Design of Helium Refrigeration and Liquefaction Systems

Simplified Concepts & Practical View Points

By

VenkataRao Ganni, Ph. D.

March, 2004

Preface

Dedicated to my guru Raymond Moore Jr. for promoting inquisitive minds to think about

'What is an optimum system and how can we provide it?'

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

- **Minimum operating cost**
- **Minimum capital cost**
- **Minimum maintenance cost**
- **Maximum system capacity**
- **Maximum availability of the system**
- **Before we can make an attempt to answer these, we**

"Need to understand the fundamentals"

Some of these are new concepts have never been formally published, although I shared with many of my colleagues over the years.

Table of Contents

1. Introduction

The helium refrigeration and liquefaction systems are an extension of the traditional household refrigeration systems.

Let us start with the question,

what is a refrigeration system?

The refrigeration system is one that transfers heat energy from low temperature to high temperature.

Normally, the term refrigeration is used for absorbing heat energy at a constant temperature.

Introduction (cont.)

The input power required for these systems mainly depends upon:

- **The temperature from heat energy extracted (load temperature)**

- **The temperature to heat energy is rejected (ambient temperature)**

- **The process used (e.g.)**
  - **Vapor compression process**
  - **Hampson process**
  - **Claude process**

- **The efficiency and the effectiveness of the components used (e.g.)**
  - **Compressor**
  - **Expander**
  - **Heat exchanger**

- **How well the real components match the process**

- **How the system is controlled**

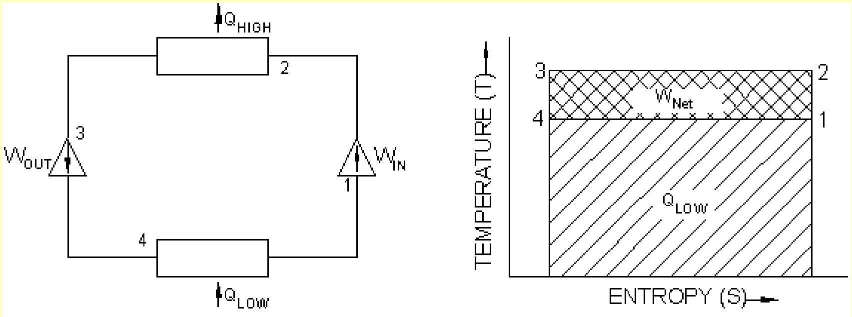
System Performance & Efficiency

- **For typical industrial processes approximately 1kW of electrical energy is required to produce 3 kW of cooling.**
- **Why is *any* input energy required to *transfer* heat energy from a cold to a hot temperature reservoir?**
- **Using an electrical analogy, a thermal transformer that permits the heat energy transfer from cold temperature to hot temperature, with no input work *does not exit*.**
- **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' of heat energy.**

Introduction (cont.)

- **The source and sink temperatures sets this limit on the conversion of thermal to mechanical energy.**
- **It is around 40 % for typical industrial processes and approximately 3kW of thermal energy is required to produce 1kW of electrical energy.**
- **In contrast, for <u>ideal systems</u> the conversion from mechanical to electrical energy (or visa-versa) can be 100%.**
- **This thermodynamic limitation is expressed by the 2nd Law of Thermodynamics and embodies the concept that the thermal energy has a ‘quality’ (or ‘availability’) that varies with the temperature from which it is being supplied and received.**
- **For our topic of refrigeration, the input energy required is due to the loss in ‘availability’ (or decrease in ‘quality’) of the thermal energy as it is transferred from a low temperature (load) to a high temperature (environment).**

Introduction (cont.)



- **For refrigeration systems the coefficient of performance (COP), which is the amount of cooling obtained per unit of input work, is used as a measure of performance.**
- **A more useful term is the inverse of the COP or COP_{INV}. This tells us how many watts of input power (i.e., the additional compressor input power with the expander output power utilized) are required to produce one watt of cooling power.**

Introduction (cont.)

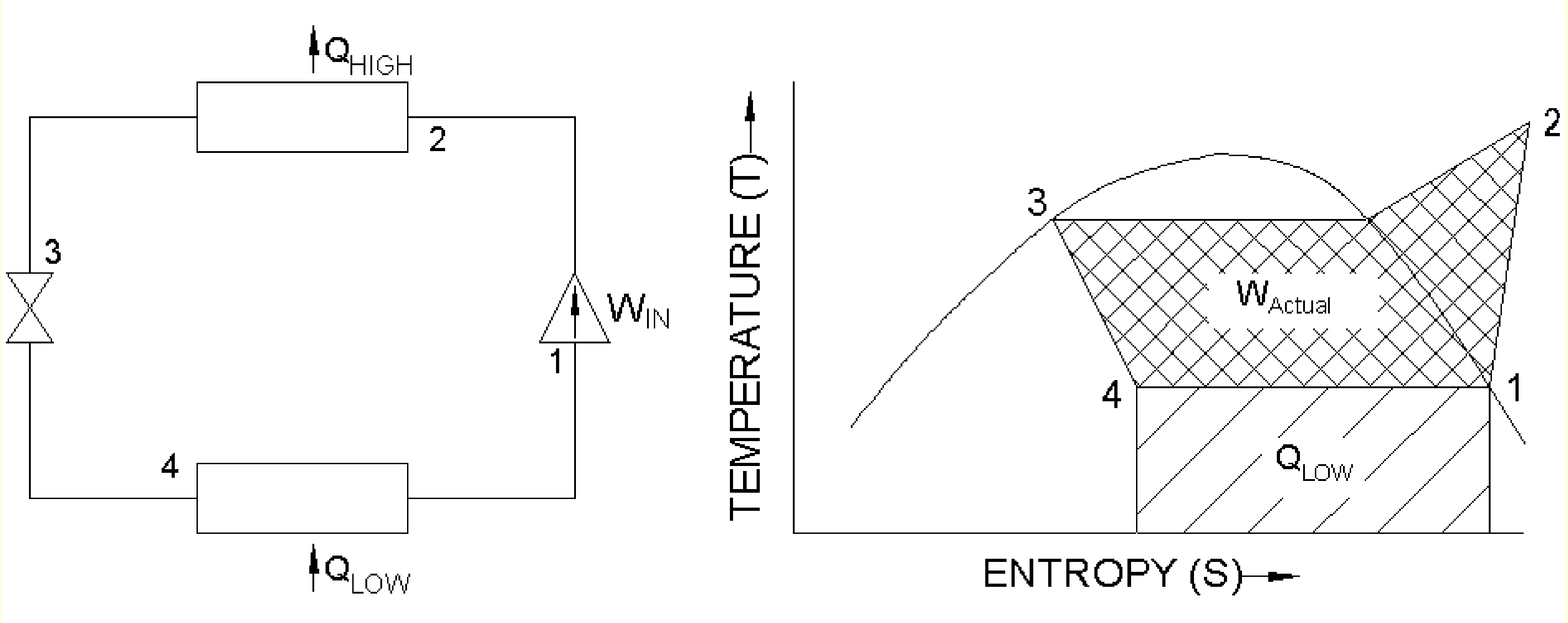
- **So, the Carnot work (WCARNOT) required for 4.4 kW of cooling is 1 kW.**

- **<u>Note</u>: This is not a violation of the first law of thermodynamics since a refrigerator is transferring energy from one temperature to another and not converting it. The input work is the energy equal to the difference in the 'quality' ('availability' or 'exergy') of the thermal energy between T1 and T2.**

Introduction (cont.)

- **The Carnot cycle is an 'ideal' cycle in the sense that it does not have any 'irreversibilities' (i.e., 'lost work').**
- ***However, the term '<u>idealized cycle</u>' will be relegated to a practical system that one can visualize using ideal components*.**
- **What differentiates the Carnot cycle is that it has the minimum COPINV (or the maximum COP) for the process of transferring heat energy between two thermal reservoirs.**
- **It is this distinction that gives the *Carnot cycle the recognized qualification* for 'efficency' comparisons (e.g., termed 'Carnot efficiency' or 'efficiency to Carnot') of other cycles performing the same function.**

Introduction (cont.)



Introduction (cont.)

For thermal systems, we use the Carnot cycle (i.e., a cycle that has the minimum COP_{INV} with no irreversibilities) as a reference to compare to all other cycles.

The Carnot cycle is a reversible cycle and has the maximum efficiency thermally and from a fundamental process viewpoint.

To be clear, so when liquefiers are discussed, the term 'Carnot cycle' (as well as 'Carnot work' and 'Carnot efficiency') are not confined only to the diagram shown in Figure.

They are applicable to an *ideal, reversible* process that performs the specified process function.

2. Carnot Helium Refrigeration and Liquefaction Systems

Clausius (In)equality

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

Carnot Refrigeration System: Minimum required input work for a given rate of *thermal energy transfer between two thermal reservoirs.*

The work input for the Carnot system expressed as:

$$W_{carnot} = T_0 \cdot \Delta S - \Delta H$$

- ***This is a very powerful equation*.**
- **The terms are as follows:**
- $T_0 \cdot \Delta S$ **is the heat rejected to the environment**
  or, the input power to an isothermal compressor
- ΔH **is the heat absorbed or the ideal refrigeration**
  or, the ideal work output from an ideal expander
- W_{carnot} **is the ideal net input work required**
  which is the difference between (a) and (b) above

Carnot Helium Refrigeration and Liquefaction Systems (Cont.)

- **A refrigerator *transfers* heat energy from a low temperature reservoir to a higher temperature reservoir. Most helium refrigerators transfer heat energy from approximately 4.22K (or in some cases at sub-atmospheric pressures).**

- **A liquefier is different from a refrigerator since the objective is to cool a quantity (flow rate) of high (or ambient) temperature fluid to a specified low (or load) temperature, which then leaves the cycle (at a low temperature). What leaves the cycle is the liquefaction flow, and may be returned at a higher or ambient temperature.**

  In comparison to the refrigerator, in a liquefier the temperature at which the heat energy is being *transferred* (removed) is constantly varying (decreasing as it is being cooled), although it is rejected at the same (high or ambient) temperature reservoir.

Carnot Helium Refrigeration and Liquefaction Systems (Cont.)

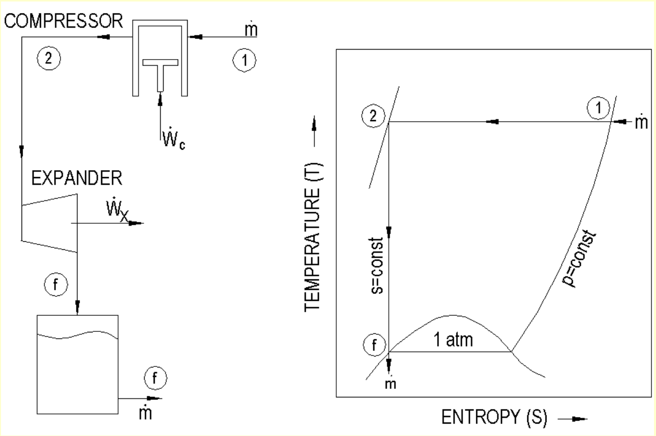
Carnot Helium Refrigerator

$$w_{carnot} = T_0 \cdot \Delta s - \Delta h$$

$$COP_{INV} = \frac{W_{carnot}}{Q_L} = \frac{T_0 \cdot \Delta s - \Delta h}{\Delta h} = \frac{(300)\cdot(4.833) - 20.42}{20.42} \simeq 70\left[\frac{W}{W}\right]$$

$$COP_{INV} = \left(\frac{T_2}{T_1} - 1\right) = \frac{300}{4.224} - 1 = 70\left[\frac{W}{W}\right]$$

Carnot Helium Liquefier



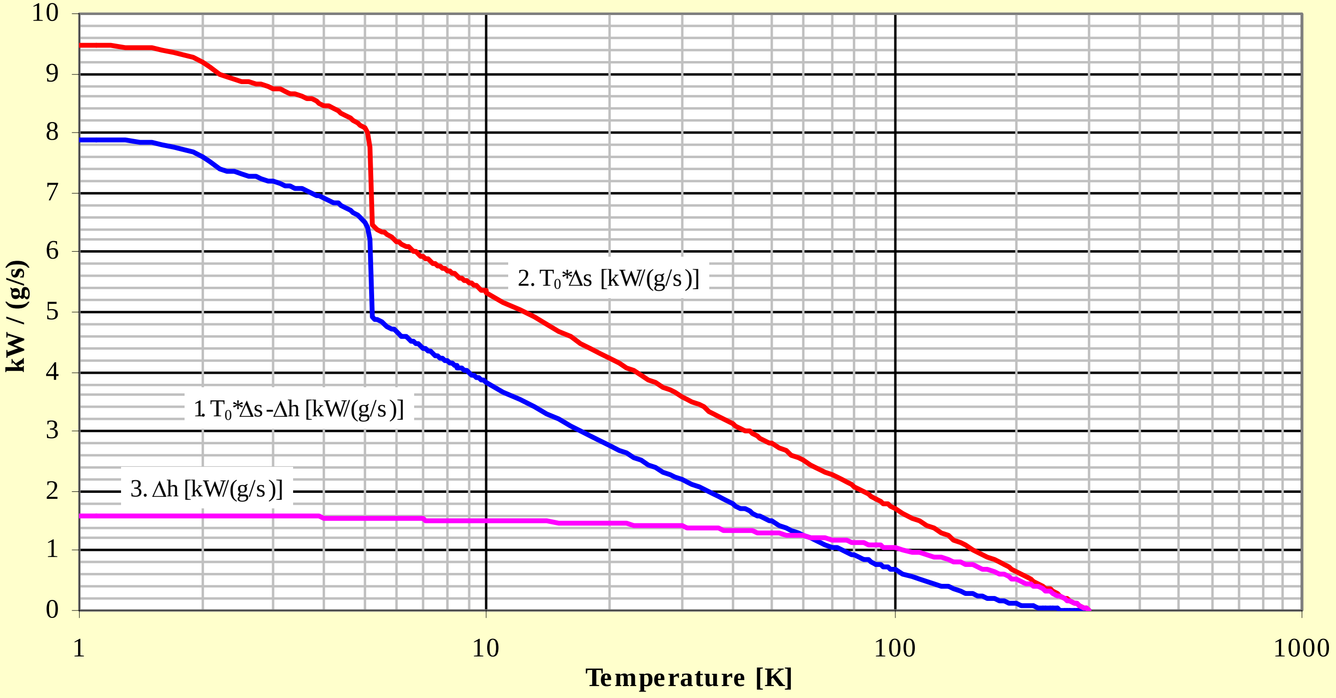
$$w_C = T_0 \cdot \Delta s = (300)\cdot(27.96) = 8387 \text{ [W/(g/s)]}$$

$$w_X = \Delta h = 1564 \text{ [W/(g/s)] (or 18.6\% of } w_C)$$

$$w_{Carnot} = w_C - w_X = 6823 \text{ [W/(g/s)] (or 81.4\% of } w_C)$$

Carnot Helium Refrigeration and Liquefaction Systems (Cont.)

- **Carnot work required for a given liquefaction load**



Carnot Helium Refrigeration and Liquefaction Systems (Cont.)

Carnot work required for liquefaction load for a given temperature range

Temperature Range (K)		$T_0 * \Delta s$ [W/ (g/s)]	%		Δh [W/ (g/s)]	%
300 - 80		2058	**24.5%**		1143	**73.0%**
80 - 4.22		6329	**75.5%**		421	**27.0%**
300 - 4.22		8387	**100.0%**		1564	**100.0%**

Carnot work for different fluids

Fluid	Tsat,0 [K]	Liquefaction (W/(g/s))	Refrigeration (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

3. Idealized Helium Systems and Carnot Step

Carnot Step

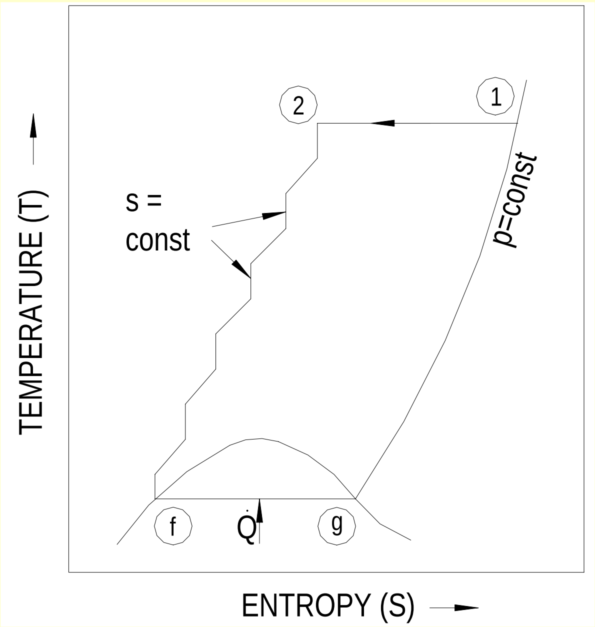
The *Carnot step* is defined *(by the author)* as the process step required for accomplishing a given *task with minimal energy expenditure*. Or, in other words, accomplishing the given task with minimal exergy usage.

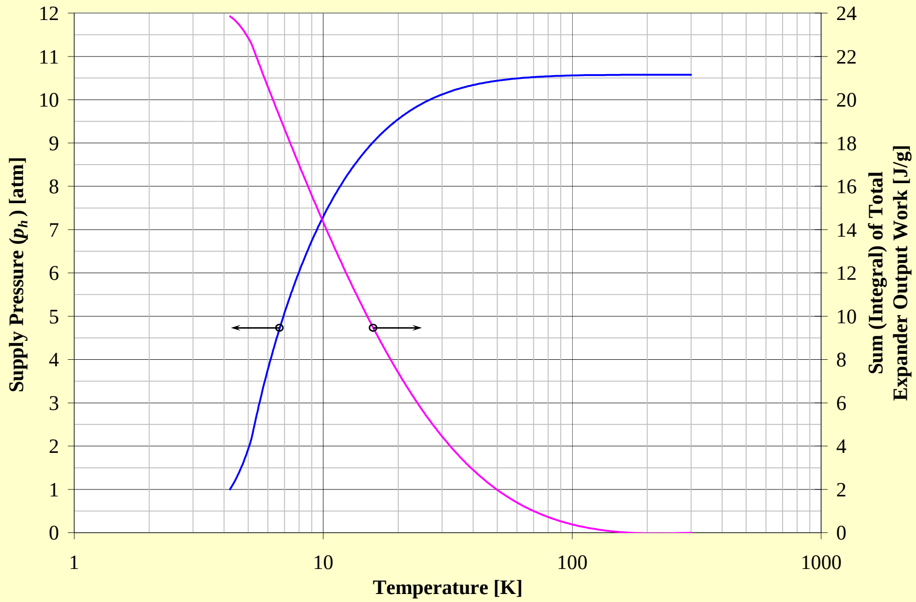
The three main parts to a helium system.

Idealized Helium Systems and Carnot Step (Cont.)

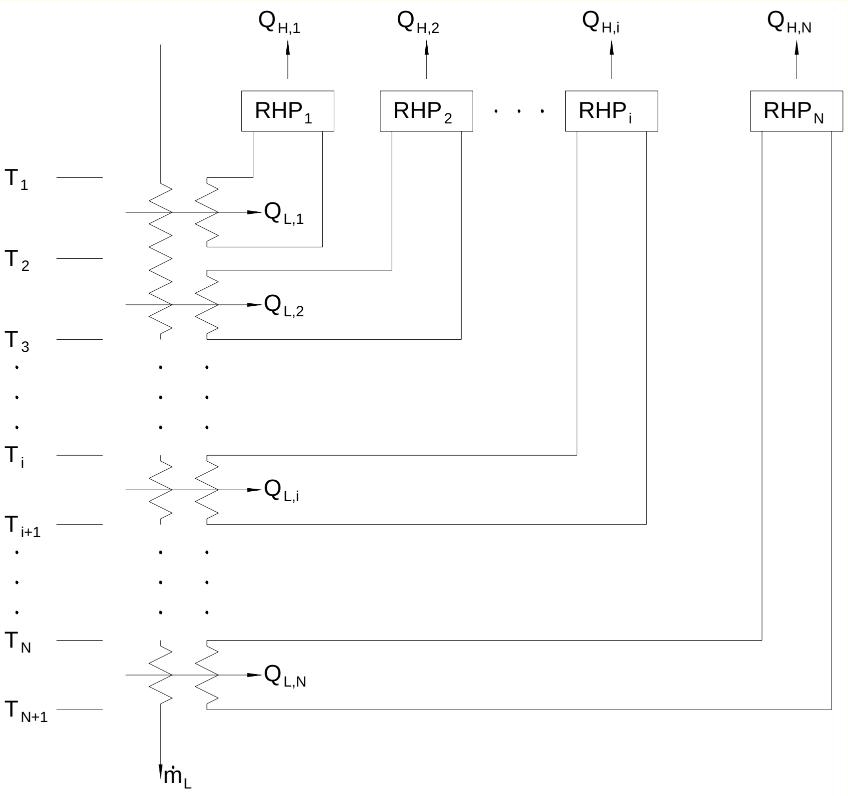
- The <u>load and distribution system *Carnot Step*</u>*:*
  - ➢ The process for load interface that has the least entropy increase (or exergy usage) is the '<u>*load Carnot step'*</u>
- The <u>cold box *Carnot Step*</u>*:*
  - ➢ The cold box provides a process path analogous to walking up the stairs from a deep basement floor (4.2K) to the ground floor (300K).
  - ➢ The size and arrangement of steps that requires a minimum expenditure of energy are the '<u>*Cold Box Carnot steps'*</u>
- The <u>compressor system *Carnot Step*</u>*:*
  - ➢ Isothermal compression requires the minimum work and this is the '<u>*Compressor Carnot Step'*</u>

Idealized Helium Refrigeration Systems:

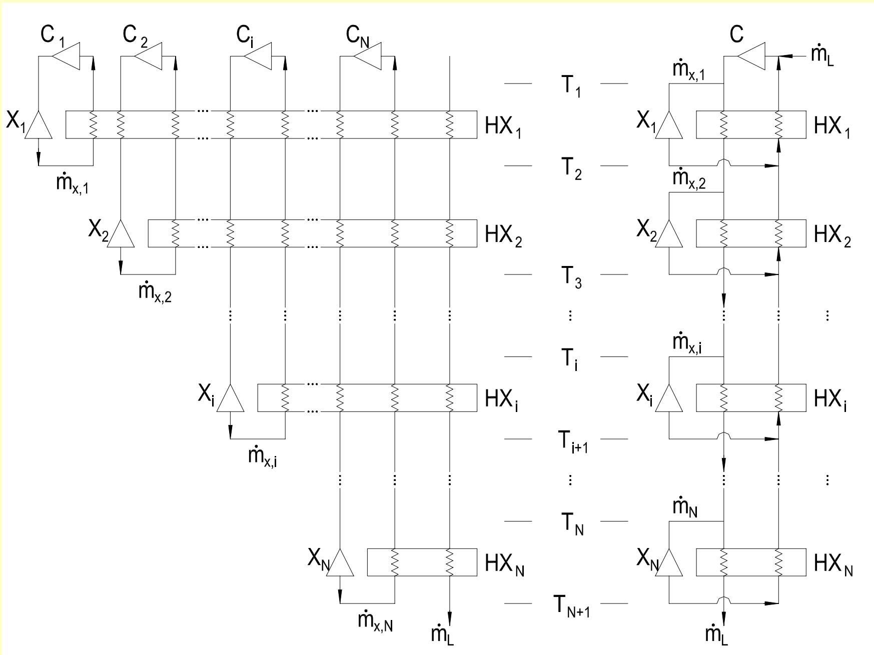


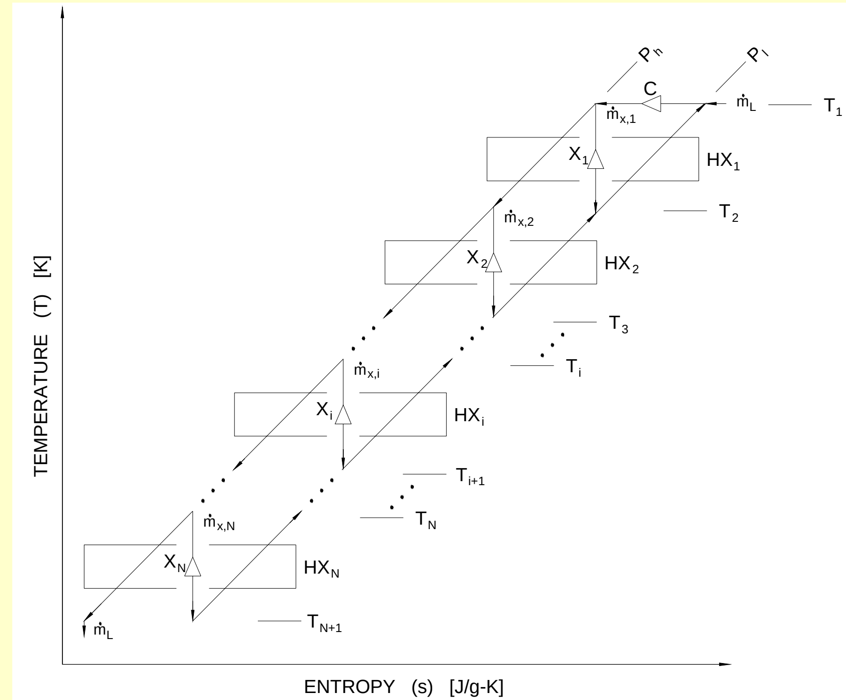


Idealized Helium Systems and Carnot Step (Cont.)



Idealized Helium Systems and Carnot Step (Cont.)





$$T_r = P_r^{\phi} = const.$$

$$T_{r,T} = \left(\frac{T_1}{T_{N+1}}\right) = (T_r)^N$$

$$N = \frac{\ell n(T_{r,T})}{\phi \cdot \ell n(P_r)} = \frac{\ell n(T_{r,T})}{\ell n(T_r)}$$

Idealized Helium Systems and Carnot Step (Cont.)

- **So, *__the Carnot step is the same for each expander stage__* (i.e., *Tr* is the same for each stage).**

- **As an example, for a 300K to 4.2K liquefier (e.g., T_1 = 300K, T_{N+1} = 4.2K), with an expander pressure ratio of 16 (e.g., *Pr* = 16), the total temperature ratio is, $T_{r,T}$ = 300 / 4.2 = 71 and the temperature ratio for each expander stage is, *Tr* = (16)0.4 = 3.03.**

- **So, the ideal number of expander stages is, *N* = *ln*(71) / *ln*(3.03) = 3.85 $\approx$ 4. As we will see later, more stages are actually required to compensate for component losses as well as process and fluid non-idealities.**

Idealized Helium Systems and Carnot Step (Cont.)

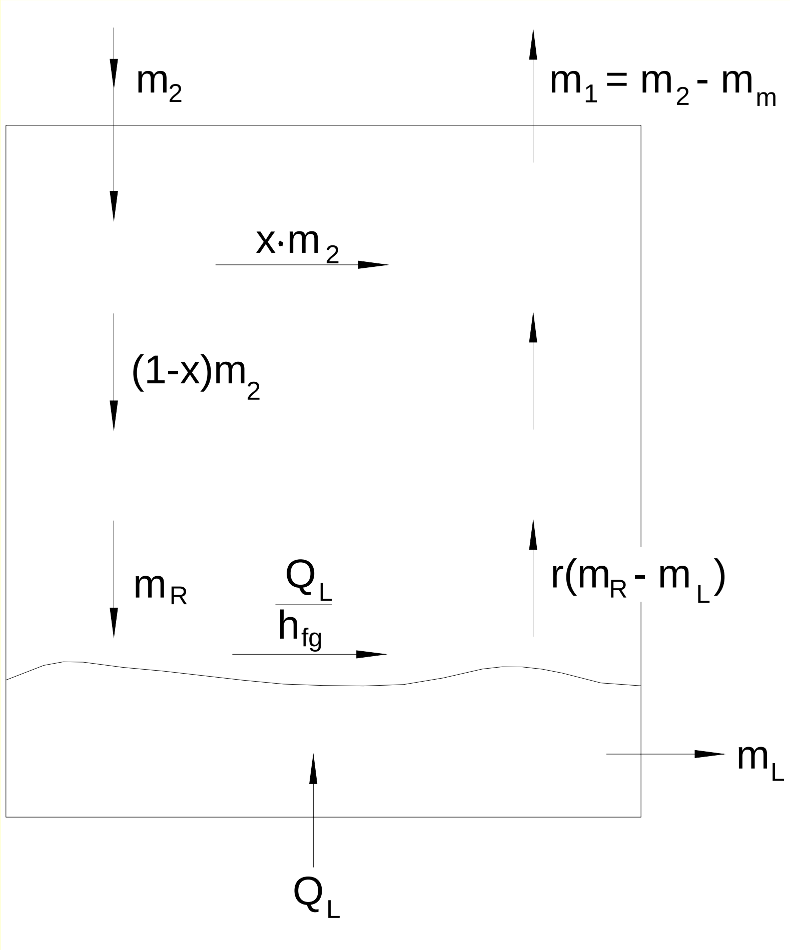
- **Referring to Figure, for an idealized gas liquefier, each expander flow is the same and equal to the liquefaction flow, e.g.,**

- **With the expander flow the same for each Carnot step (or stage), the (ideal or isothermal) *compressor work for each stage is also equal* .**

- **However, the Carnot work for each stage is *not* the same. This is the case since the expander output work, which is recovered by the Carnot liquefier and used to reduce the compressor input power, is not the same for each Carnot step.**

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Dewar Process



Dewar Process

X = Quality of m_2 $\qquad$ $r = \dfrac{\rho_g}{\rho_f}$

$m_R = (1-X)\, m_2 - \dfrac{Q_L}{h_{fg}}$ ......(1) $\qquad$ $m_m = (1-r)\, m_R + r\, m_L$ ......(2)

Case 1: $\quad m_L = 0 \quad m_R = \dfrac{m_m}{(1-r)} \quad \rightarrow \quad m_m = (1-r)\left[(1-x)m_2 - \dfrac{Q_L}{h_{fg}}\right]$

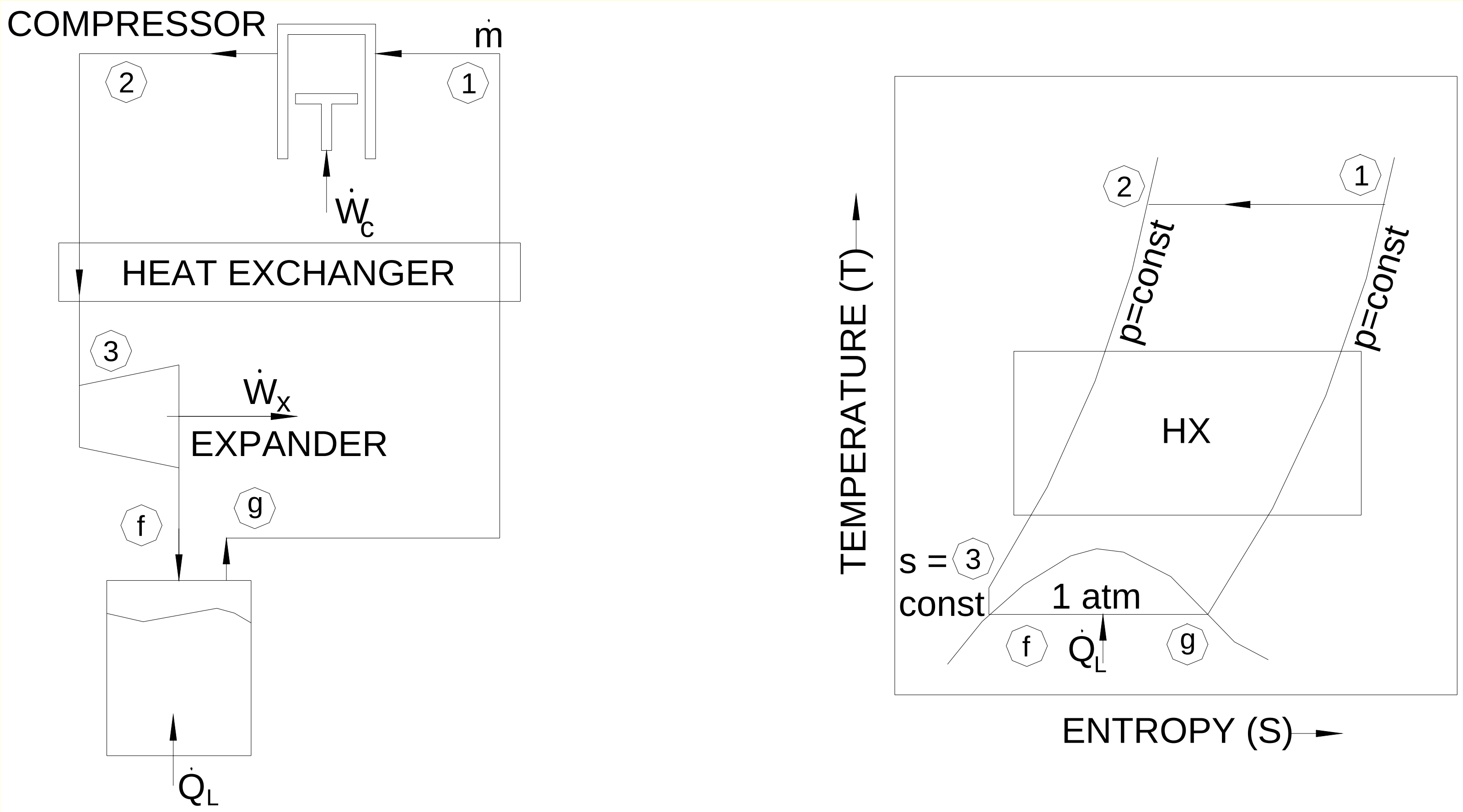
Case 2: $\quad m_R = m_L \quad \rightarrow \quad m_R = m_m \quad \rightarrow \quad m_m = m_R = m_L = \left[(1-x)m_2 - \dfrac{Q_L}{h_{fg}}\right]$

For Dewar Boil off (heat leak into Dewar) test: $m_2 = m_L = 0$

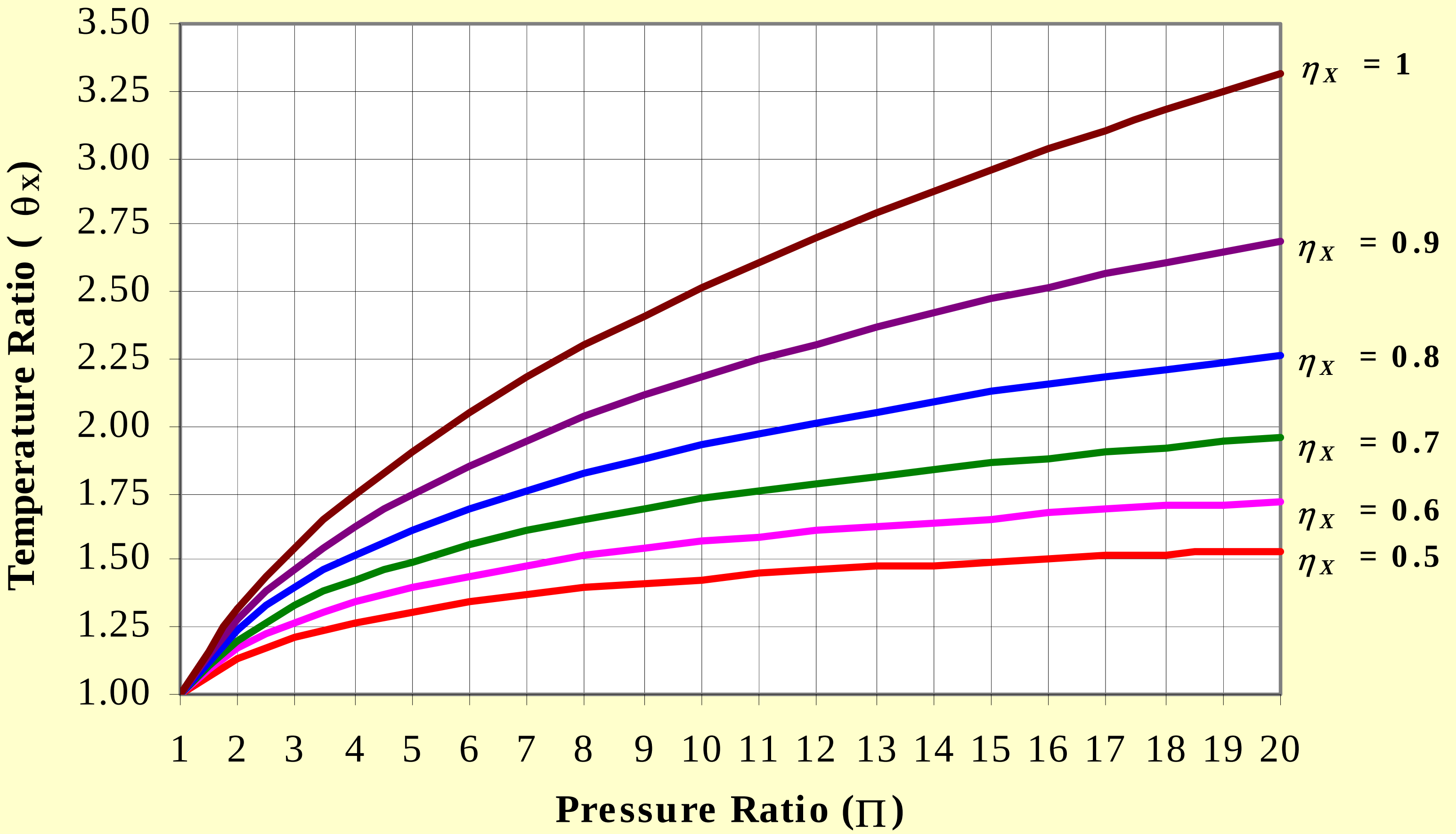
Flow leaving the Dewar $\quad = -m_m = \left[(1-r)\dfrac{Q_L}{h_{fg}}\right]$

Or Dewar Heat leak $\quad Q_L = \left[\dfrac{-m_m}{(1-r)} h_{fg}\right]$

The Theory Behind Cycle Design (Cont.)

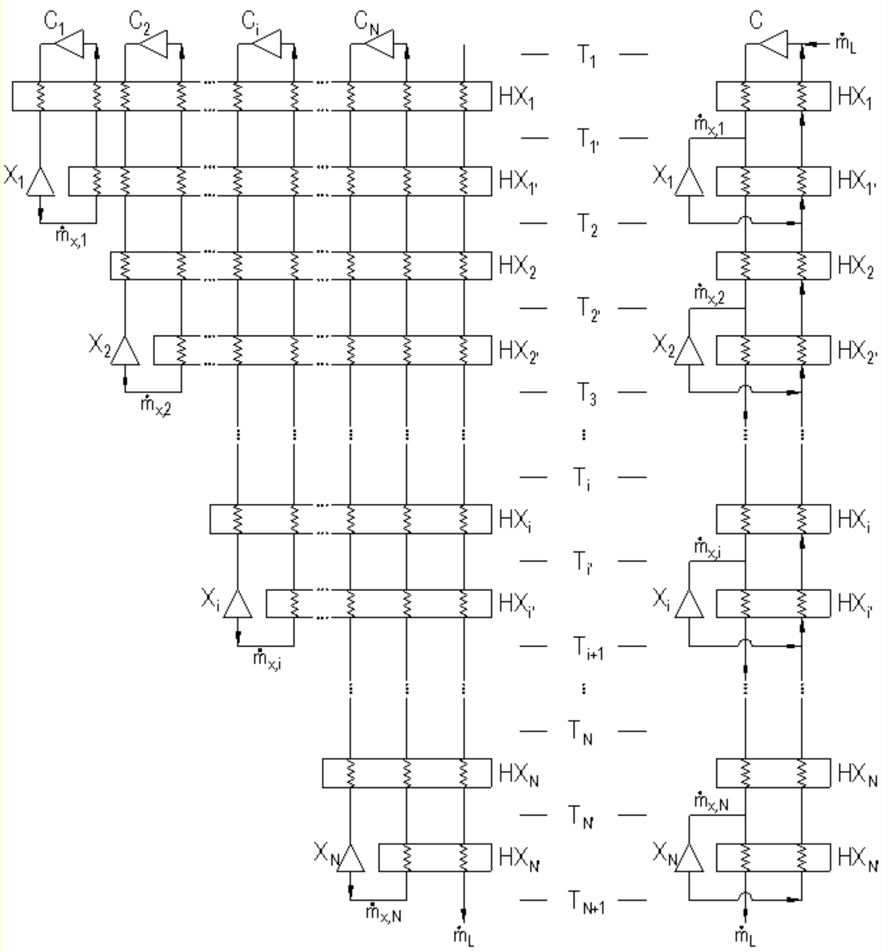


Possible High Efficiency Helium Liquefaction System



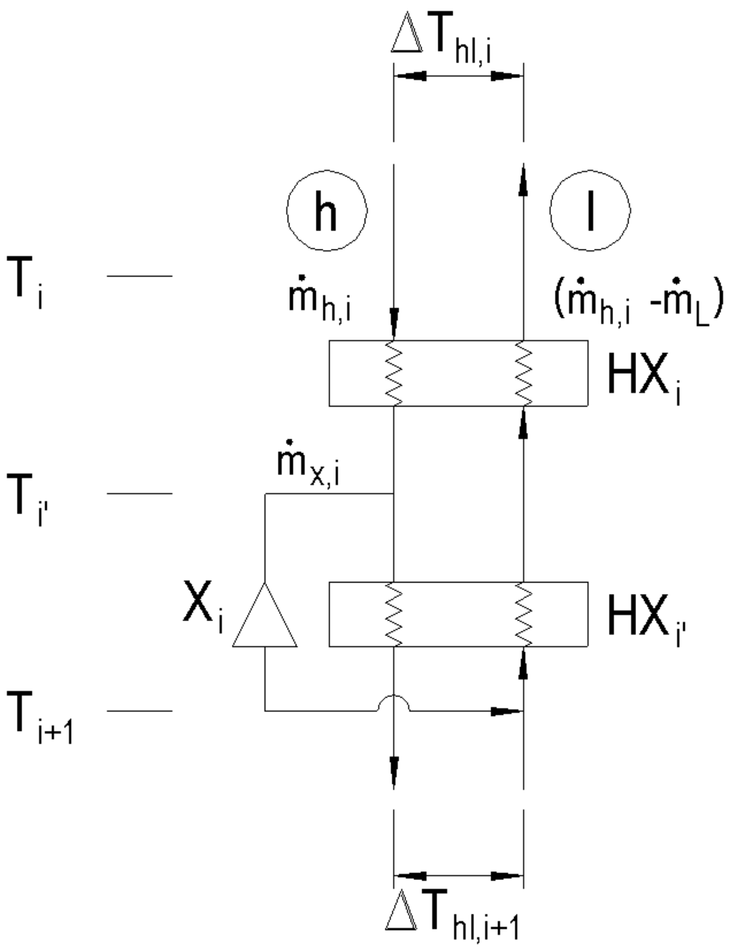
Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

The Theory Behind Cycle Design (Cont.)



Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

The Theory Behind Cycle Design (Cont.)

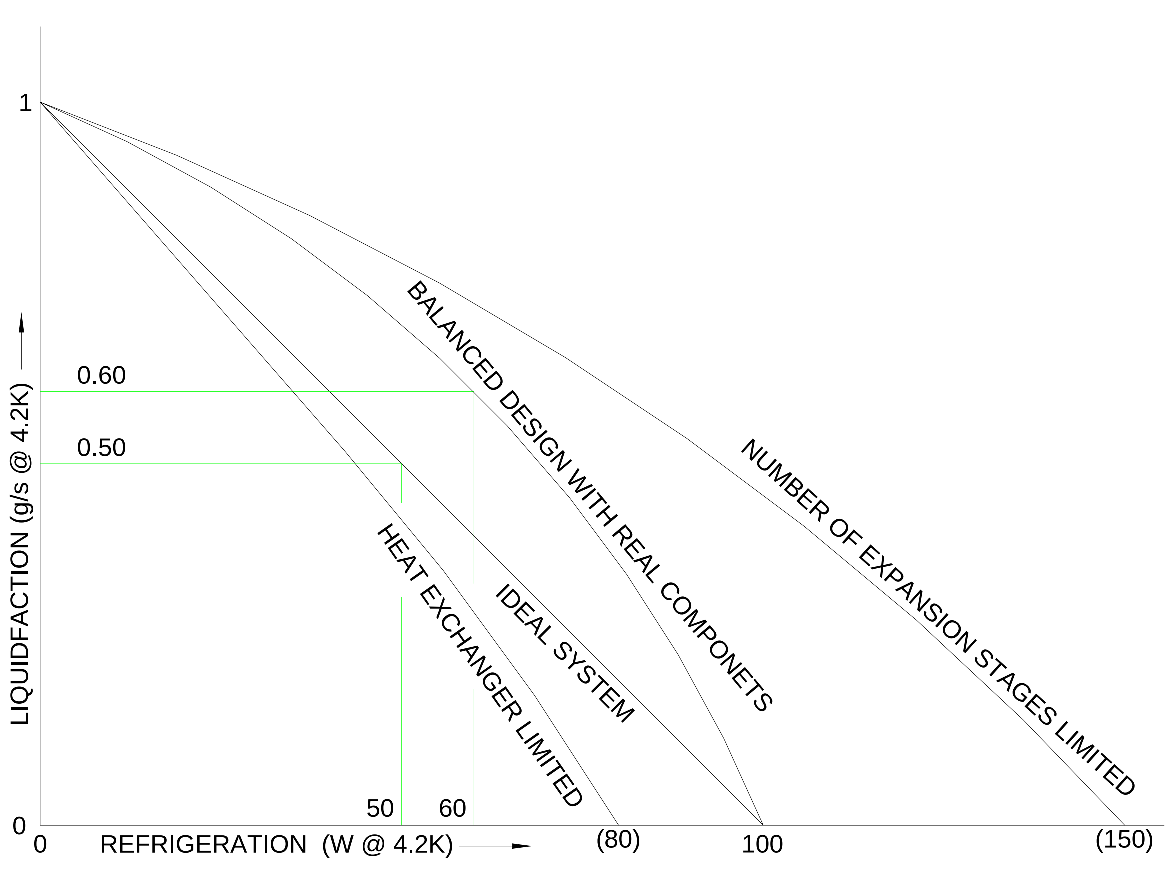


The Theory Behind Cycle Design (Cont.)

In summary, the ***Carnot step*** was explained. For a given number of expansion stages, these Carnot steps (i.e., the temperature ratio) are the same for both refrigerator and liquefier, and result in the minimum compressor flow (and therefore the minimum input power). This is indirectly saying that the ideal placement of the expanders with respect to temperature for both refrigerator and liquefier are the same. Due to practical limitations, the system will likely operate at slightly different temperatures between the two modes, and also slightly away from the Carnot step.

These limitations can be the fixed flow coefficients and efficiencies of the expanders and compressors, insufficient heat exchanger area or operating for a different optimal condition (e.g., at maximum system capacity rather than the minimum input power condition). The main difference between operating as a refrigerator vs. a liquefier in the configuration shown in Figure 4.3.2, is that the mass flow through each expander is approximately the same for a liquefier but not for the a refrigerator operating at the optimal minimum input power condition. In a refrigerator each Carnot step above the final cold expanders (i.e., above ~20K) is only required to handle the heat exchanger losses and heat leak. In contrast, in a liquefier all the expanders handle an approximately equal amount of compressor flow, and therefore an (approximately) equal amount of compressor isothermal compressor input power.

The Theory Behind Cycle Design (Cont.)



5. System Optimization

What is an optimum system?

Does it result in the:

- **Minimum operating cost**
- **Minimum capital cost**
- **Minimum maintenance cost**
- **Maximum system capacity**
- **Maximum availability of the system**

Traditionally a design for maximum efficiency is referred as the optimum system design.

System Optimization (Cont.)

- **The above five factors (or perhaps more) are rarely looked at as the optimization goals. As explained earlier, the demand on equipment varies substantially between operating as a refrigerator (i.e., heat exchanger dominance) and liquefier (i.e., expander dominance).**

- ***The challenge is to envision a cycle with these optimization goals, using <u>real components,</u> that is capable of operating close to the <u>maximum efficiency</u>, independent of the load; which may shift from a maximum to a minimum and from total refrigeration to total liquefaction mode or any partial combination.***

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

System Optimization (Cont.)

- **The trade-off relationship between the first two factors the minimum capital cost and minimum operating cost can be quantified to some extent by *exergy analysis* and the evaluated power cost.**

- **In the process industry, typically $1000 of capital investment is worthwhile if it reduces the electrical input power by 1 kW (@~$0.04/kW)**

Pressure ratio constraints

- Generally the compressor suction is maintained slightly above atmospheric pressure, the maximum discharge pressure sets the pressure ratio .
- Many of the critical components used in the system designs
- The pressure ratios selected for the cold box components must match both the type of the compressors and their operating characteristics
- A higher pressure ratio exposes the components to higher stresses
- The peak efficiency for the screw compressors is nominally in between the pressure ratios of 2.5 and 4.0
- Nominally the peak efficiency for turbo expanders is a pressure ratio between 2 and 5

The effect of higher mass flow through the cold box

- Increase the size of the heat exchangers required (and thus the size of the cold box).
- Increase the heat exchanger thermal losses associated with the stream temperature difference. This effect is approximately proportional to the flow.
- Increase the pressure drop.
- Increase the capital cost of the system

System Optimization (Cont.)

- **Balanced System Design**

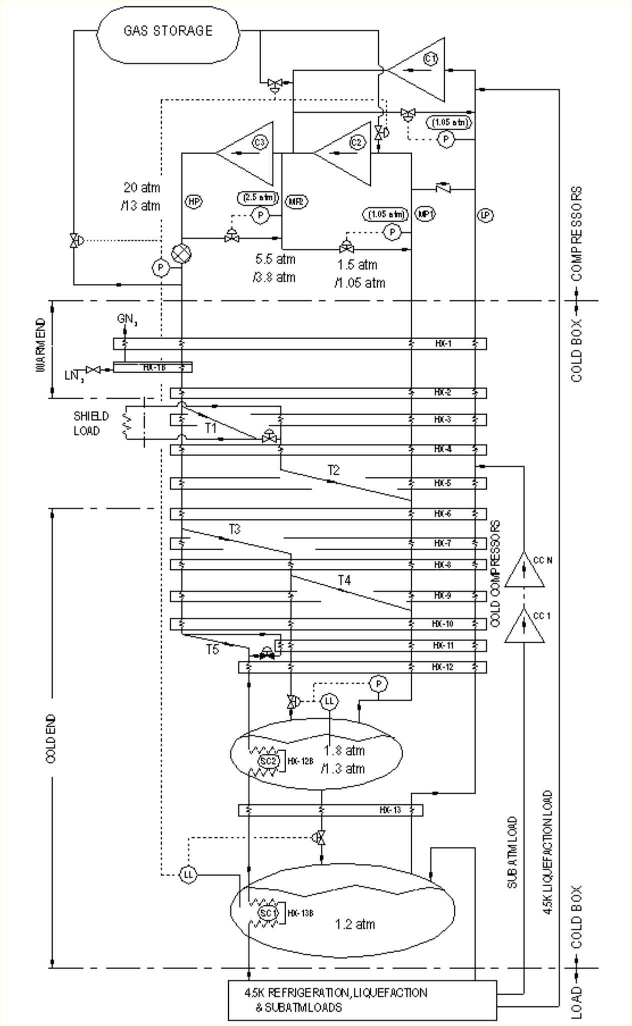
{Ganni Helium Process Cycle(s) (patent pending)}

The new helium cryogenic refrigeration and liquefaction cycle has been developed to maintain high plant operational efficiencies at full and reduced plant capacities.

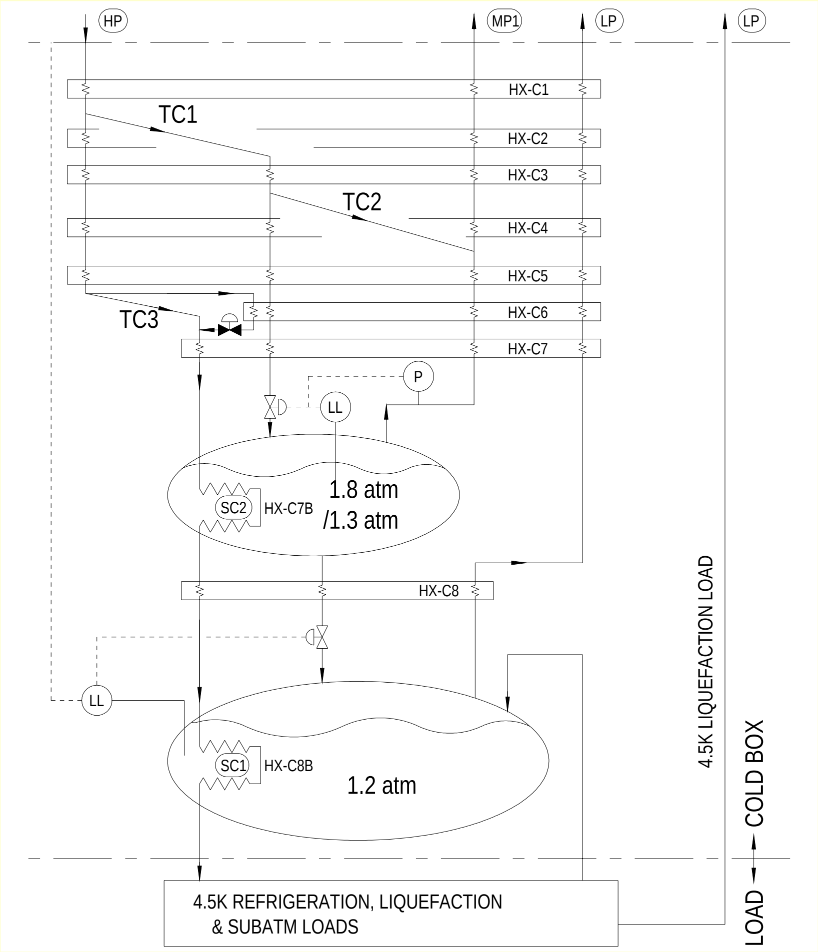
The following Figures illustrates the base variable pressure cycle design and the several cold end and warm end cycle configurations

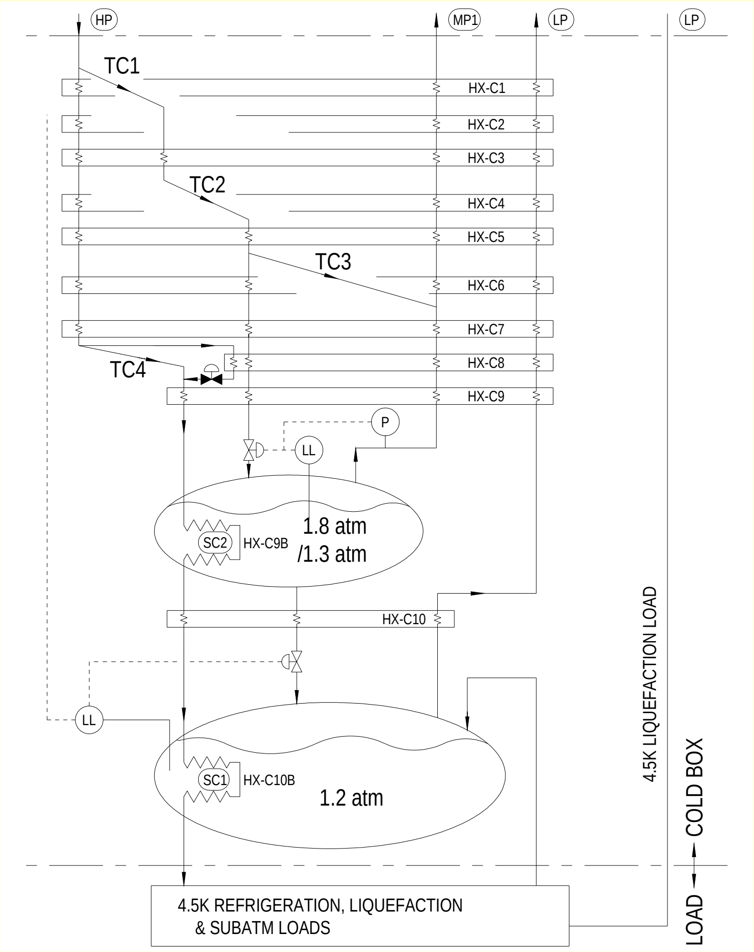
Recycle flow pressures vary with % full load, to operate at optimal pressure ratio for the compressors and the expanders

System Optimization (Cont.)

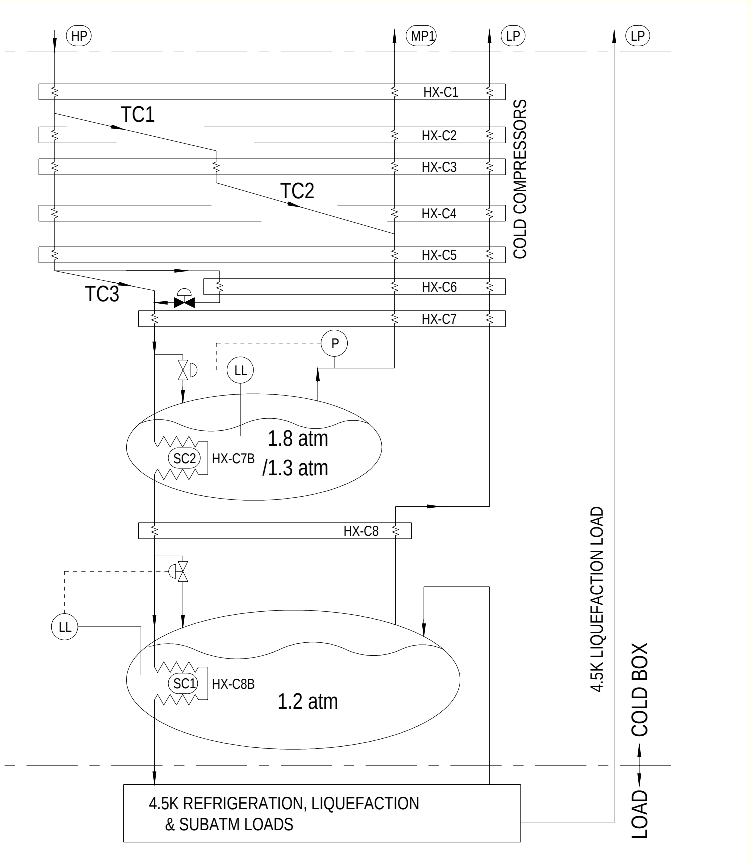


System Optimization (Cont.)

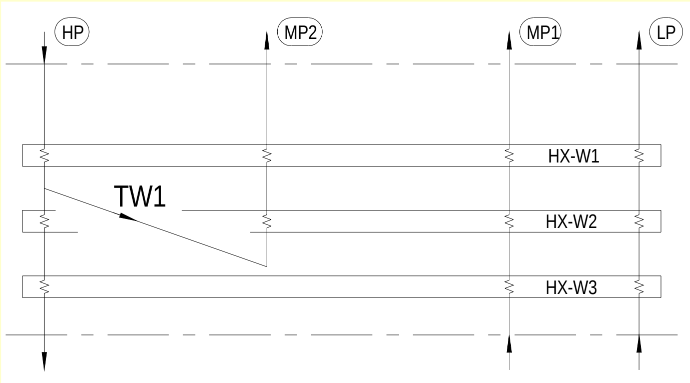


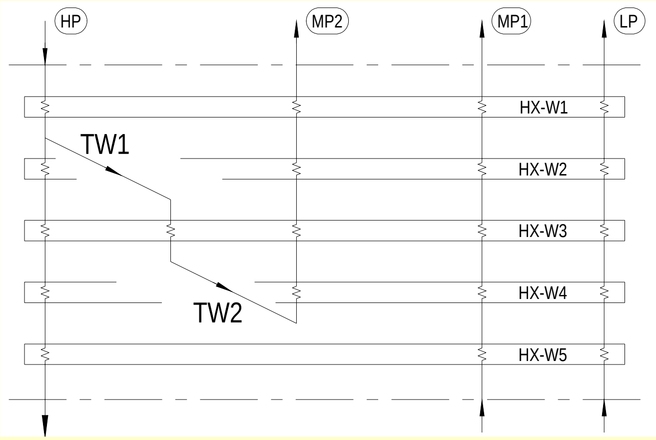


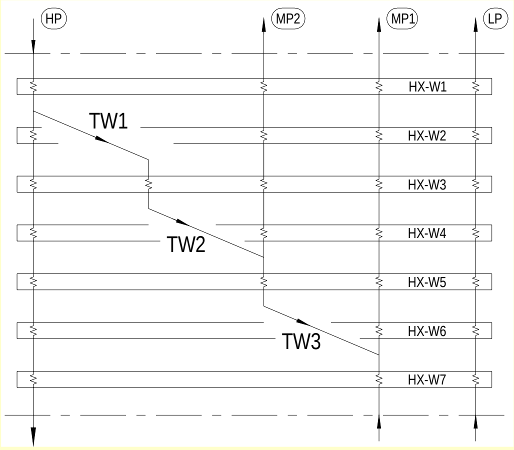
System Optimization (Cont.)

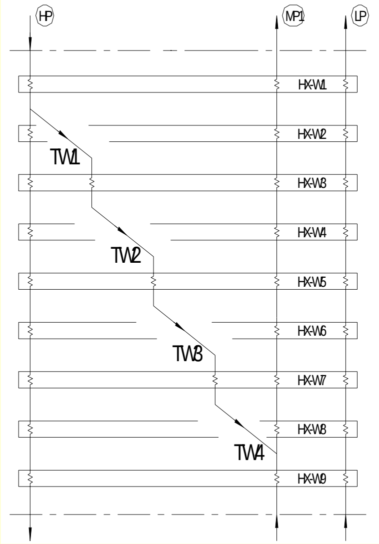


System Optimization (Cont.)









6. The Facts and Myths of LN2 Pre-cooling

What Does LN2 Pre-Cooling Do?

It provides the refrigeration capacity required for:

- **The liquefaction load (to cool the helium make-up gas) from 300K to 80K (cooling load of the beds to 80K).**
- **The heat exchanger (HX) losses associated with the cooling curves and heat leak from 300K to 80K.**

The Facts and Myths of LN2 Pre-cooling (Cont.)

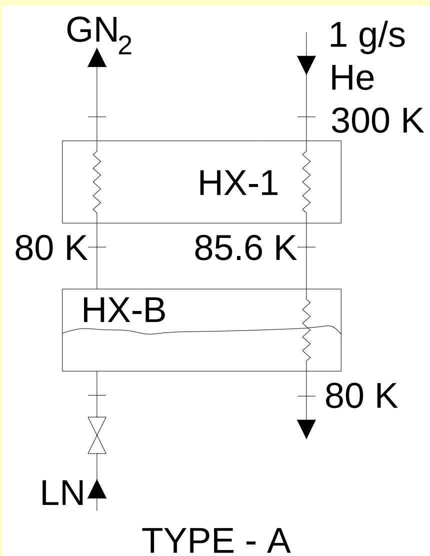
Advantages:

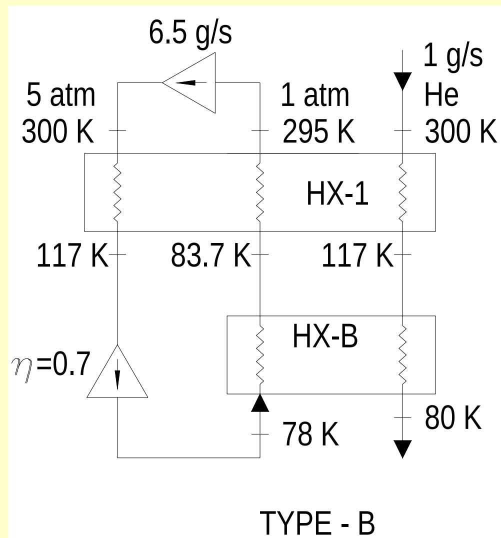
- Lower capital investment for a given cold box (refrigeration or liquefaction) capacity. For a given system, it increases the LHe production or the refrigeration capacity by a factor of 1.5 or more.
- Smaller cold box and compressor size for a given capacity (i.e., a smaller building or les. building space). However, space is required for a LN2 dewar (normally outside).
- Provides thermal anchor point of 80K for the adsorber beds.
- Stable operation over a larger operating range and a larger turndown capability.
- Fewer rotating parts and lower maintenance costs.
- Able to keep the load temperature at 80K during partial maintenance of the cold box sub systems (i.e., turbines etc.).
- Any impurities in the helium stream are frozen in the 'warm' HX and thereby protecting the lower temperature turbines from contamination and erosion damage.
- Extremely useful to handle cool down loads. In general approximately ~ 80% of the cool down loads are from 300K to 80K.

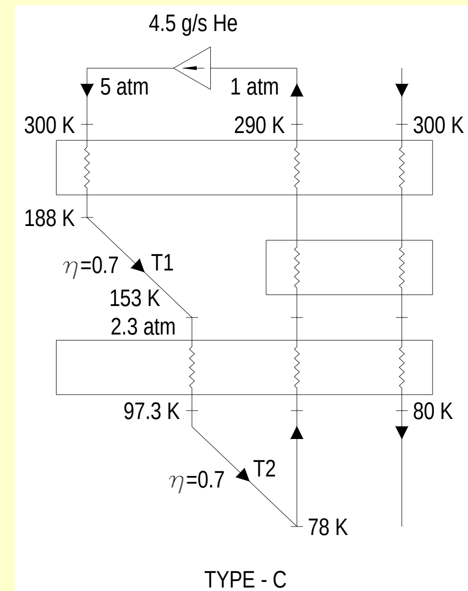
Disadvantages:

- Requires the coordination of deliveries of the LN2.
- Different fluids in the system. Cross leaks are more detrimental.
- LN2 requires additional oxygen deficiency hazard (ODH) monitoring.
- Typically operating costs are greater.

The Facts and Myths of LN2 Pre-cooling (Cont.)



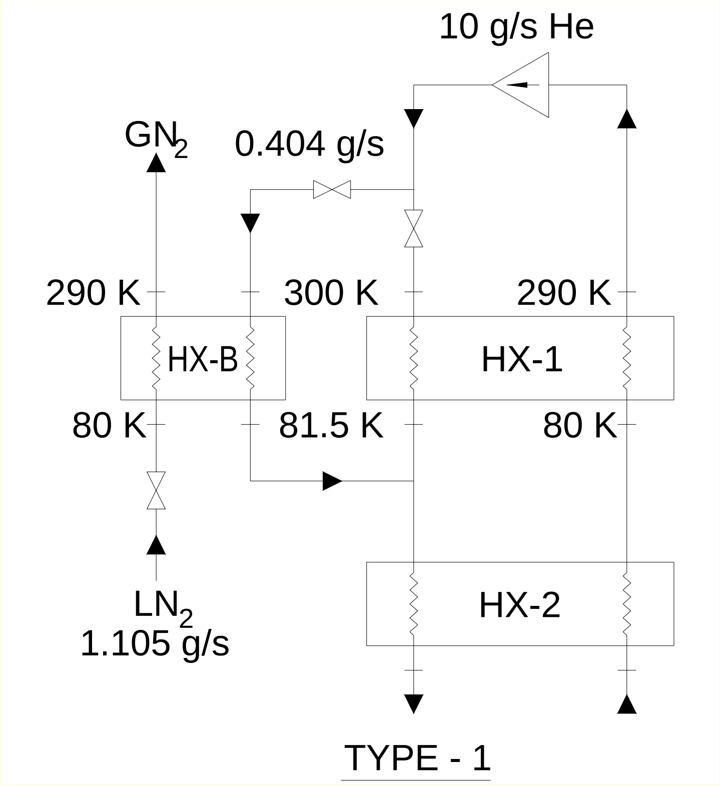


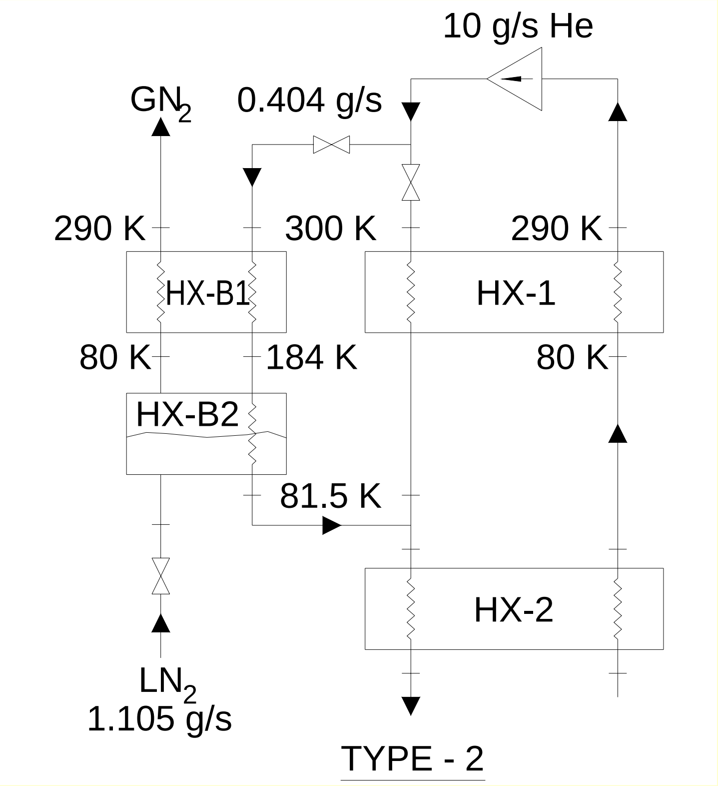


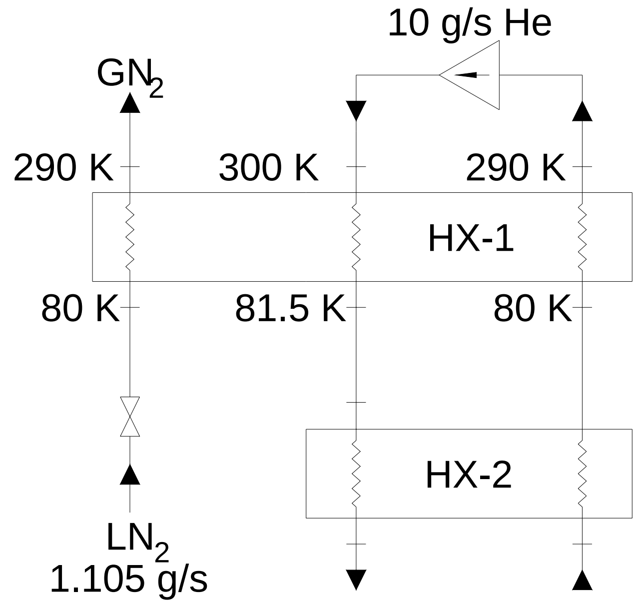
The Facts and Myths of LN2 Pre-cooling (Cont.)

	LN_2 Cost Break-Even Point Analysis			
	Units	**TYPE-A**	**TYPE-B**	**TYPE-C**
Helium Liquefaction Flow	g/s	1.0	1.0	1.0
LN_2 Flow	g/s	2.7	—	—
	l/hr	12	—	—
Expander Efficiency(s)		—	0.7	0.7
Compressor Recycle Flow	g/s	—	6.5	4.5
Comp. Isothermal Eff.		—	0.5	0.5
Comp Power Input	kW	—	13	9
Given:				
LN_2 Cost	$/liter	0.06	—	—
Electric Power	$/kW-h	0.04	—	—
LCF		—	**1.38**	**2.00**

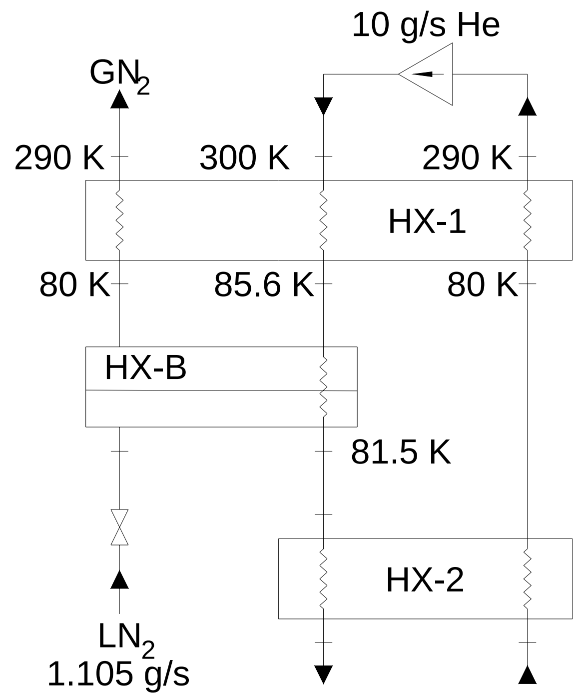
The Facts and Myths of LN2 Pre-cooling (Cont.)





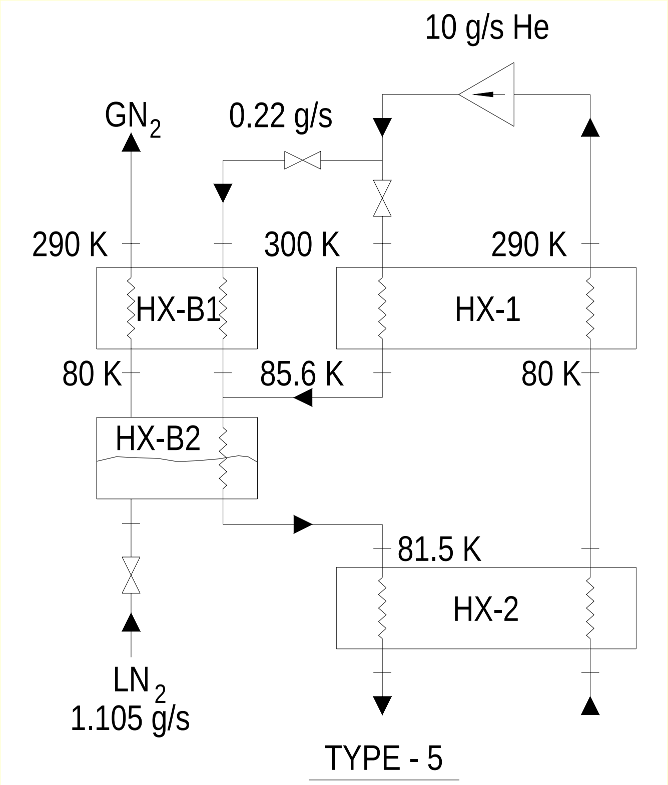

10 g/s He
GN2
290 K
300 K
290 K
HX-1
80 K
81.5 K
80 K
HX-2
LN2
1.105 g/s

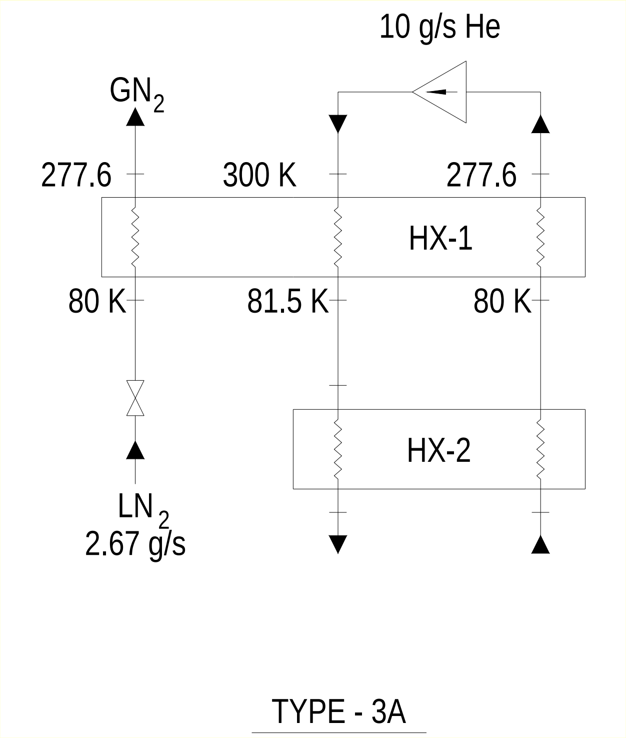
TYPE - 3


10 g/s He
GN2
290 K
300 K
290 K
HX-1
80 K
85.6 K
80 K
HX-B
81.5 K
HX-2
LN2
1.105 g/s

TYPE - 4

The Facts and Myths of LN2 Pre-cooling (Cont.)



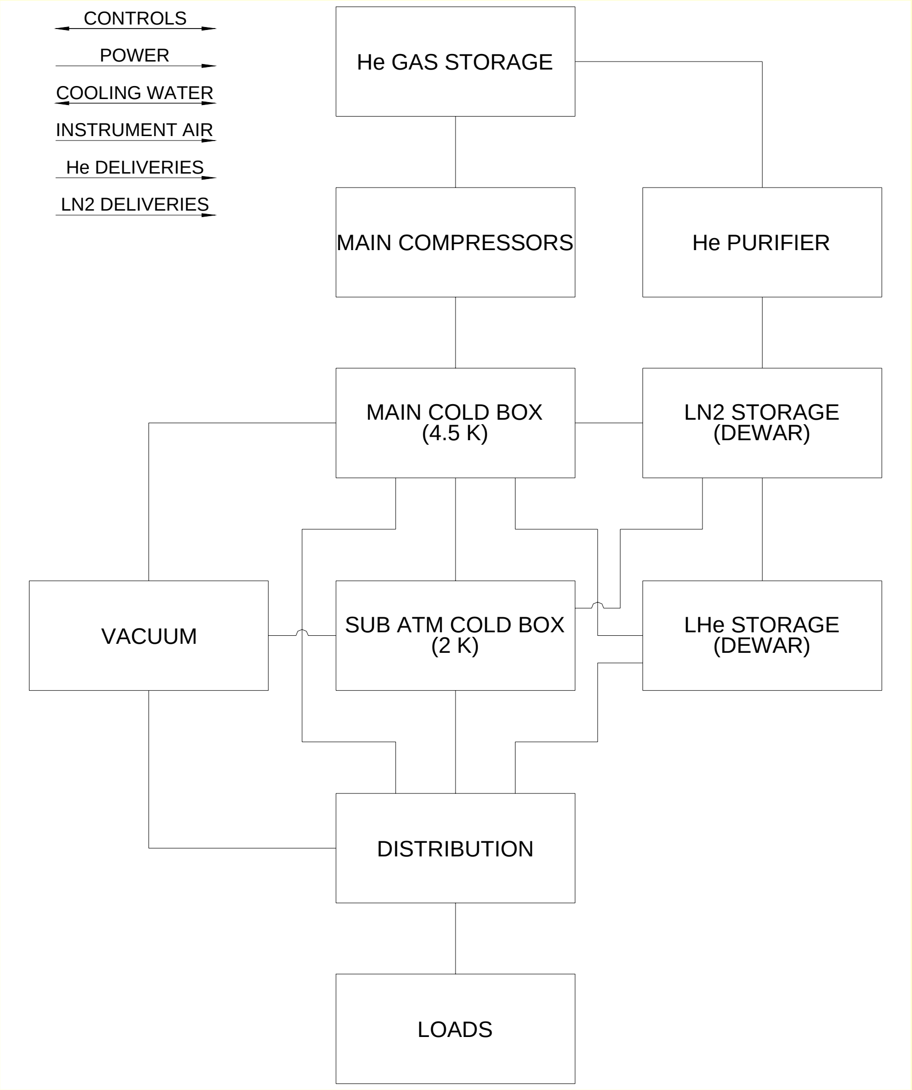


The Facts and Myths of LN2 Pre-cooling (Cont.)

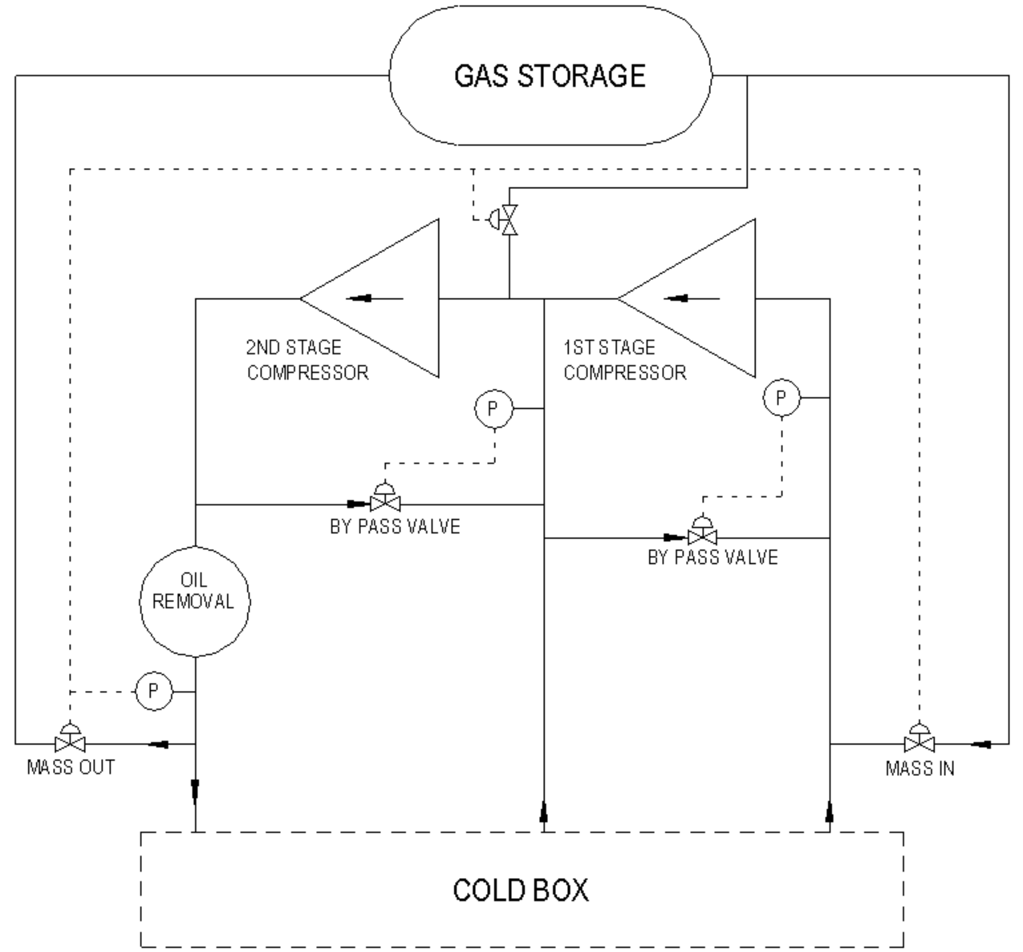
Comparison of HX Parameters

		Duty	Δ Tm	C_{min}	C_{max}		UA	NTU	ε
Type	HX	[W]	[K]	[W/K]	[W/K]		[W/K]		
Type-1	HX-1	10888	4.48	49.83	51.85	0.961	2430	48.8	0.993
	HX-B	458	4.48	2.10	2.18	0.961	102	48.8	0.993
Type-2	HX-1	10888	4.48	49.83	51.85	0.961	2430	48.8	0.993
	HX-B1	243	40.14	1.16	2.10	0.552	6	5.2	0.955
	HX-B2	215	24.18	2.10	∞	0.000	9	4.2	0.986
Type-3	HX-1	11347	4.48	51.93	54.03	0.961	2532	48.8	0.993
Type-4	HX-1	11134	7.59	51.93	53.02	0.979	1467	28.3	0.975
	HX-B	213	3.11	51.93	∞	0.000	68	1.3	0.732
Type-5	HX-1	10889	7.59	50.79	51.85	0.979	1435	28.3	0.975
	HX-B1	245	7.59	1.14	1.17	0.979	32	28.3	0.975
	HX-B2	213	3.11	51.93	∞	0.000	68	1.3	0.732
Type-3A	HX-1	11347	7.73	51.93	57.42	0.904	1468	28.3	0.993

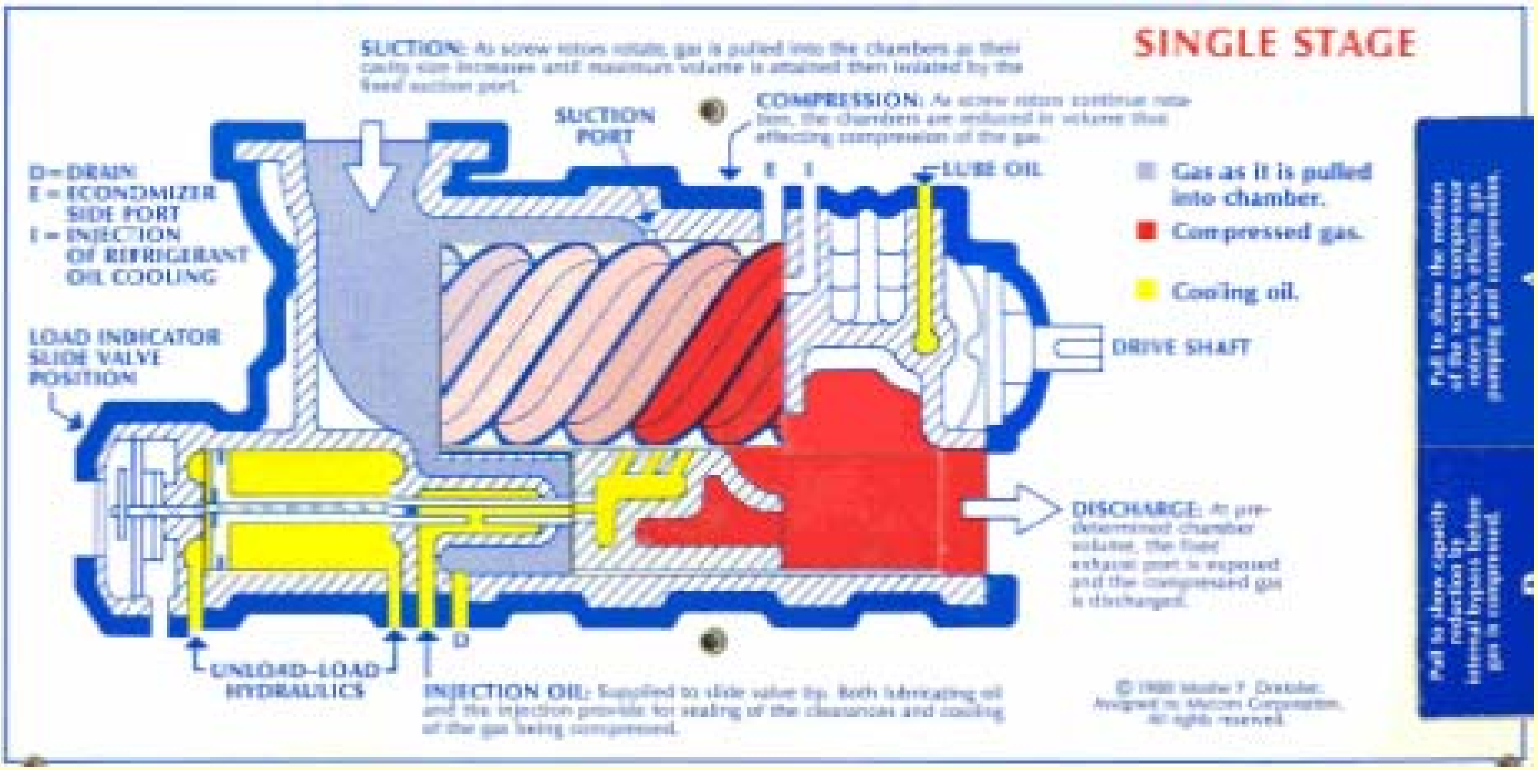
7. Typical Helium Cryogenic System and its Basic Components



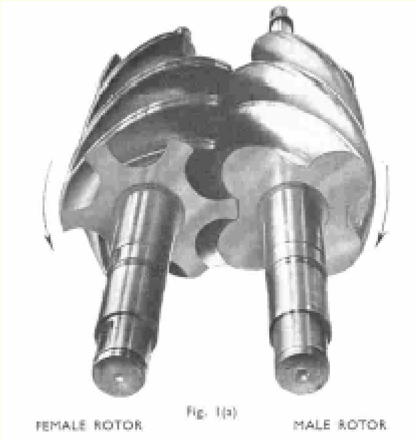
Typical Helium Cryogenic System and its Basic Components (Cont.)

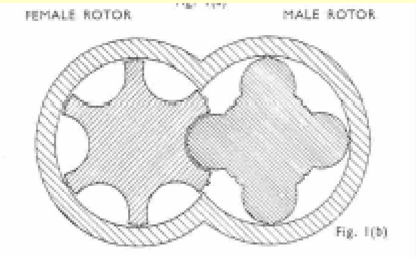


Typical Helium Cryogenic System and its Basic Components (Cont.)

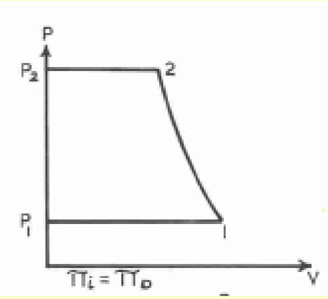


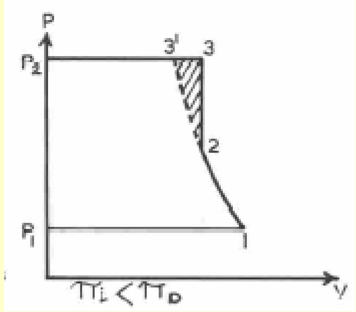
Typical Helium Cryogenic System and its Basic Components (Cont.)

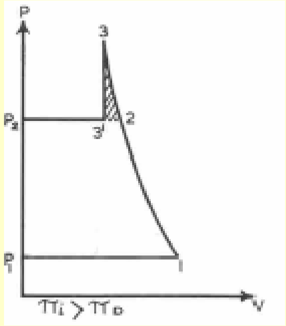




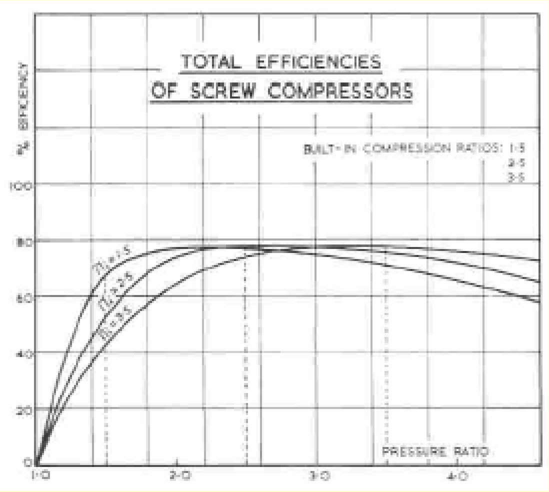
Typical Helium Cryogenic System and its Basic Components (Cont.)

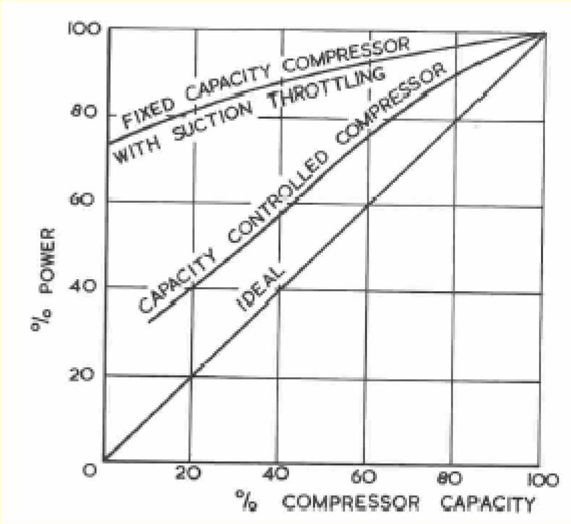




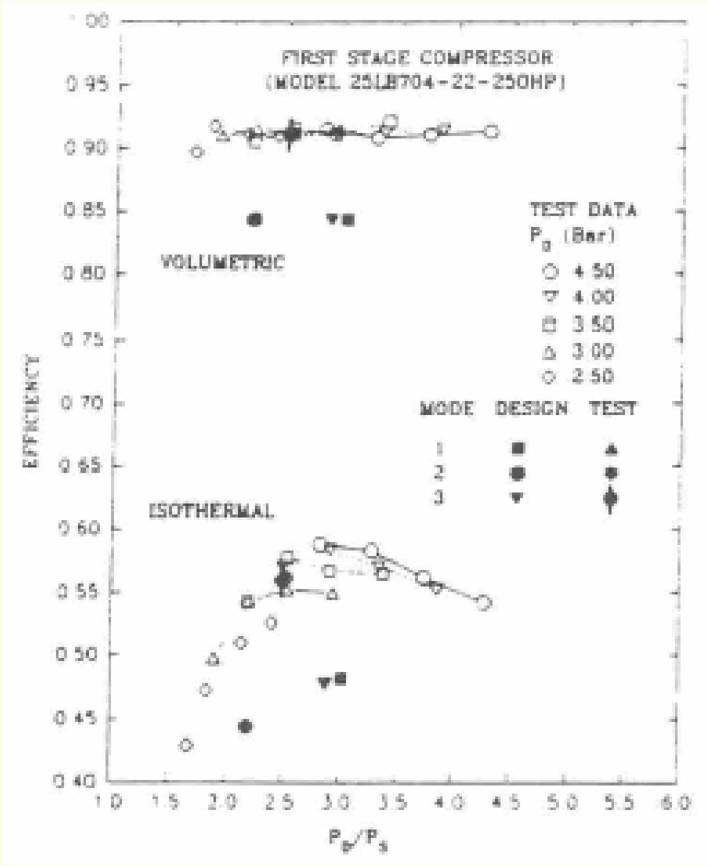


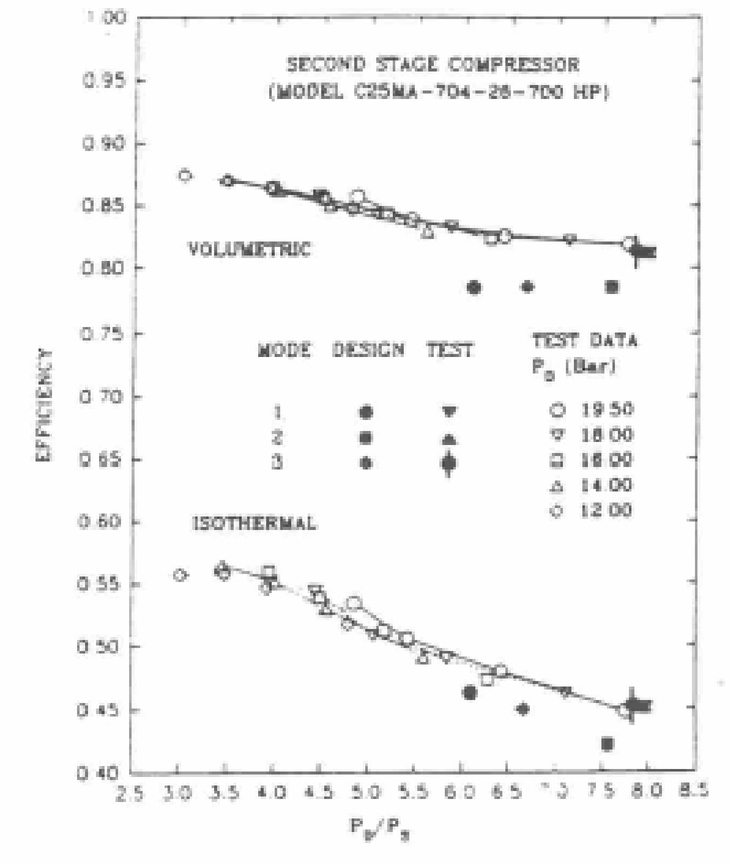
Typical Helium Cryogenic System and its Basic Components (Cont.)





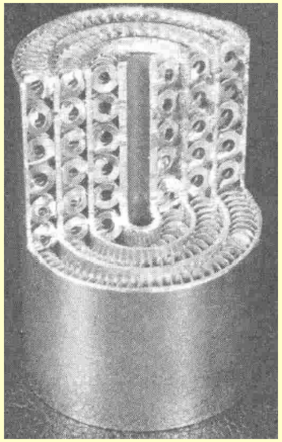
Typical Helium Cryogenic System and its Basic Components (Cont.)

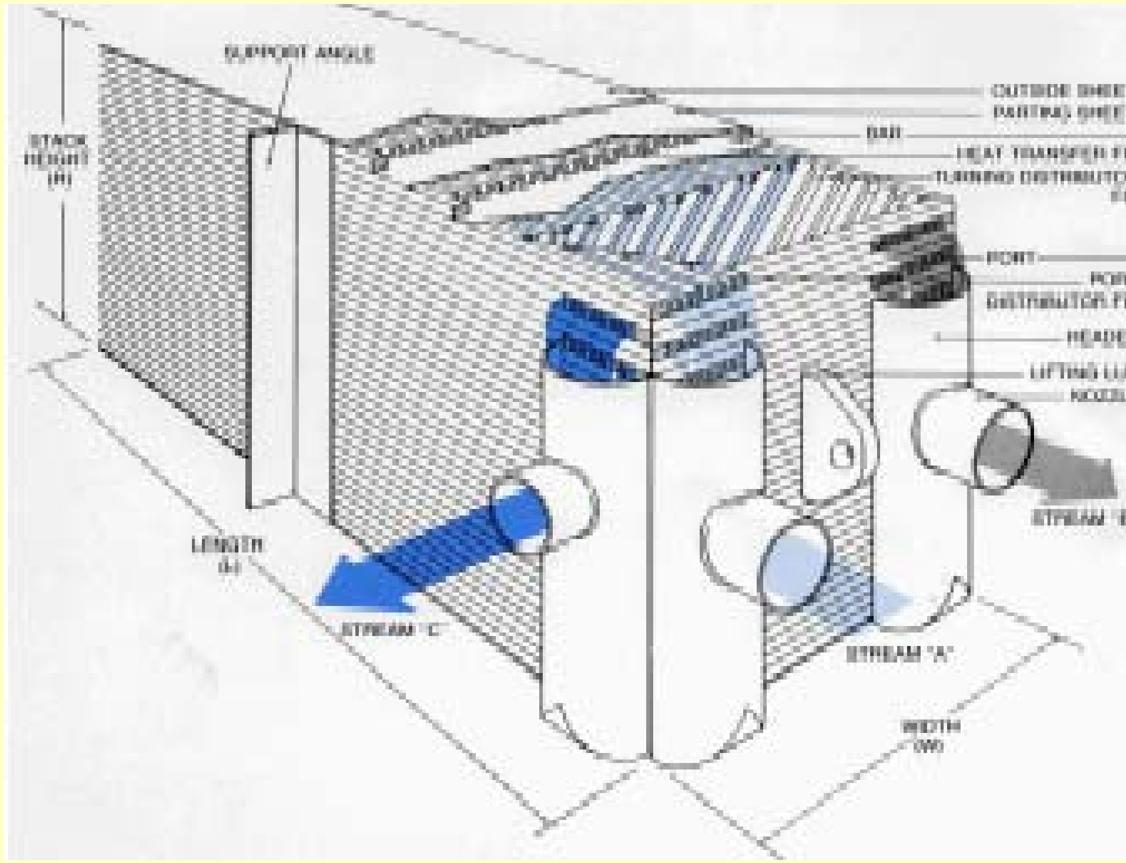




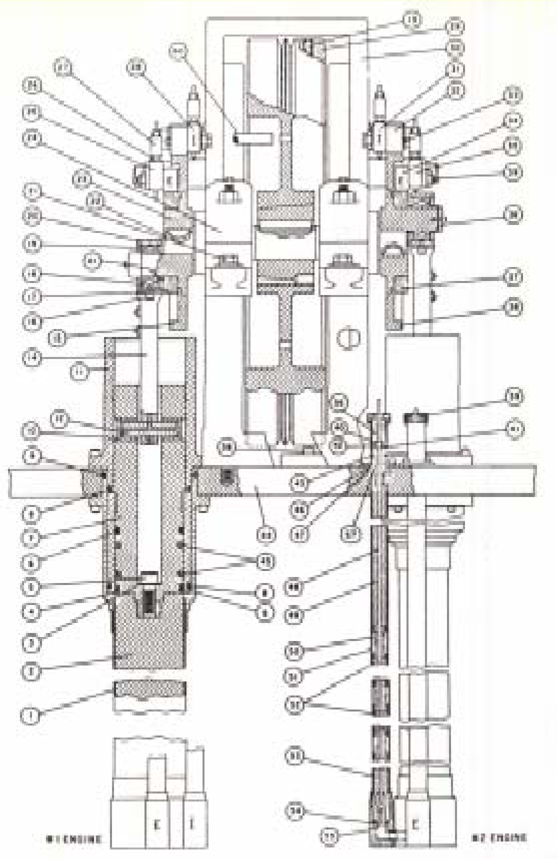
Typical Helium Cryogenic System and its Basic Components (Cont.)

Typical Helium Cryogenic System and its Basic Components (Cont.)

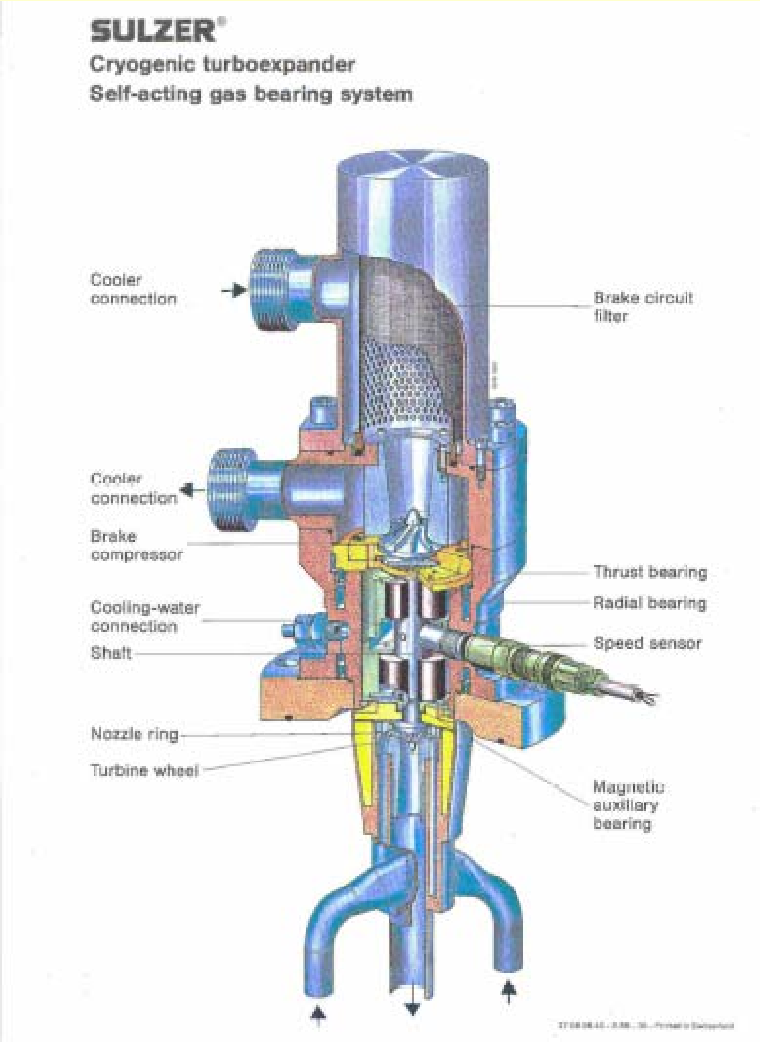




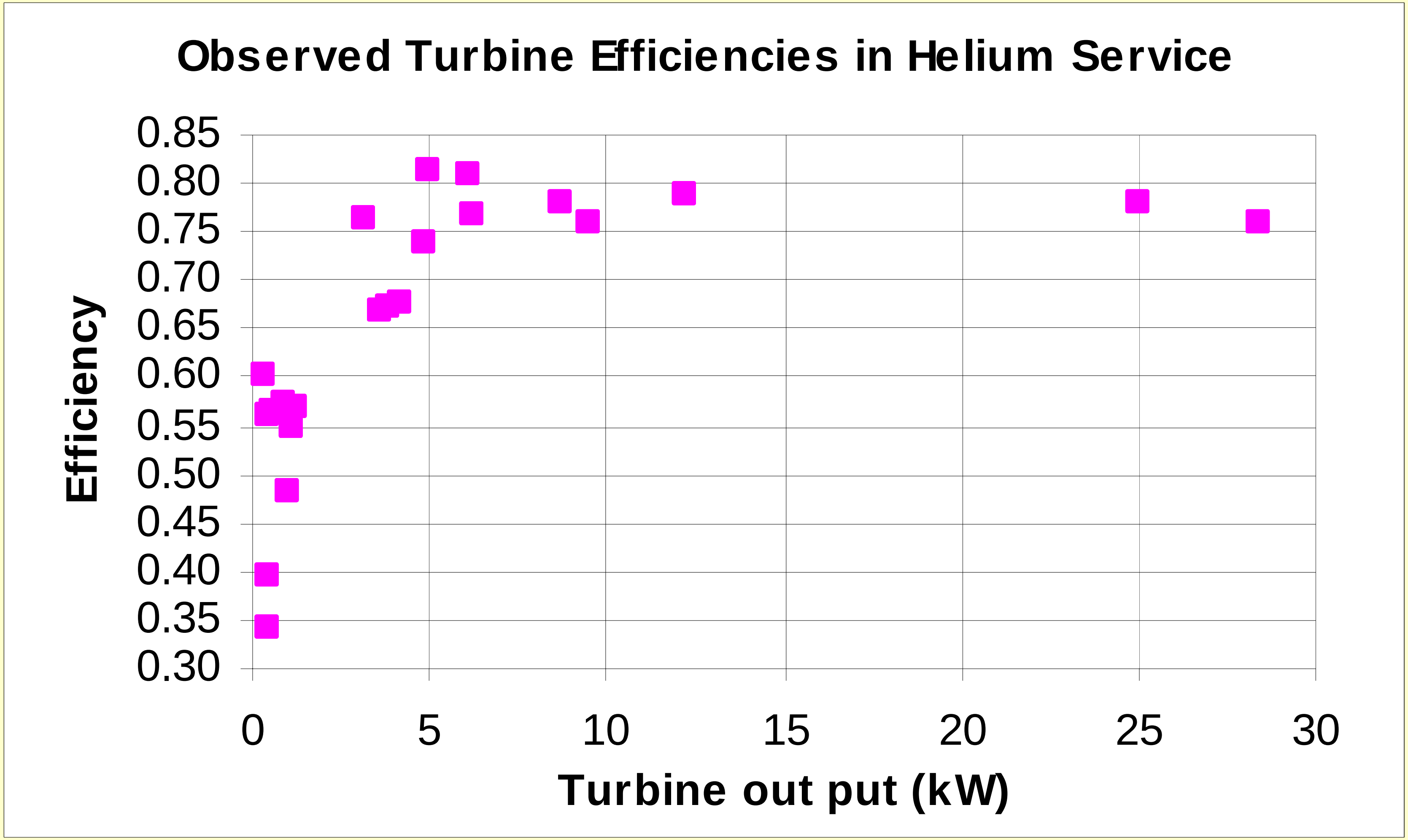
Typical Helium Cryogenic System and its Basic Components (Cont.)



Typical Helium Cryogenic System and its Basic Components (Cont.)



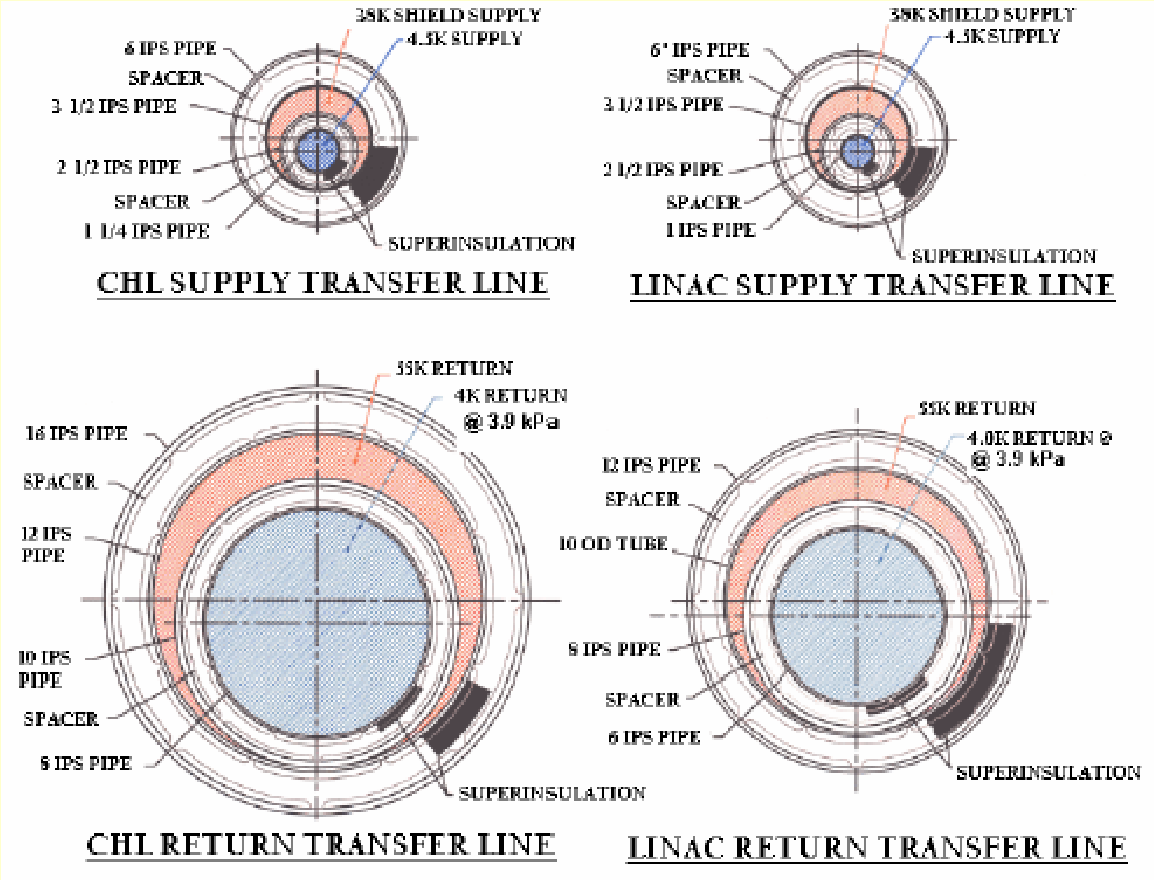
Typical Helium Cryogenic System and its Basic Components (Cont.)



Typical Helium Cryogenic System and its Basic Components (Cont.)

Typical Helium Cryogenic System and its Basic Components (Cont.)

Typical Helium Cryogenic System and its Basic Components (Cont.)

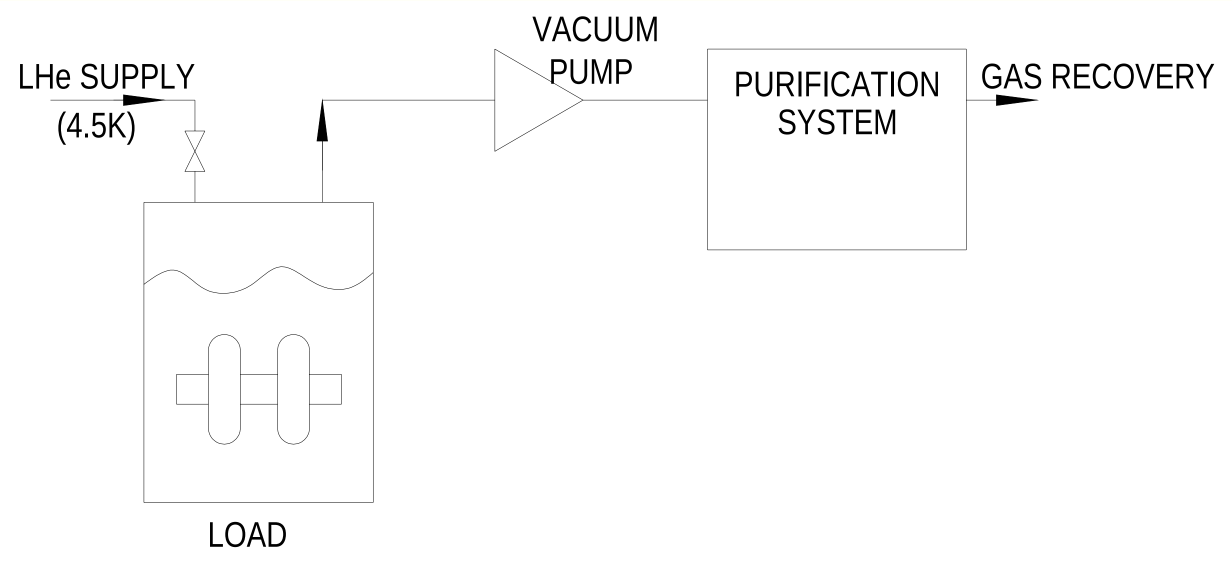


Typical Helium Cryogenic System and its Basic Components (Cont.)

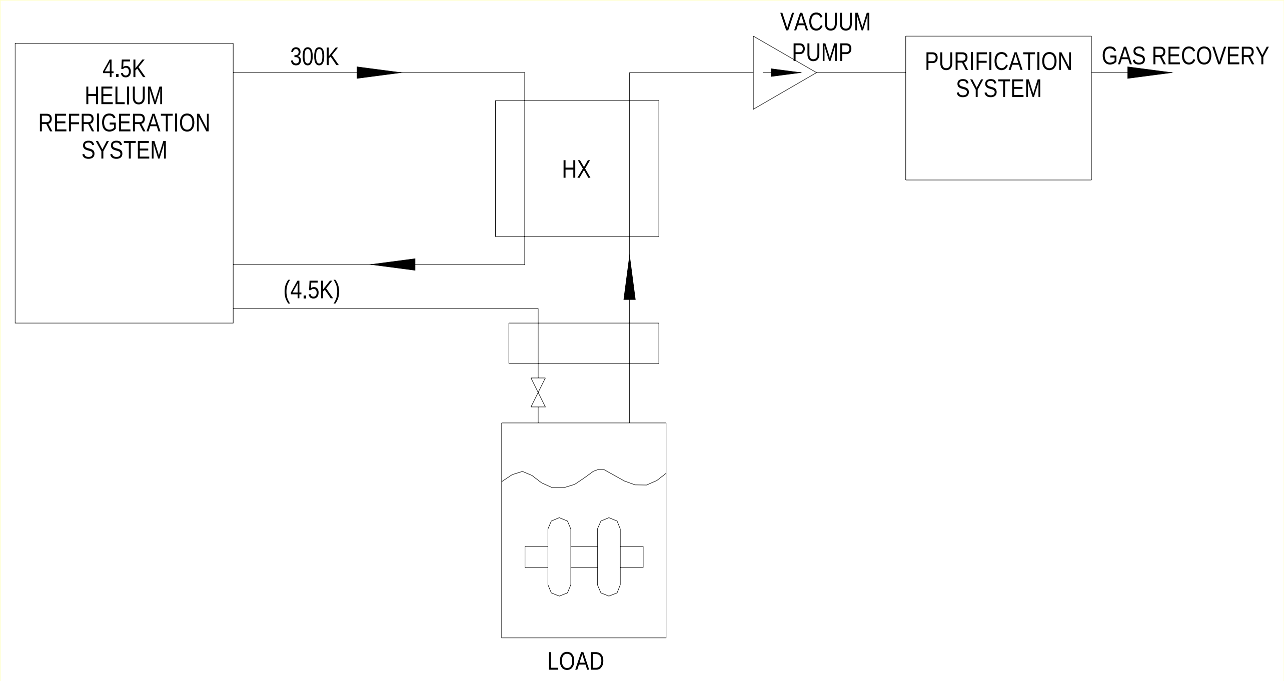
8. Sub Atm. Systems

1. Vacuum pumping on the helium bath
2. Sub atmospheric refrigeration system design
3. Cold compressors
4. Hybrid systems

Sub Atm. Systems (Cont.)

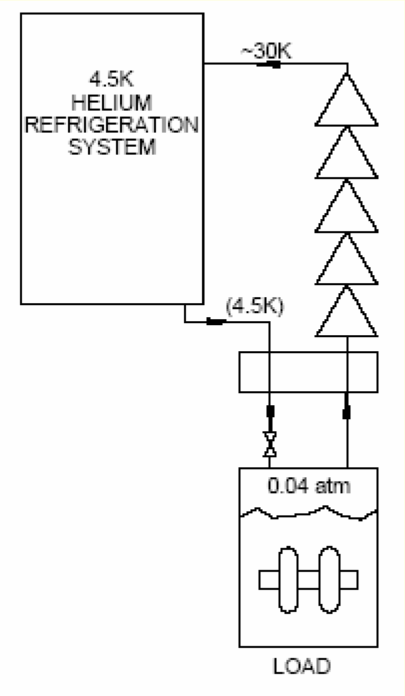


Sub Atm. Systems (Cont.)

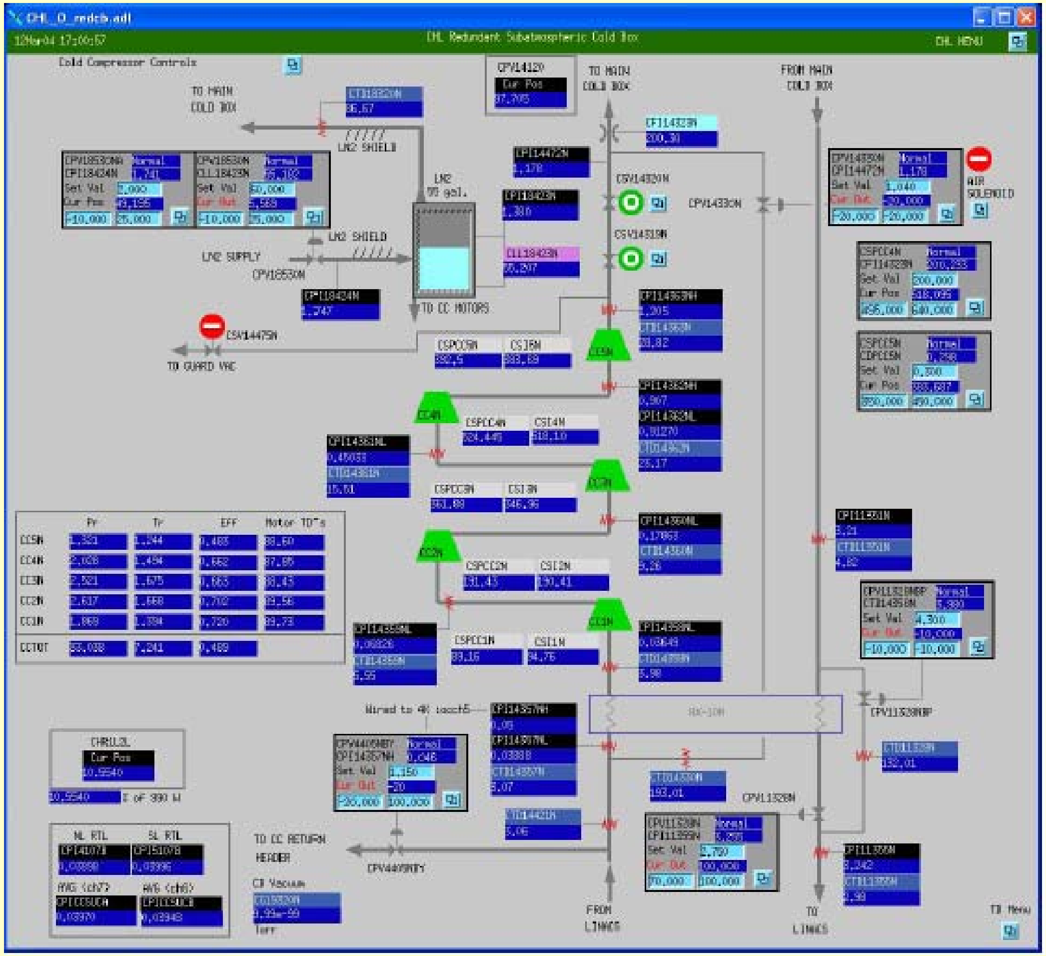


Sub Atm. Systems (Cont.)

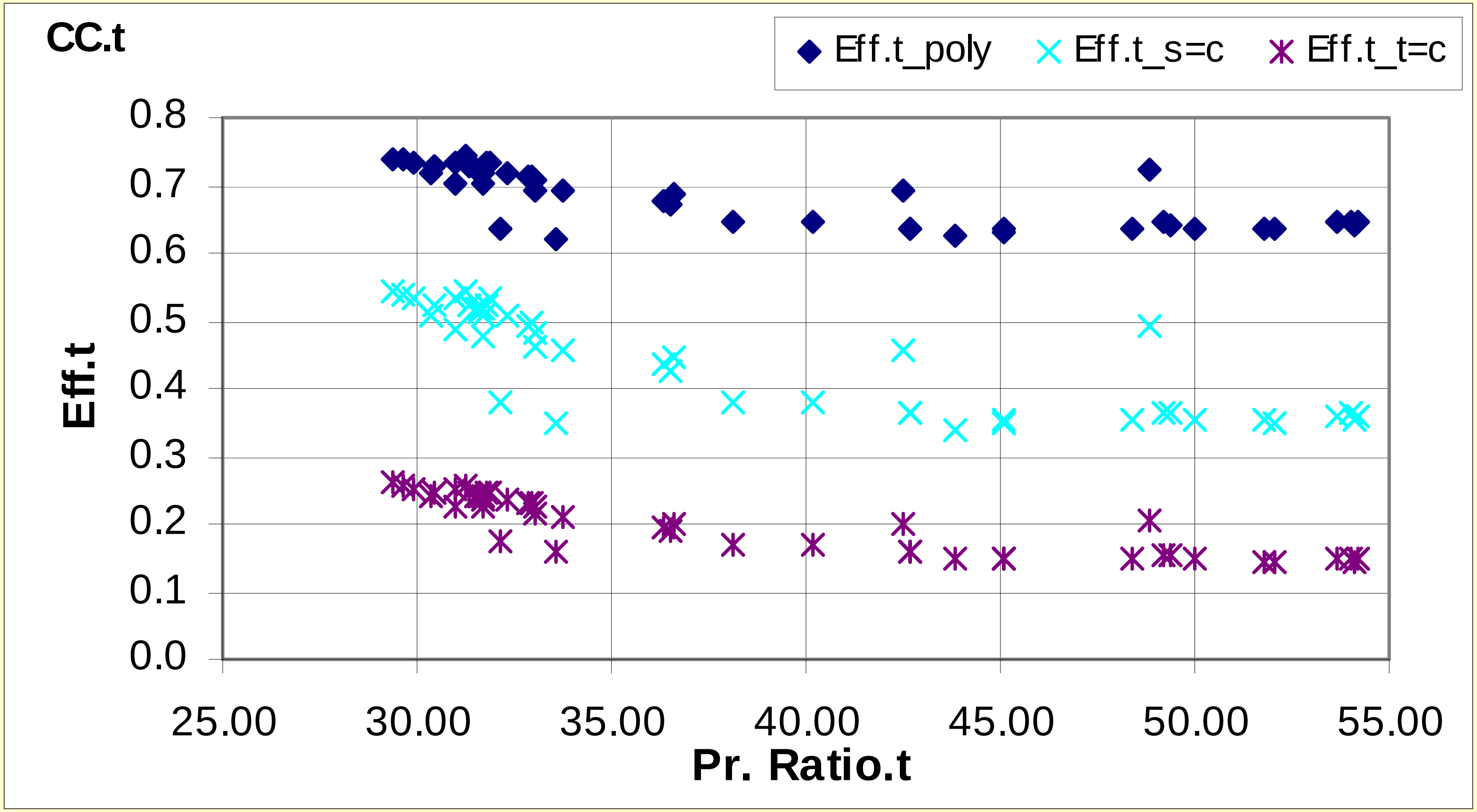
Sub Atm. Systems (Cont.)



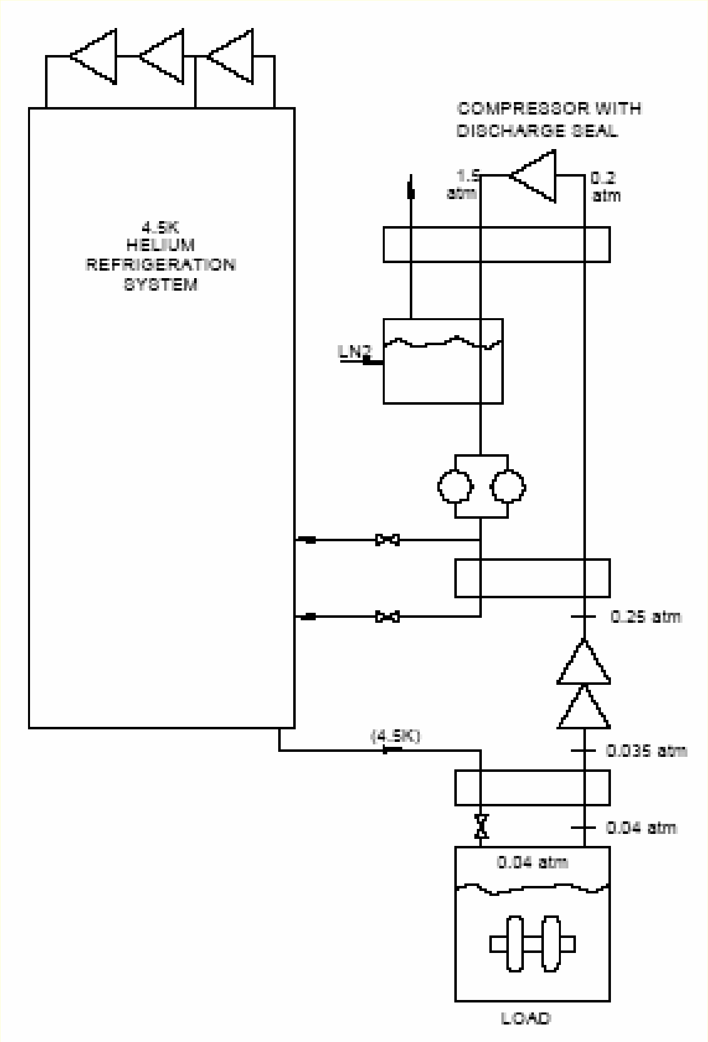
Sub Atm. Systems (Cont.)



Sub Atm. Systems (Cont.)



Sub Atm. Systems (Cont.)



9. System Capacity Specification and Margin Allocation

Specify the system requirements

Capacity or Carnot capacity and Carnot Efficiency

For at least the three following cases; They are:

- **100% Liquefaction**
- **100% Refrigeration**
- **50% Liquefaction and 50% Refrigeration**

System Capacity Specification and Margin Allocation (Cont.)

Some of the factors to be considered for margin are:

- **Uncertainty of the primary load estimates**
- **Uncertainty of the heat leak into distribution system load estimates**
- **Capacity for system and load control (~5%)**
- **Uncertainty of instrumentation**
- **System degradation with time due to contamination and allowance for valve leaks before requiring a system shut down and rebuild**
- **Cool down and bringing the loads to steady state conditions**
- **Critical reduced-capacity operation with some component failures (make sure each major component failure is analyzed)**
- **In general the sum of all these factors adds up to 25 to 50% of the primary loads.**

10. Design Verification and Acceptance Testing

The required devices to test the equipment should be designed into the system components itself.

They will help to:

- **verify the system performance from the vendor**
- **operate the system at partial loads using the test devises if required**
- **verify the system capacity from time to time; especially after major maintenance and for major component change out periods**
- **handle the load and system transients by providing the capacity modulation**

11. Some of the Lessons Learned over the Years

We can learn a great deal from operating systems and they can be good, bad or even ugly.

Analyze the data carefully before reaching any conclusions.

Make sure the decisions are based on the proven test data and operational experience. Many times the perceptions are very different from the realities.

For new projects, make sure the scope includes all the items required for the project.

Some of the Lessons Learned (Cont.)

It helps a great deal if the project is well organized; the cost estimates are based on present data, and schedule planning and execution are performed by an experienced team.

Make sure at least the following areas of concern are addressed and the lessons learned in these areas are implemented in the new system designs.

Some of the Lessons Learned (Cont.)

Compressors:

- **Oil removal under sizing in general and in particular for minimum capacity or reduced pressure (capacity) operation**
- **Improper selection of compressor frame sizes (either too large or too small)**
- **Number of compression stages**

Some of the Lessons Learned (Cont.)

Cold Box

- **Cycle selection and not addressing all aspects of operation by single point design**
- **Undersized HX's**
- **Over estimated turbine efficiencies**
- **Inadequate cool down and warm up taps**
- **Nonfunctioning 80K and 20K beds (leaky isolation valves)**
- **Oil contamination**

Some of the Lessons Learned (Cont.)

Sub atm Cold box design

- Evaluation of cycle options and cold box design
- Undersized HX's
- Over estimated compressor pressure ratios and efficiencies
- Underestimated torque requirements or over estimated torque performance

Auxiliary Systems

- Inadequate Purifier Size
- Excessive time to regenerate the purifier beds

Some of the Lessons Learned (Cont.)

Helium Storage

- Dewar(s) size requirement estimates
- Operable dewar specification including heaters
- Warm storage sizing

Distribution System

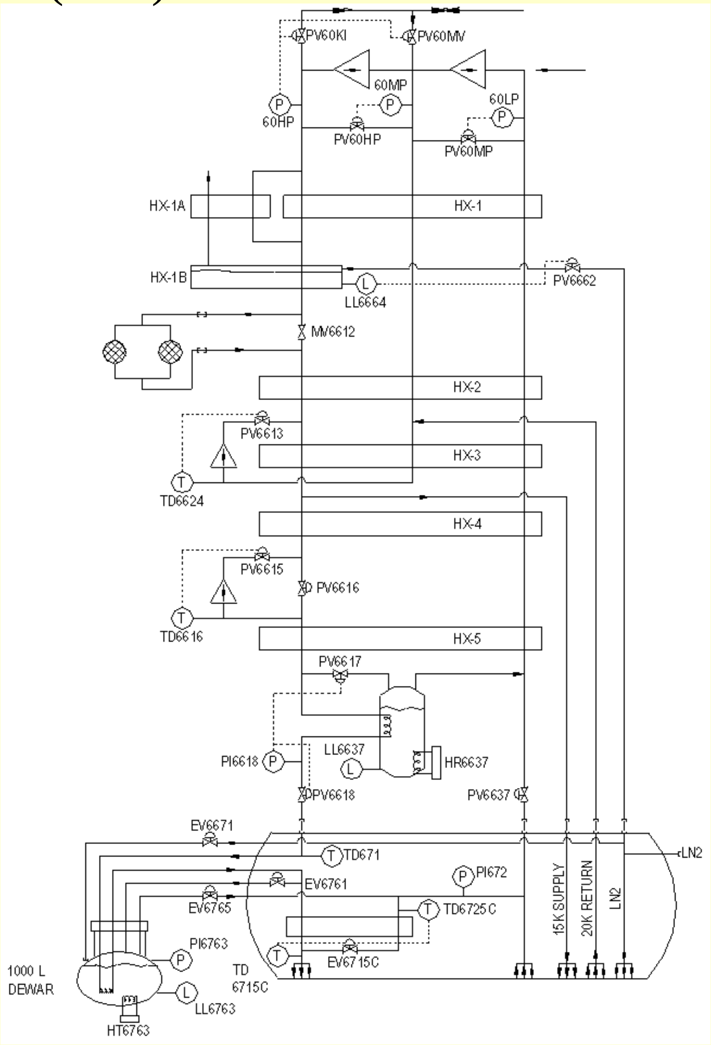
- High heat leak to transfer lines and distribution systems

12. Optimal Operation of the Existing Helium Refrigeration Systems

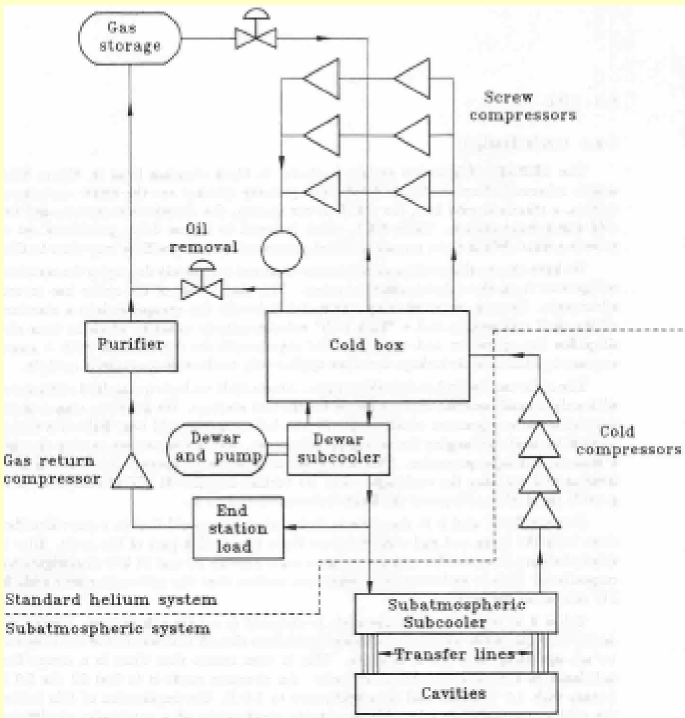
Optimal operation addresses the following goals:

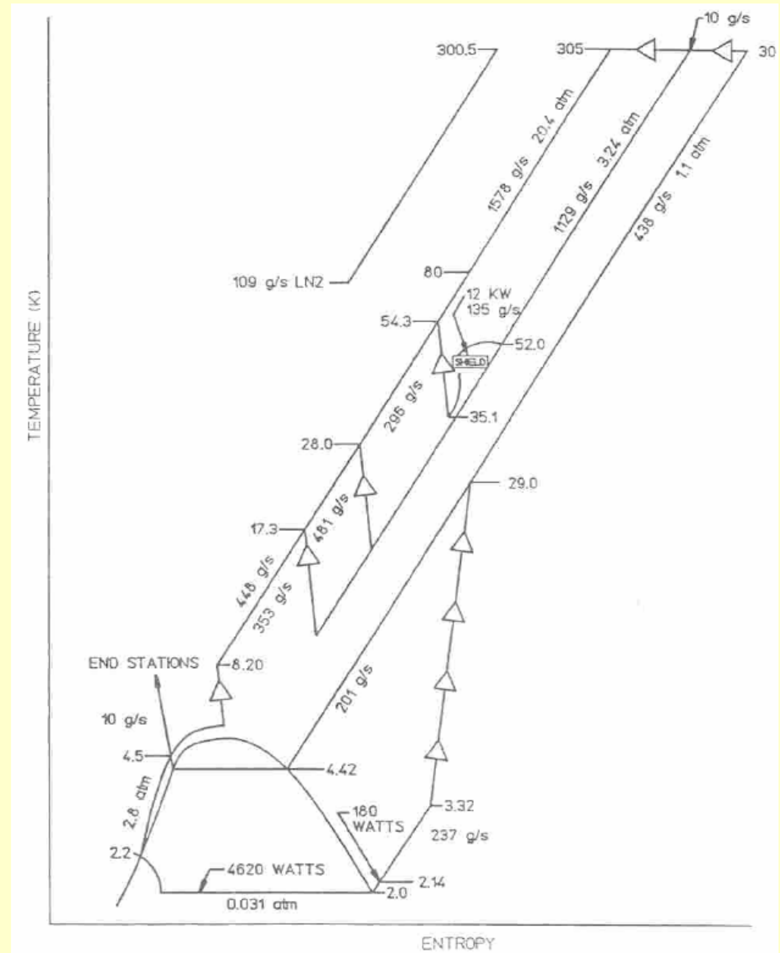
- **Operation of the system at the design TS diagram.**
- **Operation of the system at optimal operating conditions to meet the present loads. Again the same five questions need to be asked as explained in the chapter 5, *System Optimization*.**
- **Modify the system to fit optimal operating conditions to meet present loads with current optimal goals.**

End Station Refrigeration System (ESR) at JLab



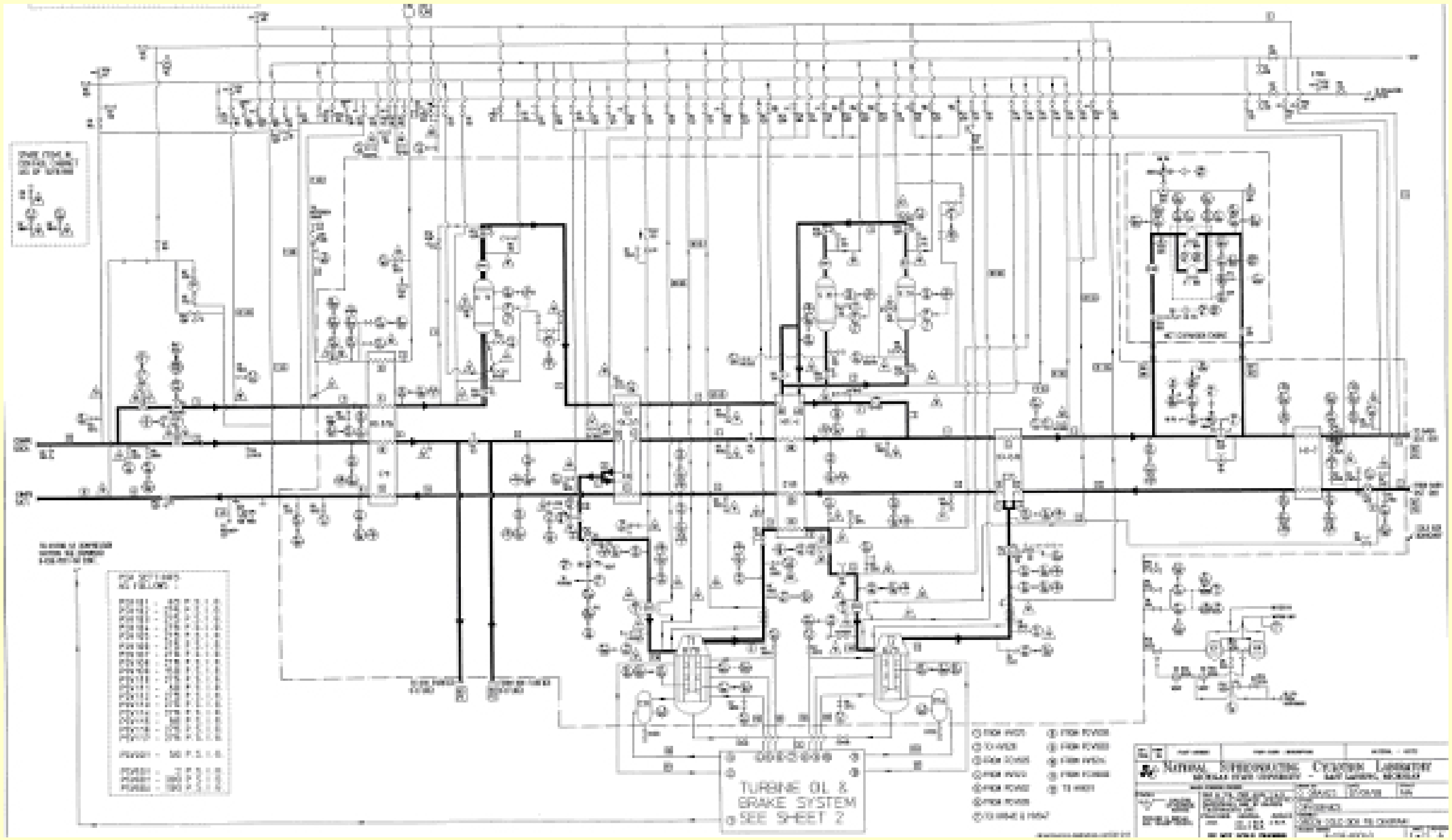
Central Helium Liquefier (CHL) at JLab



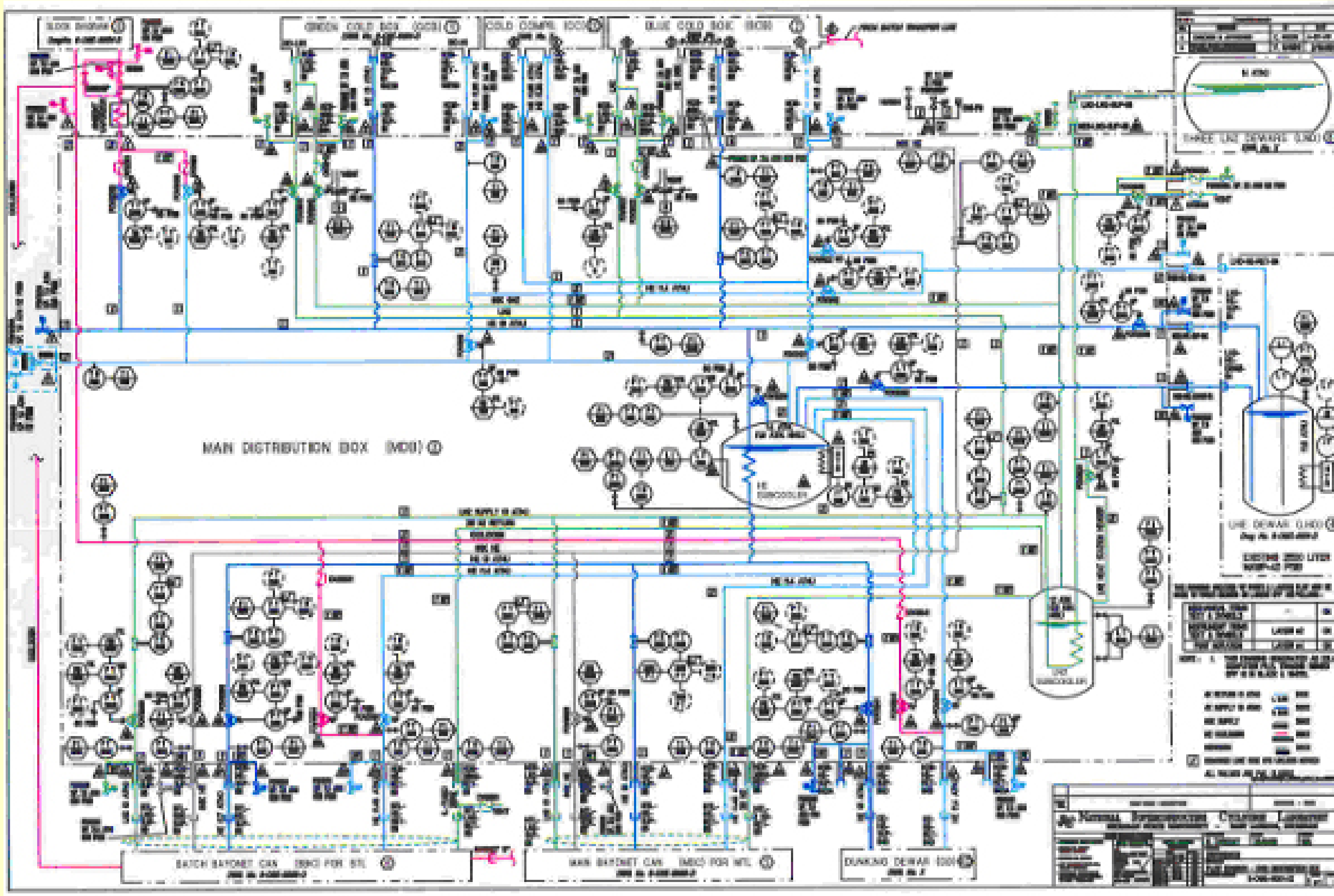


Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Office of Science
U.S. DEPARTMENT OF ENERGY

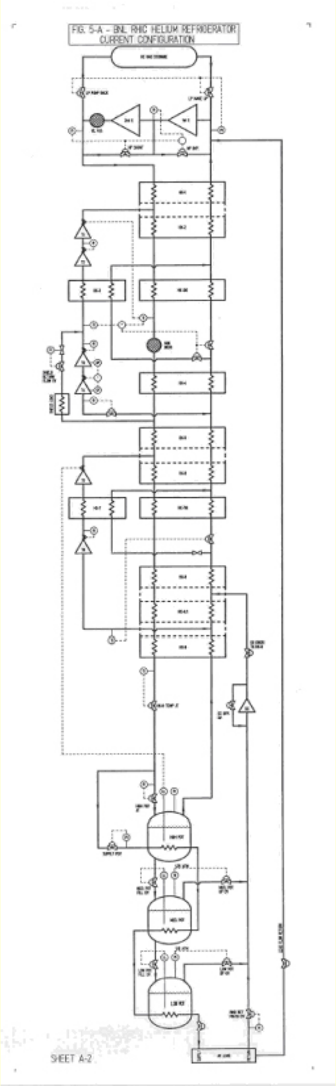
Optimal Operation of the Existing Helium Refrigeration Systems (Cont.)

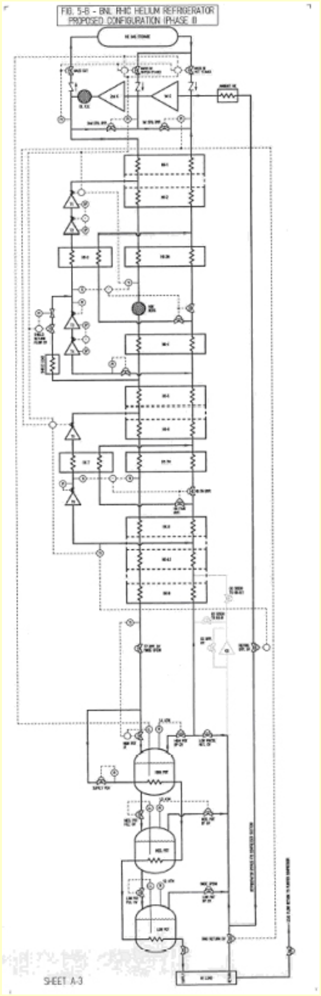


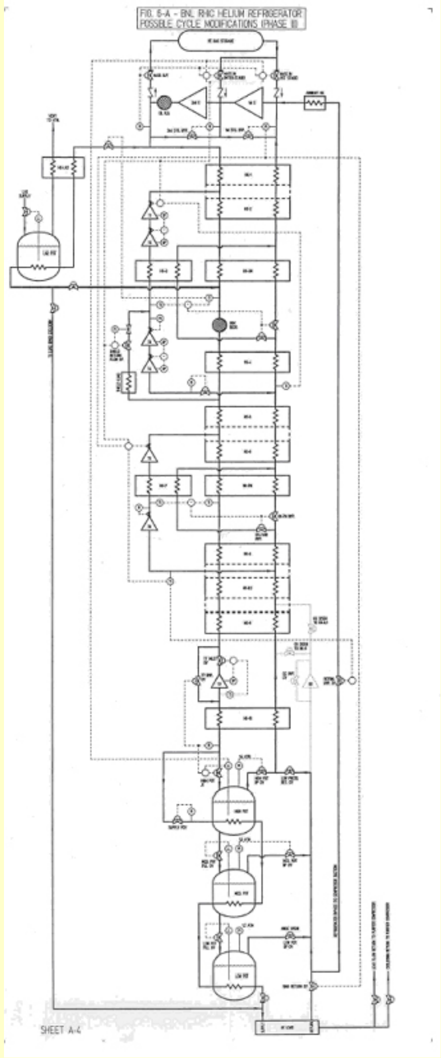
Optimal Operation of the Existing Helium Refrigeration Systems (Cont.)



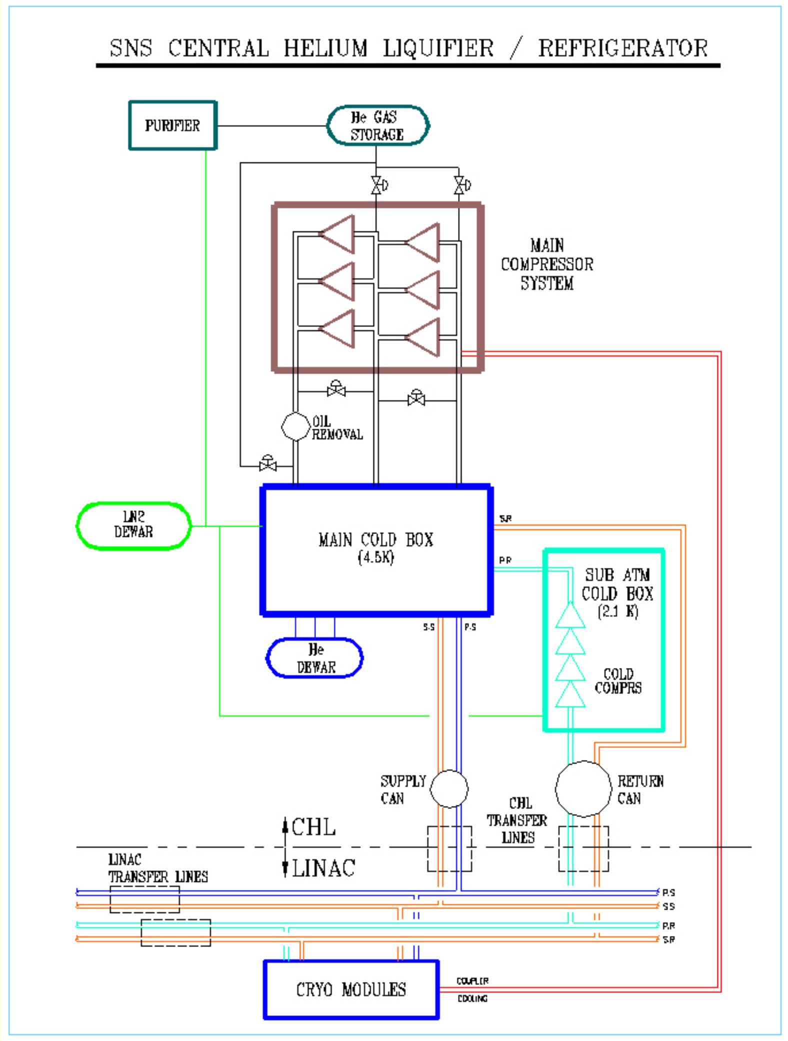
Optimal Operation of the Existing Helium Refrigeration Systems (Cont.)







Optimal Operation of the Existing Helium Refrigeration Systems (Cont.)



13. Some Areas of Interest for Future Developments

Variable system capacity operating modes with modulating pressures and with the appropriate gas management scheme should be implemented at other labs and helium system users in general. This already saved many MW of electric power for JLab, MSU, BNL and will be for SNS.

Software models for operating helium cryogenic systems (with the real components in the system) to help them operate close to the practically possible maximum efficiency for the actual operating load conditions

Some Areas of Interest for Future Developments (Cont.)

Bayonet design:

More and more labs are using bayonet type connections between the systems similar to the ones developed originally at FNAL. It has been proven many a times that the load from these components far exceeds the load estimates. The majority of the heat load estimates are based on pure longitudinal conduction and neglect the convective loops in the annular gap.

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Some Areas of Interest for Future Developments (Cont.)

Industry has used tight clearances or end seals to minimize this effect. It is also questionable how well the heat intercepts on these bayonets are anchoring the temperature or in fact, contributing to the overall load increase by setting up the convective loops.

Mass flow meter:

Develop a mass flow meter to measure the vapor flow from a load with very low pressure drop.

Some Areas of Interest for Future Developments (Cont.)

Screw compressor:

Test a screw compressor to establish the effect of built-in volume ratio on the pressure ratio and the efficiency for helium systems. Also establish the other process parameters like operating temperature for minimum input power and minimum maintenance.

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Some Areas of Interest for Future Developments (Cont.)

Expanders:

Develop turbo expanders which can utilize commercially available magnetic bearing technology and operate with a large pressure ratio and high efficiency.

Develop multi-cylinder reciprocating expansion system, which can utilize the mass produced parts from the auto industry.

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy
Office of Science
U.S. DEPARTMENT OF ENERGY

Some Areas of Interest for Future Developments (Cont.)

High efficiency small helium refrigerator / liquefier:

Develop a high efficiency small helium refrigerator / liquefier for labs (can be used for small 4.5K targets etc.) and universities

14. Conclusions

For new systems, develop the requirements very carefully while taking into consideration the load requirements including all of the anticipated transients and the practical strengths and weakness of the components chosen for the system.

Make sure the design goals are carried through the selection of all the components and into the detailed system design and are not skewed with perceived constraints.

If the end user does not understand the requirements or how to achieve them in the specification, it certainly can not be assumed that the vendor will provide it.

•

Conclusions (Cont.)

Hopefully these and other information will help you to design and operate cryogenic systems at optimal conditions and minimize the input power (the wasted natural resources) and feel good about your positive contributions.

Hope you saw the

“Need for understanding the fundamentals”

Conclusions (Cont.)

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

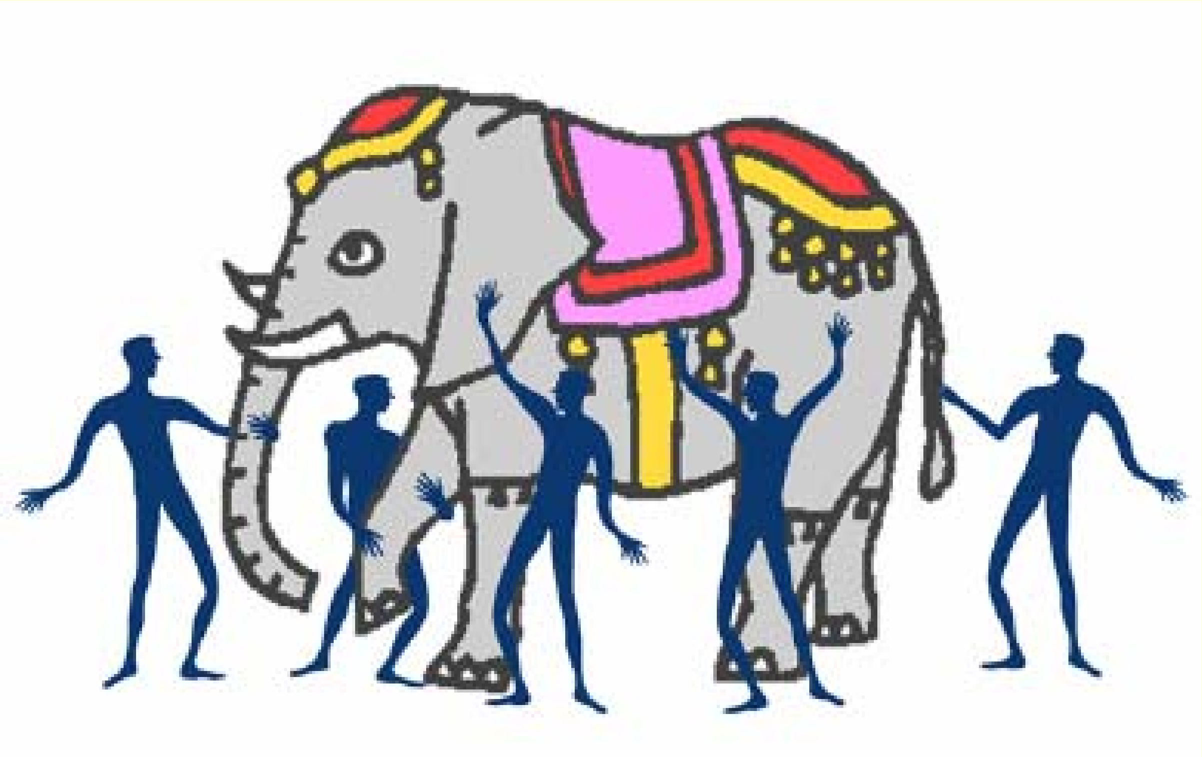
1) **Minimum operating cost**
2) **Minimum capital cost**
3) **Minimum maintenance cost**
4) **Maximum system capacity**
5) **Maximum availability of the system**

Or, A combination of some or all the above

Or, Some other factors?

What do you think?

Conclusions (Cont.)



Conclusions (Cont.)

My special thanks

to the members of JLab cryo department and especially to *Peter Knudsen* for helping me in developing these notes.

Thank you all

for showing the interest and hopefully you all sincerely participate in reducing the wasted natural resources.