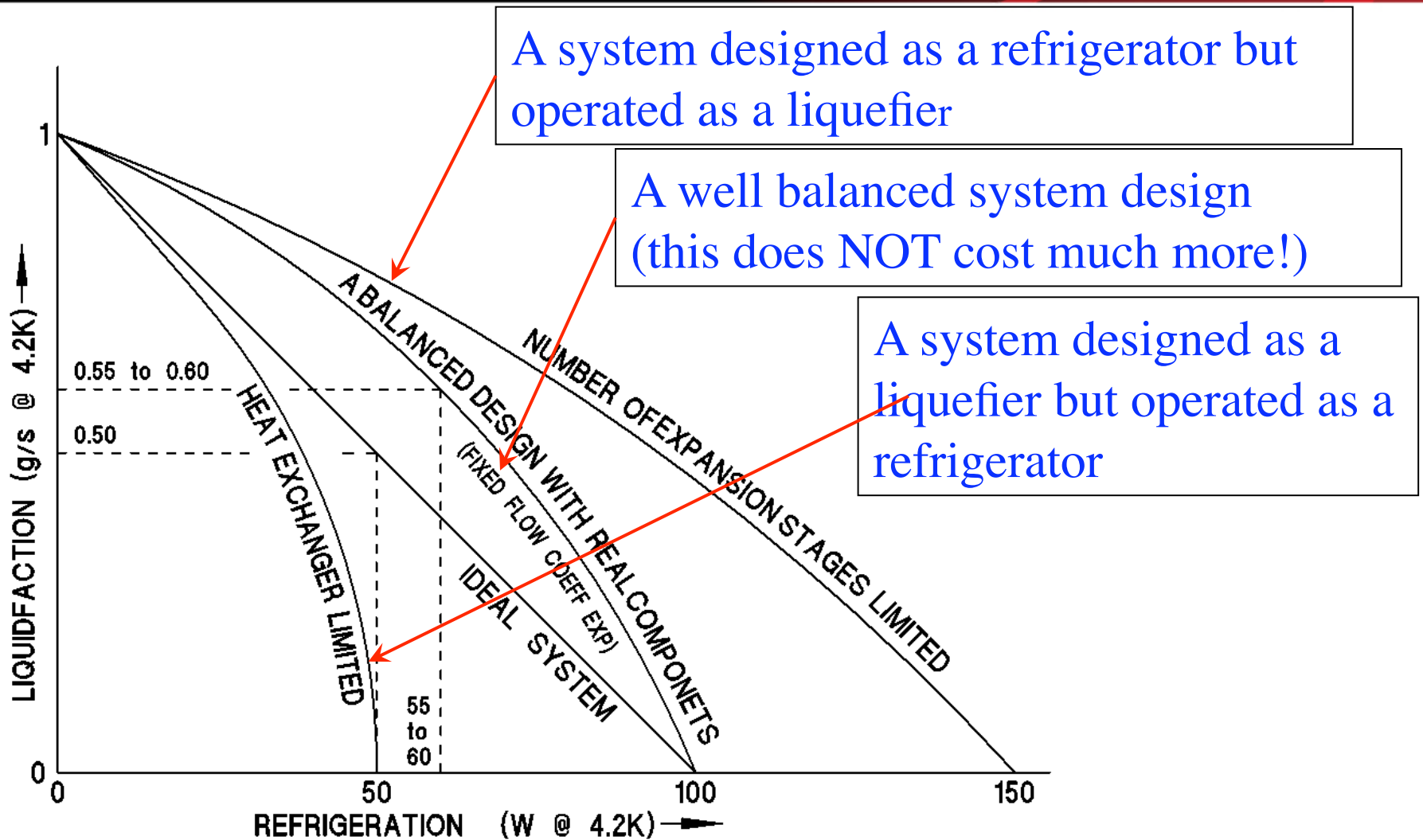
Less total HX
than a refrigerator

Many high output expanders

Claude liquefier with additional HX per stage



Effect of Components on the Cycle Design



The Effect of Components on System Load Capacity

System Optimization

Returning to the question...

What is an optimum system? Does it result in the:

- 1) **Minimum operating cost**
- 2) **Minimum capital cost**
- 3) **Minimum maintenance cost**
- 4) **Maximum system capacity**
- 5) **Maximum availability of the system**

A combination of some or all the above
or, Some other factors?

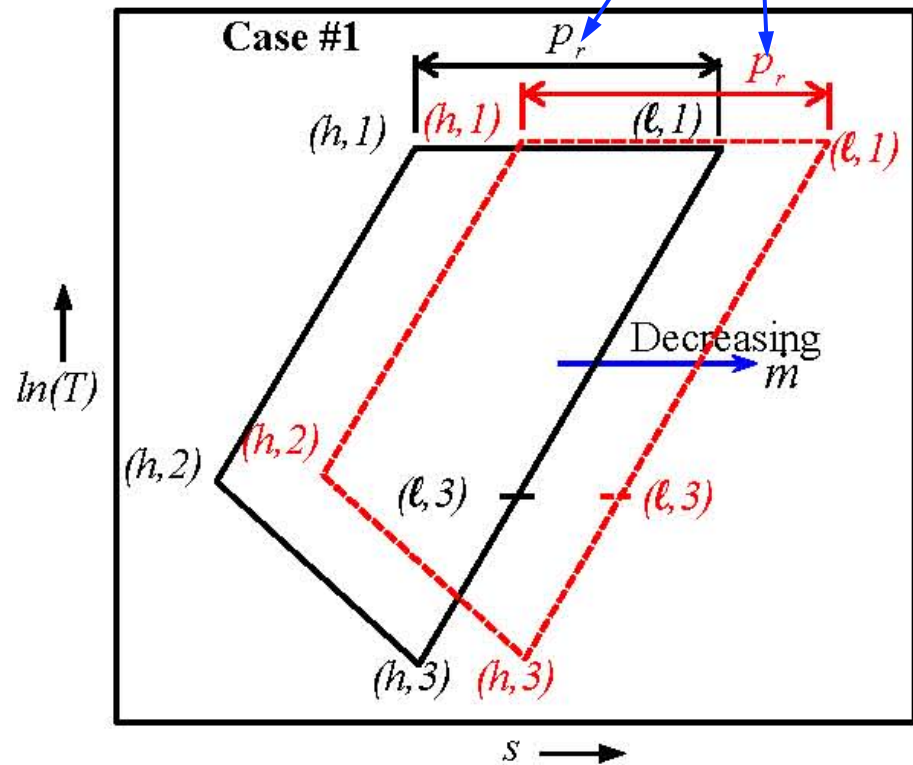
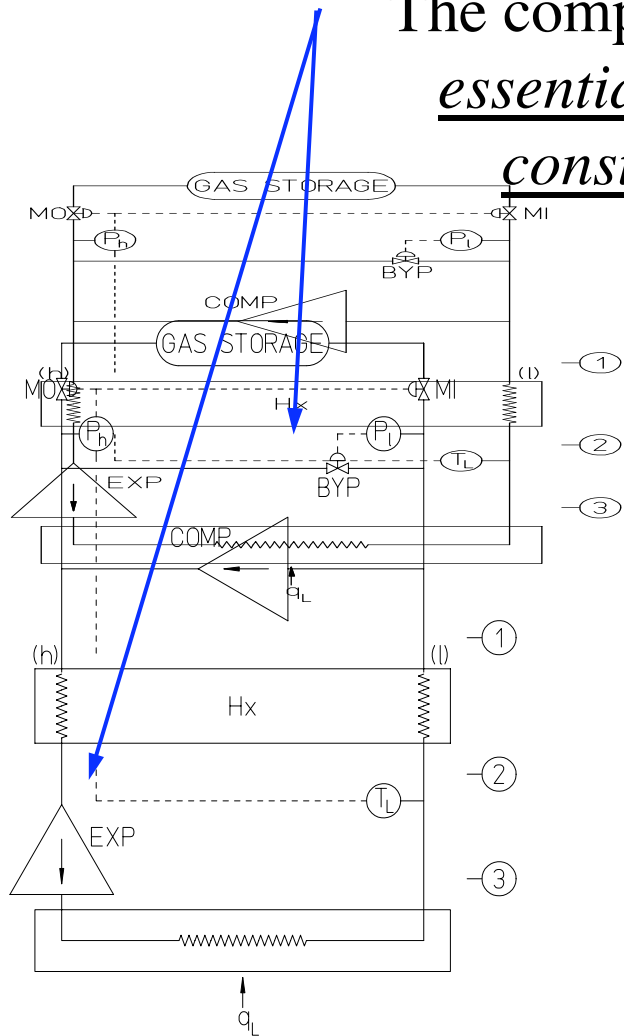
What do you think?

Floating Pressure Process - System Optimization (Cont.)

- Recall that the compressor provides the availability (i.e., high quality energy) to the cold box, i.e.,
$$\text{Availability to CBX} \sim (\text{mass flow}) \cdot \ln(\text{pressure ratio})$$
- Consider a system connected to a *non-isothermal load* that is composed of a single,
 - Heat exchanger (HX)
 - Expander
 - Compressor
- Both the expander and compressor are essentially *constant volume flow devices*, so for a given mass charge, the,
 - Expander establishes the discharge pressure and,
 - Compressor establishes the suction pressure
- With these, the *gas charge establishes the system mass flow rate*
- If left unconstrained, these two devices establish an *Essentially constant pressure ratio* and an, *Essentially constant Carnot efficiency*

Floating Pressure Process - System Optimization (Cont.)

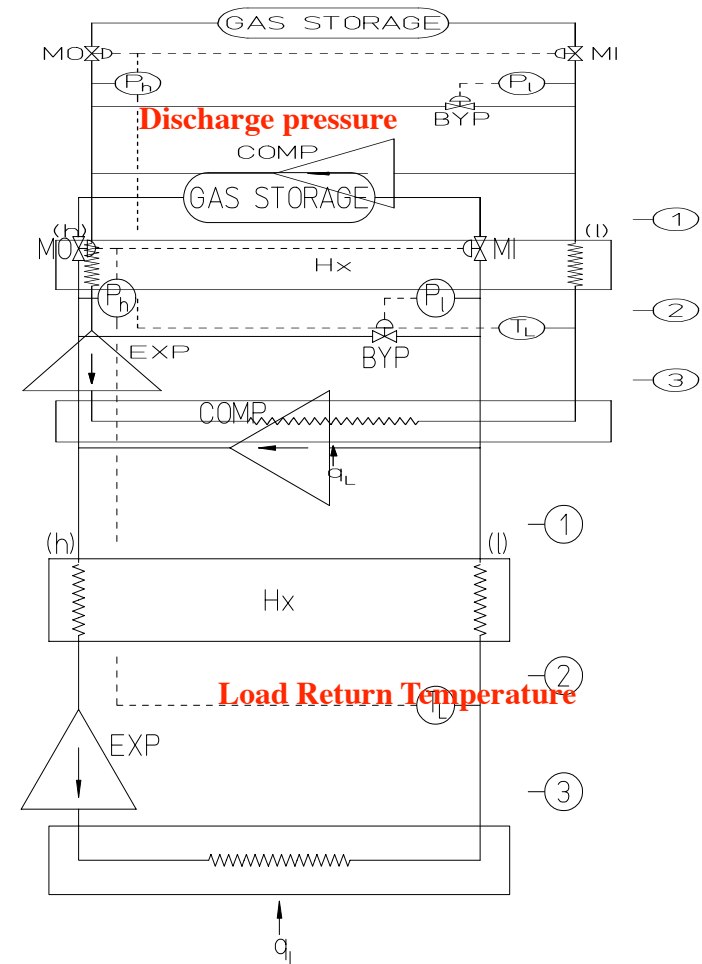
The compressor and expander establish an essentially constant pressure ratio and constant system Carnot efficiency



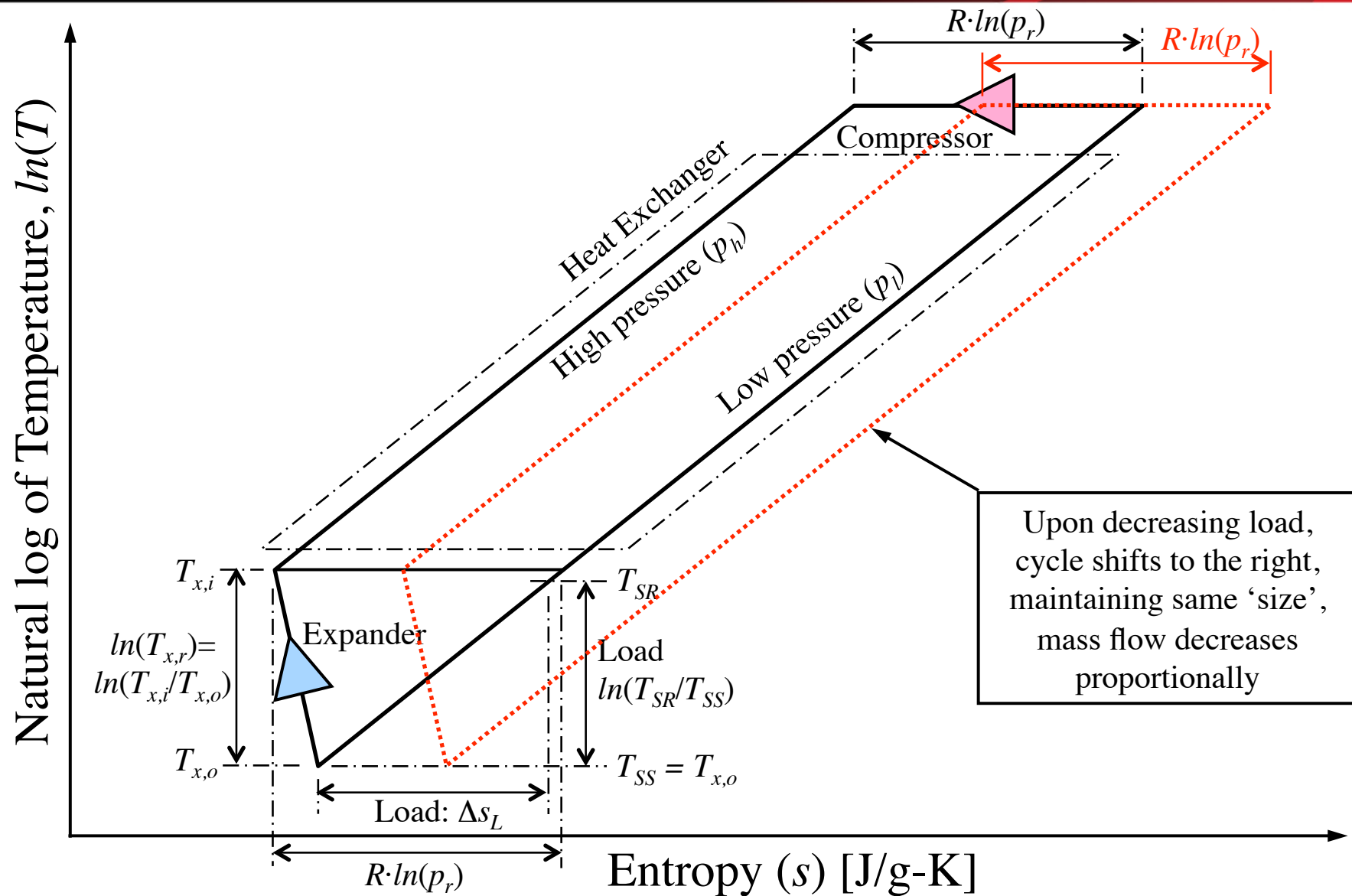
General Arrangement for Floating Pressure Process Cycle (*patent pending*)

Floating Pressure Process - System Optimization (Cont.)

- Gas management valves establish how to respond to a given load, i.e.,
 - **Compressor bypass (BYP)**
 - Does not open except to prevent compressor suction from going below some minimum (usually ~1 atm)
 - **Mass-Out (MO)**
 - Discharges mass from compressor discharge to gas storage, decreasing p_h
 - **Mass-In (MI)**
 - Brings mass from gas storage to compressor suction, increasing p_h
 - **Off-set between MO & MI (to prevent competition)**
 - **Discharge pressure (p_h) is linearly related to difference between actual (T_L) and desired load return temperature.**
 - i.e., if T_L increases, then p_h increases



Floating Pressure Process - System Optimization (Cont.)



System Optimization (Cont.)

As the “Claude Cycle” is essentially a constant pressure process

and, the “Sterling Cycle” is a constant volume process

the “Floating Pressure Cycle” is a constant pressure ratio process

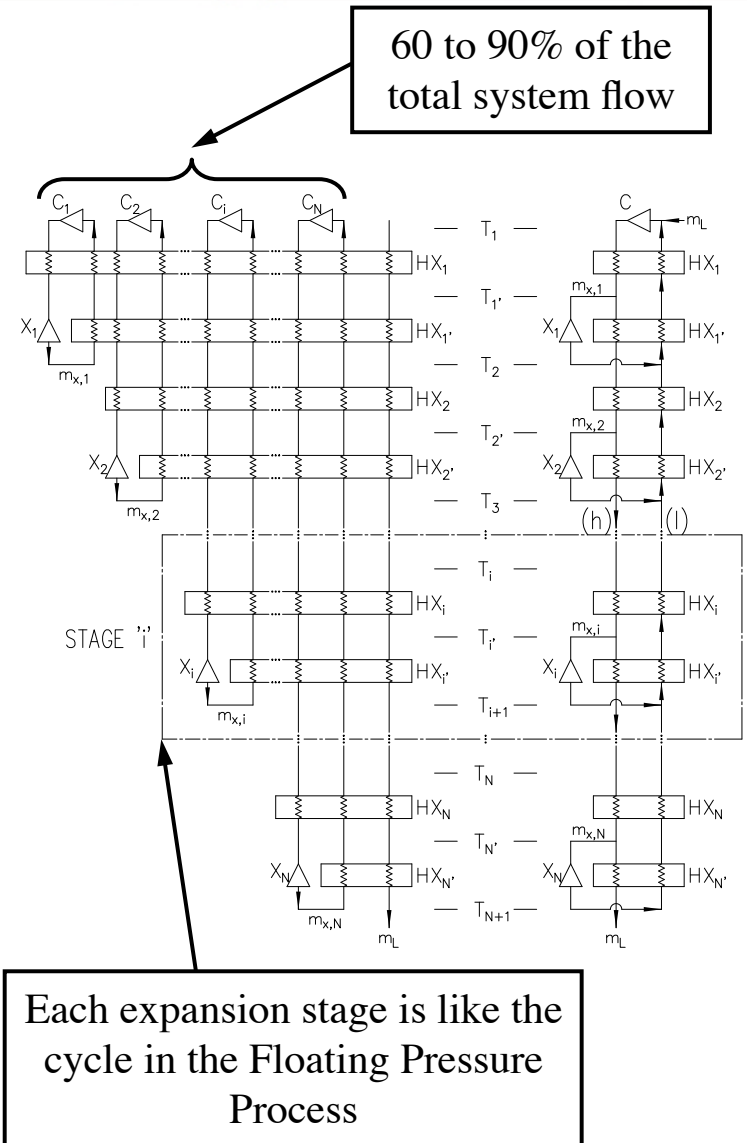
$$p_r \equiv \frac{p_{h,2}}{p_{l,1}} = \left(\frac{\eta_v \cdot Q_C}{\kappa_x} \right) \cdot \left(\frac{1}{\phi \cdot C_p} \right) \cdot \frac{\sqrt{T_{h,2}}}{T_{l,1}} \equiv \text{Constant}$$

$$\eta_{carnot} = \frac{E_L}{\dot{W}_C} = \frac{\Delta \varepsilon_L}{w_C} \equiv \text{Constant}$$

That maintains essentially constant Carnot efficiency
over a very wide operating range
(100% to ~35% of maximum capacity)

System Optimization (Cont.)

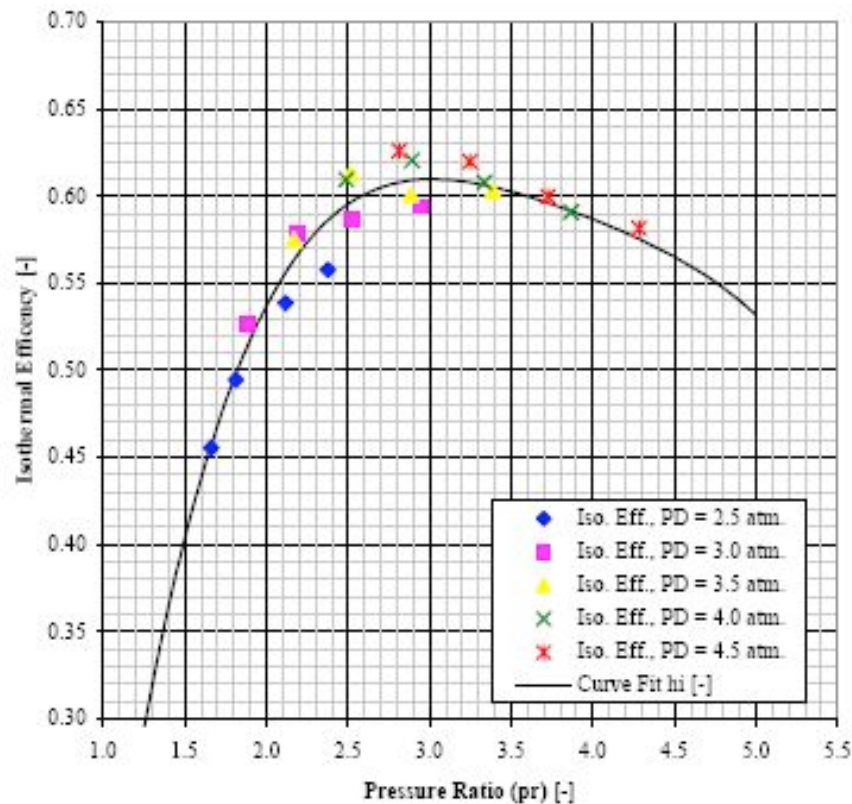
- So, how does this apply to helium liquefiers and refrigerators?
- Recall that **each expansion stage is basically the cycle described in the Floating Pressure Process**
- For liquefiers and mix-mode systems, 60 to 90% of the total system flow is through the turbines (providing the cooling)
- Also, recall that $\sim 2/3^{\text{rd}}$ of the total system losses are in the compressor system; so we must consider what it means to properly match the compressor and cold box system



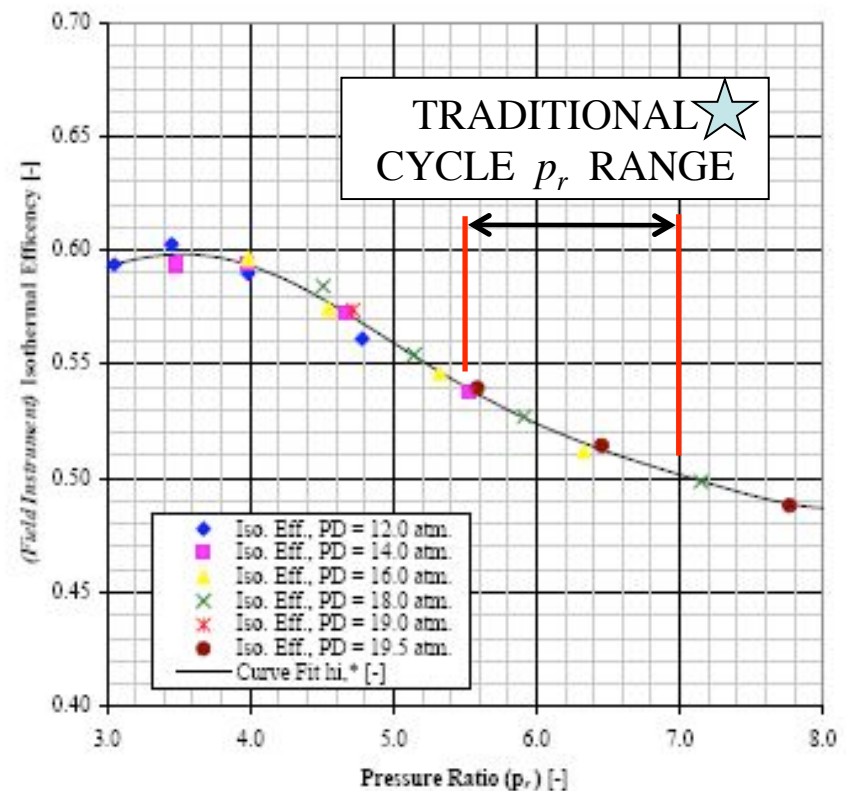
System Optimization (Cont.)

Typical 1st & 2nd stage RS compressor isothermal efficiencies

Optimum $p_r \approx 3$ to 4 ★

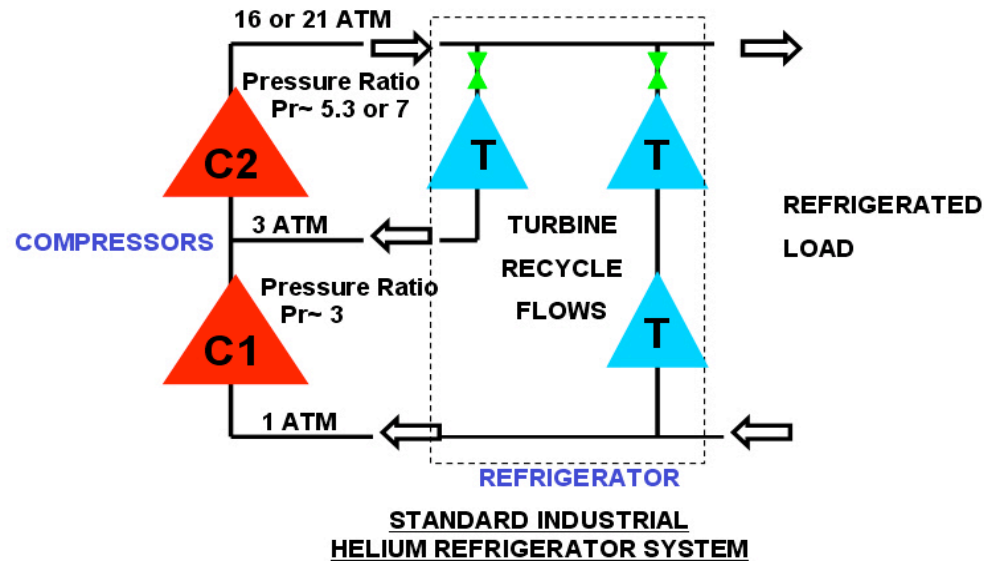


1st Stage Compressors



2nd Stage Compressors

Ganni Cycle - System Optimization (Cont.)

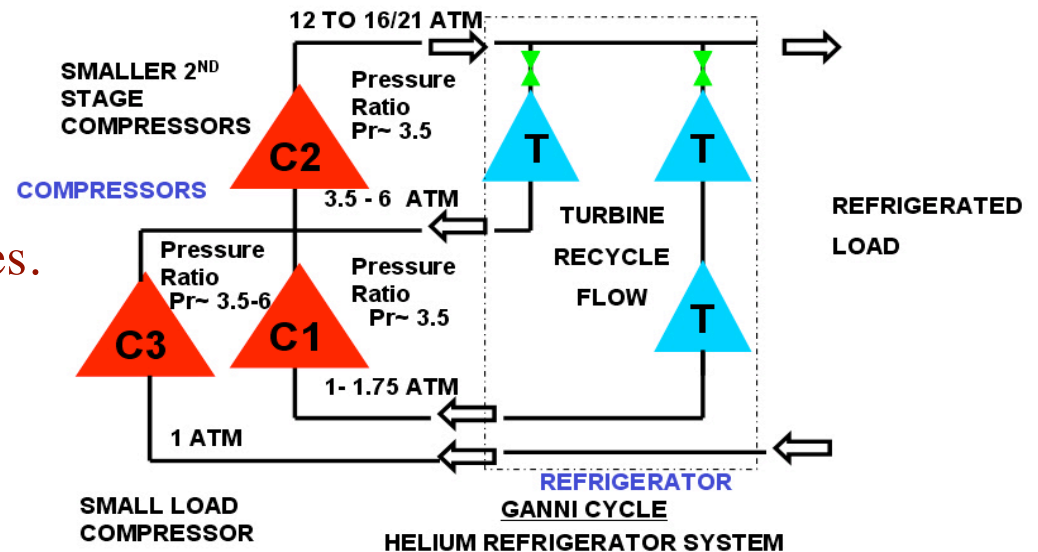


Traditional Helium Cycles

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

Ganni Cycle

Good (even optimum) pressure ratio matching.
Resulting in low losses for both stages.
Flow from load is separated from turbine flow (since it is a smaller fraction of the total flow).



History



Galileo discusses his discoveries with his colleagues

History (Cont.)

Some Historical Reasons given (for the last 18 years) to stay status quo:

➤ Industry,

An increase in system efficiency comes with,

- “Increase in capital cost”
- “Reduced availability”
- “High risk to the basic program”
- “We have done this before” (*but JLab has the patents!*)

➤ Users,

- “T-S design is the optimum, force the system close to it”
- “You should not change system operation from the basic design and/or the operation method”
- “Cryogenics is not the experiment”
- “The cryo system is running fine. Don’t change it”
- “Scale the new system from an existing one”
- “Requires re-training of the operators”

And many many more !!!

Licensing Agreement _

***JLab has commercially licensed the Ganni Cycle – Floating Pressure Technology
to “Cryogenic Plants and Services”
a Division of Linde BOC Process Plants, LLC***



Some Results So Far

NASA-JSC/JLab Collaboration

James Webb Telescope

Replaces Hubble
~1 million miles out



Telescope Mockup at the National Mall, D.C.

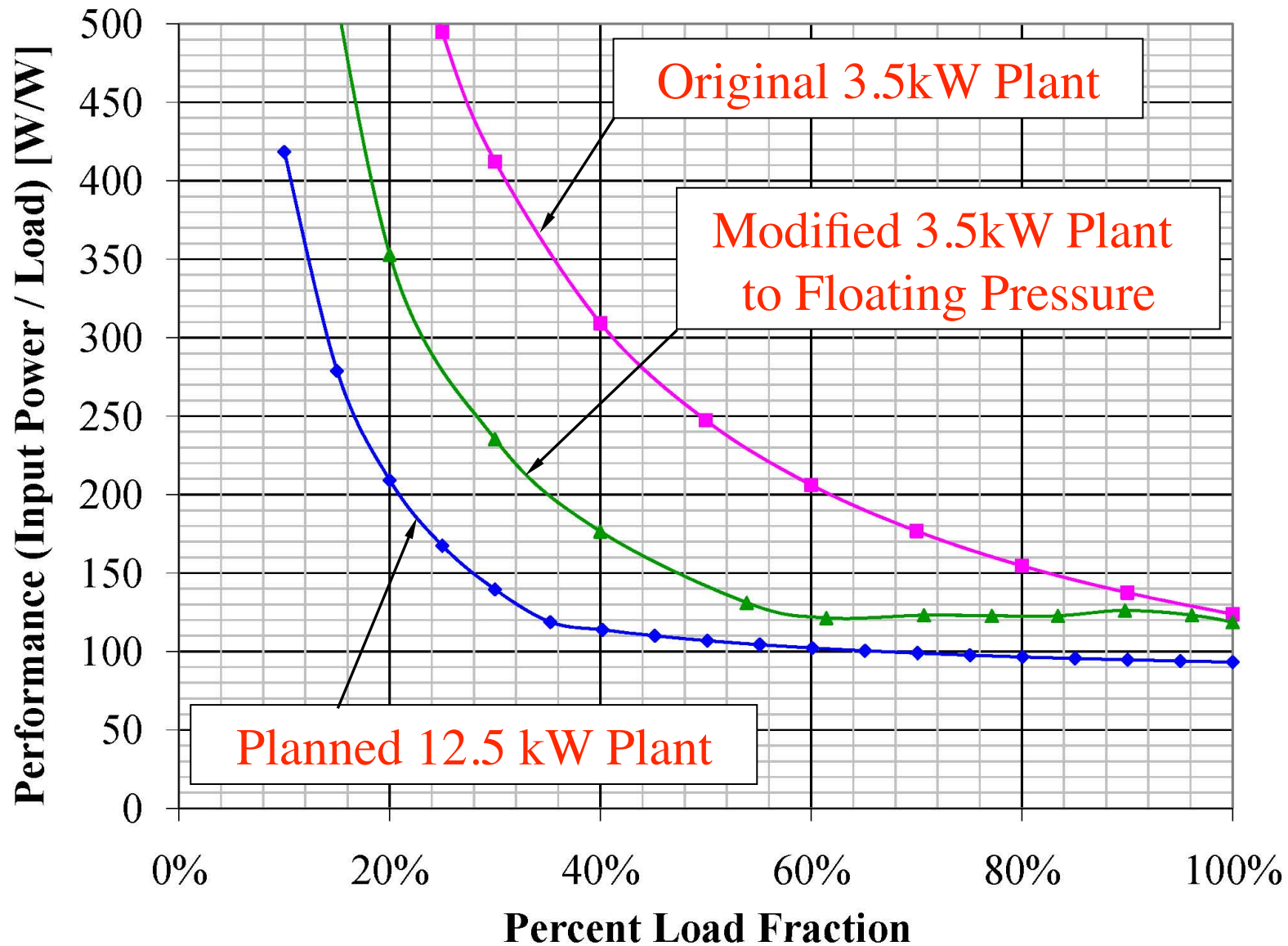
Floating Pressure Technology For Telescope Testing

- Environmental Space Simulation Chamber-A

The existing 3.5 kW 20K cryogenic system is converted to JLab's Floating Pressure Technology. *Improved temperature stability from 2.5K to 0.25K and efficiency (follows)*

- New 20K, 13kW refrigerator design is based on the Floating Pressure Cycle

NASA-JSC 2008 3.5kW Plant Test Results



Brookhaven Reports on Operational Results

Brookhaven Reports Its Program Results

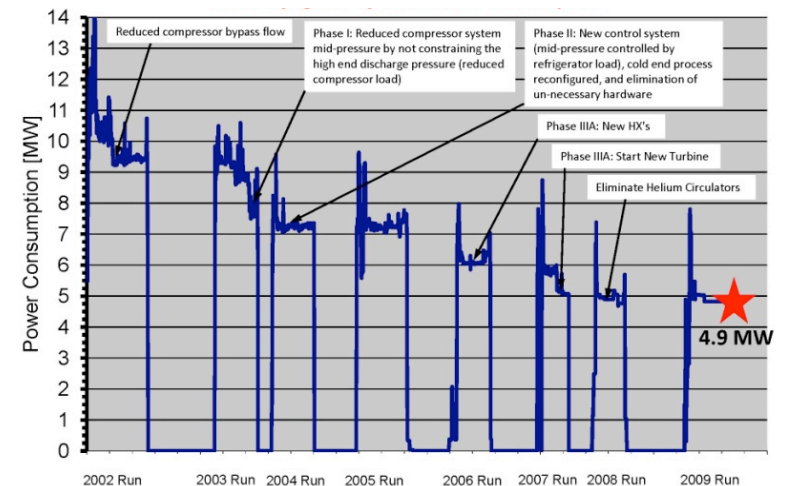
Brookhaven TODAY, Feb 11, 2008 http://www.bnl.gov/today/story.asp?ITEM_NO=544

**“Jefferson Lab technology saving BNL
\$1.5M in electricity alone for typical 30
week experiment”**

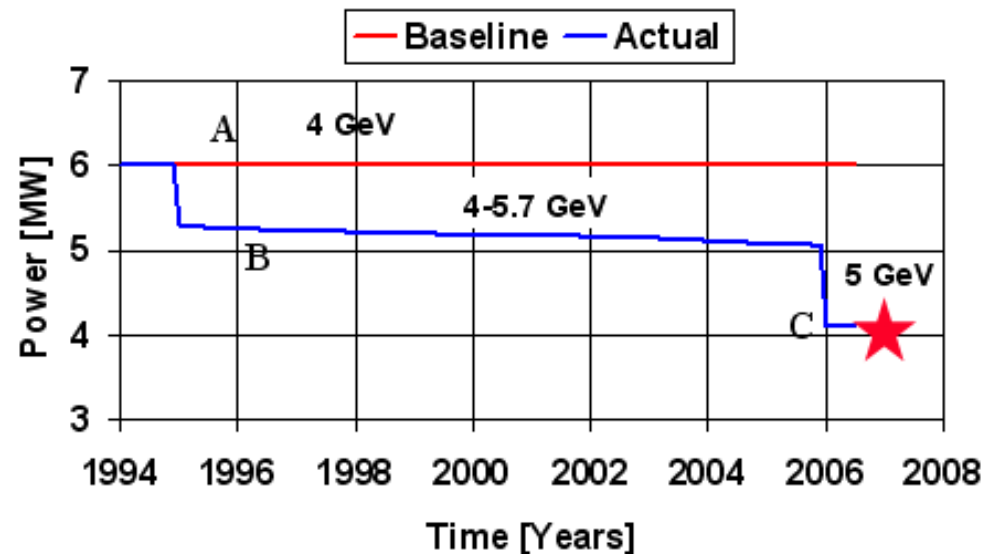
**“ Seen increased reliability, stability,
and efficiency”**



Brookhaven RHIC Cryogenic Staff



Optimal Operation of JLab-CHL Helium Refrigeration System



This cryogenic plant supports operation of the Continuous Electron Beam Accelerator Facility (CEBAF) cryomodules in the tunnel. The accelerator power is adjustable from 500MeV to 6GeV but the original cryogenic plant was designed to operate only at one design capacity consuming more than 6MW of electrical power. Through the years the Cryogenics Group has completed several phases of technological improvement and increased the plants operational envelope to allow its capacity to be varied to better match the cryogenic load. The operational envelope now allows the plants power consumption to be varied from 4.2MW up to 6MW in conjunction with the CEBAF accelerator requirements.

As Time Progresses

The Ganni Cycle- Floating Pressure Technology

Recognitions & Awards

Awards

2006 DOE Office of Science
Pollution Prevention and
Environmental Stewardship P2
“Best in Class Award”



2007 White House
Closing the Circle Award
Washington, DC



Conclusions

- In the past (not too long ago!), most of the time the cryogenic system was the 'long pole', with the experimenters waiting for it to be commissioned and then routinely waited for it to recover from trips during normal operations
- Many shunned away from the superconducting technologies due to the pains associated with the cryogenics systems
- Now the cryogenic system availability is >99% at JLab for the 2K system (CHL) and even higher for our 4.5K systems
- Warm helium compressor maintenance requirements at JLab have dropped from every 35,000 hours to 74,000 for the rebuilds after implementation of the Floating Pressure cycle.
- JLab continues to work on improving system efficiency and also to make the cryogenics as dependable as any other utility; despite that there is more than three orders of magnitude difference in the energy quality (>1000 W/W)

Conclusions

As Cryogenic engineers we would very much like to see at the user level:

- Recognition of the importance of this complex and expensive utility (similar to blood flow for super conducting technology machines)
- Support for fundamental development in contrast to believing it as a 'mature technology'
- Allocate experimental/development time and resources for the cryogenic system similar to the other systems

We like to see all users to take personal interest in how you use the precious commodity energy in accomplishing the end goal !!!

Thank you all for listening