Lecture 6
Refrigeration & Liquefaction

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Goals

- Introduce basic concepts of cryogenic refrigeration & liquefaction
- Describe the Carnot cycle
- Define Coefficient of Performance and Figure of Merit
- Describe practical helium refrigeration/liquefaction cycles
- Present examples of typical cryogenic refrigeration equipment

Introduction
How do we get things cold?

- In general, cooling is done by using a working fluid (in cryogenics this is almost always helium) and making it under go a closed thermodynamic cycle that removes heat at low temperature and rejects the heat at room temperature.
  - This process requires work
  - There are many thermodynamic cycles – we will only examine a few key ones
- Here we will concentrate of refrigeration systems of ~ 100 W or greater
  - Systems of less than ~ 100 W are known as cryocoolers and tend to use different cycles. These will be covered in a later lecture

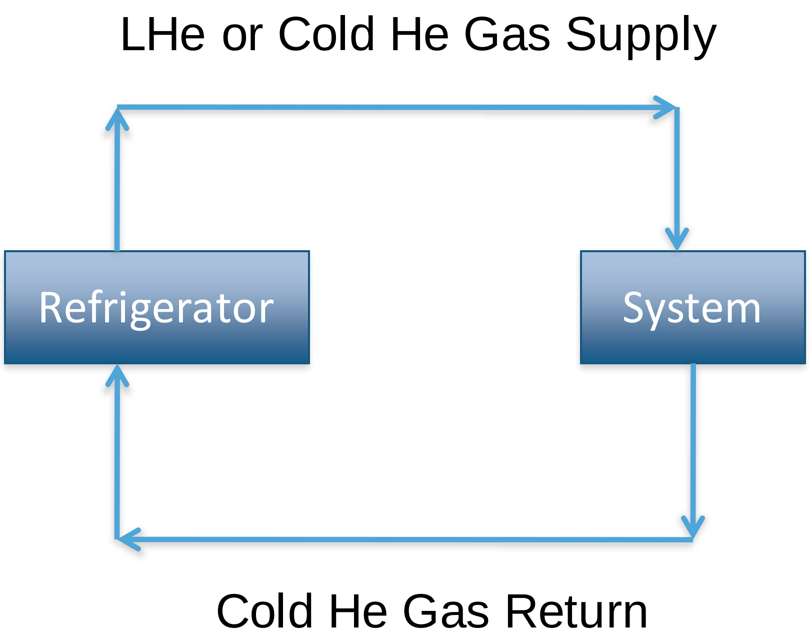
Introduction

- There are other approaches to cooling
  - Non cryogenic refrigeration e.g. home refrigerators, AC etc – not covered here
  - Very low temperature (<1.5 K) approaches : Magnetic refrigerators, adiabatic demagnetization refrigerators, dilution refrigerators etc – will be mentioned (at least) later
- Remember – no matter the technique, the Laws of Thermodynamics apply

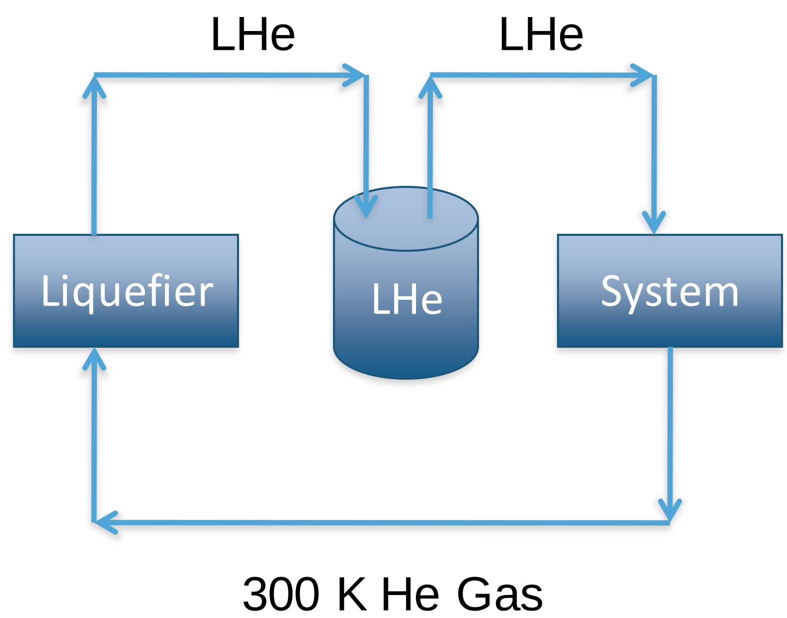
Refrigerators vs. Liquefiers

- Refrigerators are closed cycle systems
  - They provide cooling and can create liquids but all the mass flow is returned to the start of the cycle
  - Such systems are said to have "balanced flow"
- Liquefiers are open cycle systems
  - They provide a liquid which is then drawn off and used elsewhere
  - These have "unbalanced flows" the amount of mass returned to the start of the cycle is less than the amount that started by the mass that was converted to liquid.
  - In order to keep the cycle running this mass would have to be added as room temperature gas.

Refrigerators vs. Liquefiers



Closed Cycle Refrigerator



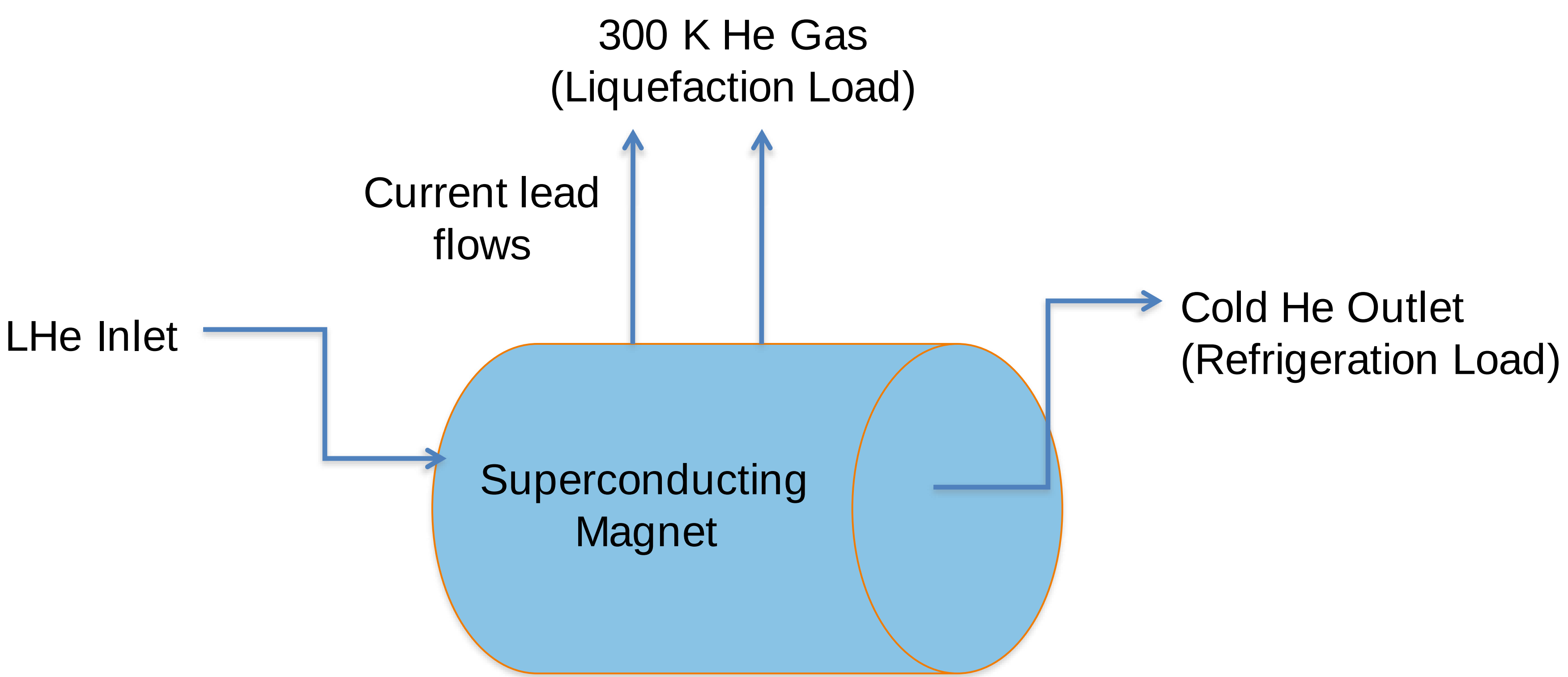
Open Cycle Liquefier

From Helium Cryogenics – Van Sciver

Refrigerators vs. Liquefiers

- In practice, this distinction is less clear cut
  - Modern cryogenic plants can operate either as refrigerators or liquefiers and in fact, generally operate as a mixture of the two.
  - We talk about refrigeration loads & liquefaction loads
  - A key issue is at what temperature is the boil off gas from a cryogenic liquid returned to the cycle?
    - If brought back at a cryogenic temperature and used to cool incoming warmer gas then this is a refrigeration load
    - If brought back warm and not used to cool incoming warmer gas this is a liquefaction load
- The thermodynamic rules are the same for refrigerators and liquefiers

Consider the cooling of a superconducting magnet and its current leads



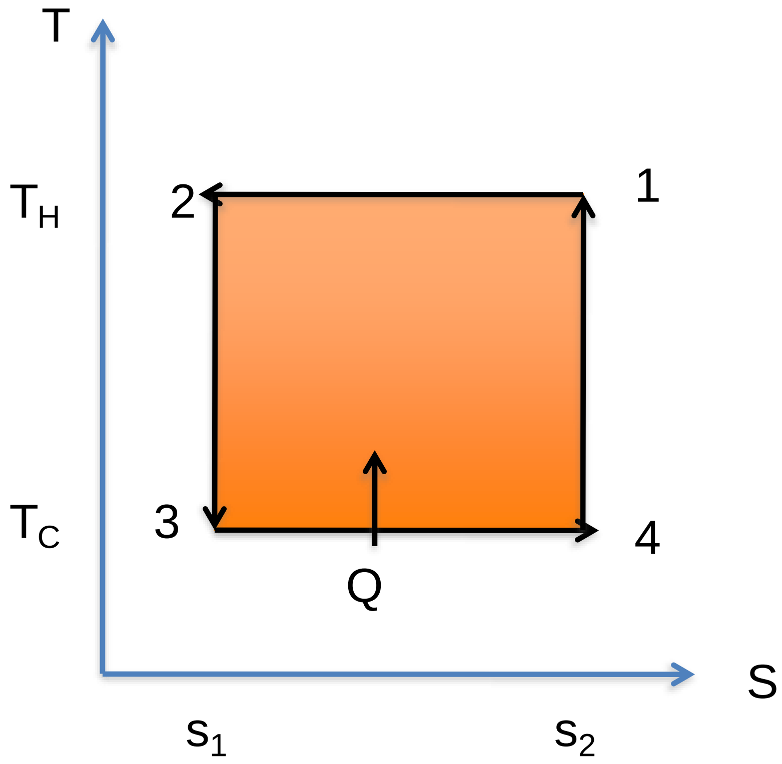
Catching Cold

- Before we get involved in thermodynamic cycles, let's go over the basics
- There are really only a few ways in which to make a pure fluid such as helium colder
  - Cause the fluid to do work by making it expand against a piston or turbine while keeping it thermally isolated from the outside environment Isentropic Expansion
  - Transfer heat from the fluid to a colder surface
  - Cause the fluid to do "internal work" by expanding it through a valve while keeping it thermally isolated Isenthalpic Expansion
    - Joule-Thomson expansion (more later)
  - Once the fluid is a liquid, reduce the pressure above the fluid below atmospheric pressure thus reducing the saturation temperature
- All modern cryogenic plants do the first 3. Ones that provide cooling below 4.2 K also do the last item

Carnot Cycle

- This is an ideal cycle: all processes are reversible
  - Entropy is only changed by absorbing or removing heat at constant temperature
  - 2nd law of Thermodynamics, in a reversible process dQ = -TdS
- The Carnot Consists of 4 steps
  - Compress the working fluid isothermally at T_H (1-2)
  - Expand the working fluid isentropically from T_H to T_C (2-3)
  - Absorb heat into the working fluid isothermally and reversibly at T_C (3-4)
  - Compress the working fluid isentropically from T_C to T_H (4-1)
  - Note isentropically = reversibly and adiabatically

Carnot Cycle



- How do we describe the performance of such a cycle?

Coefficient of Performance & the Carnot Cycle

- Coefficient of Performance: the heat absorbed from the cold sink divided by the net work required to remove this heat

$$\text{COP} = -\frac{Q_a}{W_{net}} = -\frac{\left(Q_a / m\right)}{\left(W_{net} / m\right)}$$

  – Minus sign takes into account that the heat absorbed by the cycle is positive while the work do is negative

- Since this is a closed cycle, the net work done is equal to the net heat transferred. Since this cycle completely reversible, the 2nd law gives the net heat transferred as:

$$Q_{net} = \oint mTds = 0 + mT_C(s_2 - s_1) + 0 + mT_H(s_1 - s_2)$$

Coefficient of Performance & the Carnot Cycle

- Thus $$Q_{net}/m = W_{net}/m = -(T_H - T_C)(s_2 - s_1)$$

- Again from the 2nd Law:

$$Q_a/m = T_C\left(s_2 - s_1\right)$$

- Thus, for the Carnot cycle the COP may be written as:

$$COP = -Q_a/W_{net} = \frac{T_C}{T_H - T_C}$$

  – For the Carnot cycle the COP is dependent only on the temperatures

Coefficient of Performance & the Carnot Cycle

- For a plant operating between room 300 K and 4.2 K, the Carnot COP is

4.2/(300 – 4.2) or 0.0142

- The Carnot cycle is the ideal case. It is the best you can do without violating the laws of thermodynamics
- Note that the form of the Carnot COP shows that you have a better COP (thus a more efficient process or refrigerator) if T_C is large
  - It is always thermodynamically more efficient to intercept heat (provide cooling) at higher temperatures
  - This fact drives a lot of cryogenic design
- In practice, we generally discuss the inverse of the COP because this allows us to describe the number of watts of work required to provide 1 Watt of cooling at a given temperature. For a Carnot cycle providing cooling at 4.2 K. This is **70 W/W**
  - People will frequently and incorrectly refer to this as a COP as well

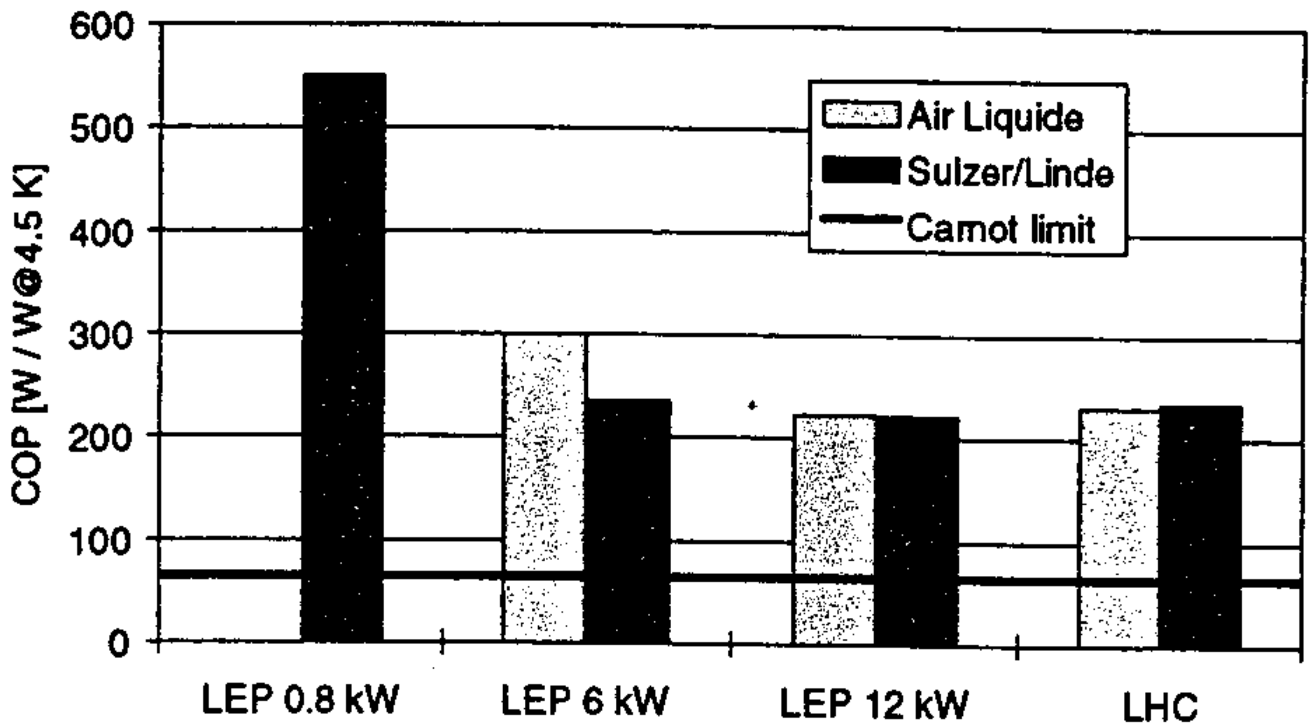
Carnot Cycles & the Real World

- Can we build a real machine using a Carnot cycle?
  - In a word NO
- Why?
  - Compressing a fluid isothermally is very hard to achieve, Normally the fluid is compressed and then cooled back down to 300 K
  - Expanding or compressing fluid isentropically is basically impossible
  - We can absorb heat into a boiling fluid isothermally but not with out irreversible losses
- How close can we get to Carnot? We define the Figure of Merit (FOM) as:

$$FOM = \frac{COP}{COP_{Carnot}}$$

We also speak in terms of "percent Carnot" i.e. FOM of 0.2 is 20% Carnot

The real world is sometimes not kind to cryogenic engineers



- These are state of the art helium refrigerators. Note that the best of them (for LHC) runs at about 220 W/W or a FOM of 0.318 or at 32% Carnot

Practical Impact of Plant Performance

- How much power does it take to operate a large cryogenic refrigeration plant?
- AT ESS we have a refrigeration plant capable of removing as much as 9 kW at 4.5 K. The FOM of the plant is measured to be expected to be 0.25

If the plant operates as expected this means we will need:

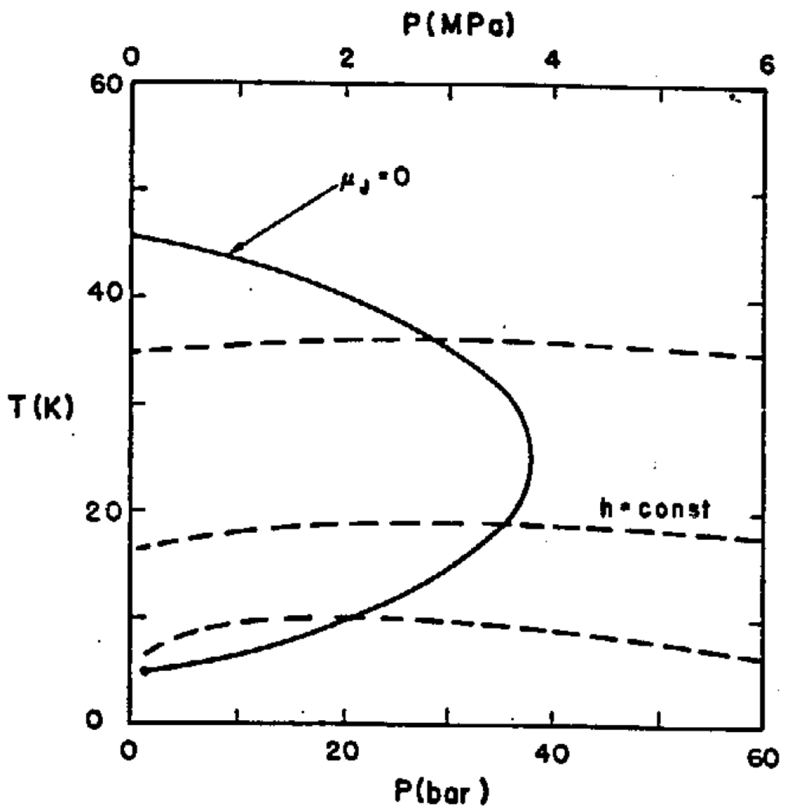
(66/0.25) x 9000 = 2.4 MW of mechanical power

- We added some additional margin to the electrical power requirements and have at least 2.6 MW available for powering the compressors

Joule-Thomson Expansion

- Isenthalpic (h=constant) expansion
- Fluid cools as is it is expanded at constant enthalpy through a valve
- However, depending on both the fluid and the temperature, such an expansion can also cause heating.
- Define the Joule-Thomson expansion coefficient $\mu_j \equiv \left(\frac{\partial T}{\partial P} \right)_h$
- μ_j must be positive for cooling to occur
- Cooling by JT expansion has some advantages
  - No moving parts
  - Can easily handle two-phase mixtures

JT Inversion Curve & Maximum Inversion Temperatures

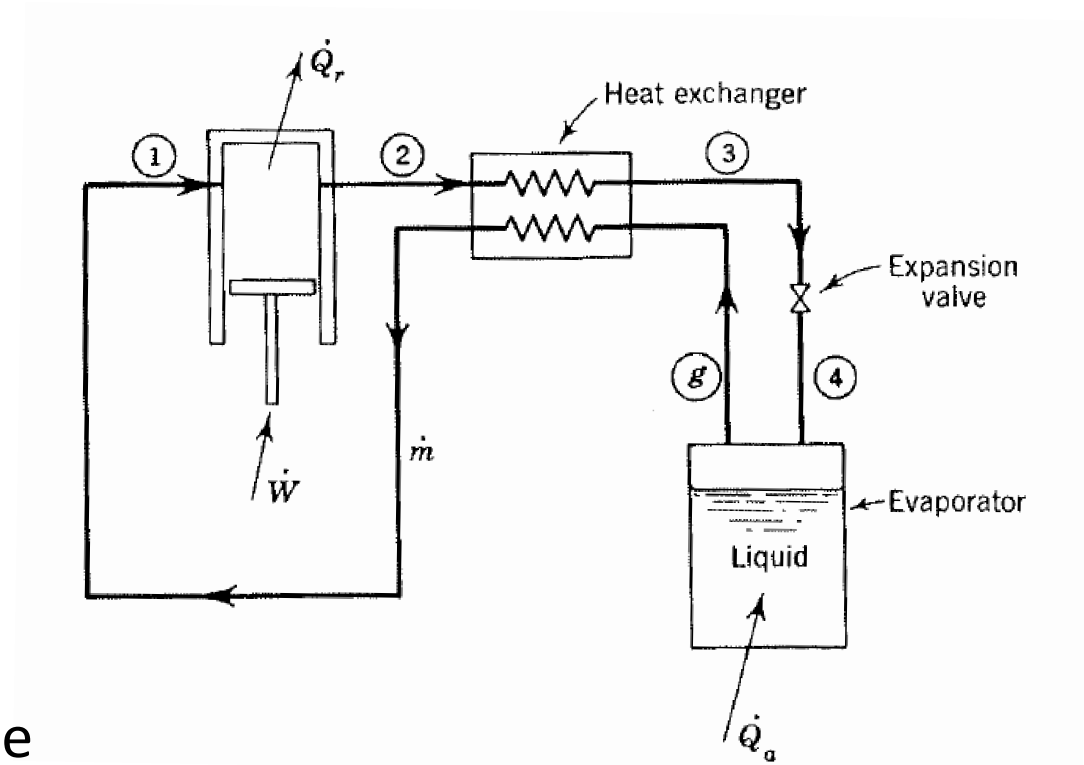


Inversion curve for Helium

Fluid	Max Inversion Temperature (K)
Nitrogen	623
Argon	723
Hydrogen	202
He	43

- Maximum inversion temperature for helium is 43 K
- Note that below ~ 2 K He again warms on JT expansion
- Many fluids, such as N_2 can be liquefied using JT expansion – JT cycle

Joule-Thomson Refrigerator



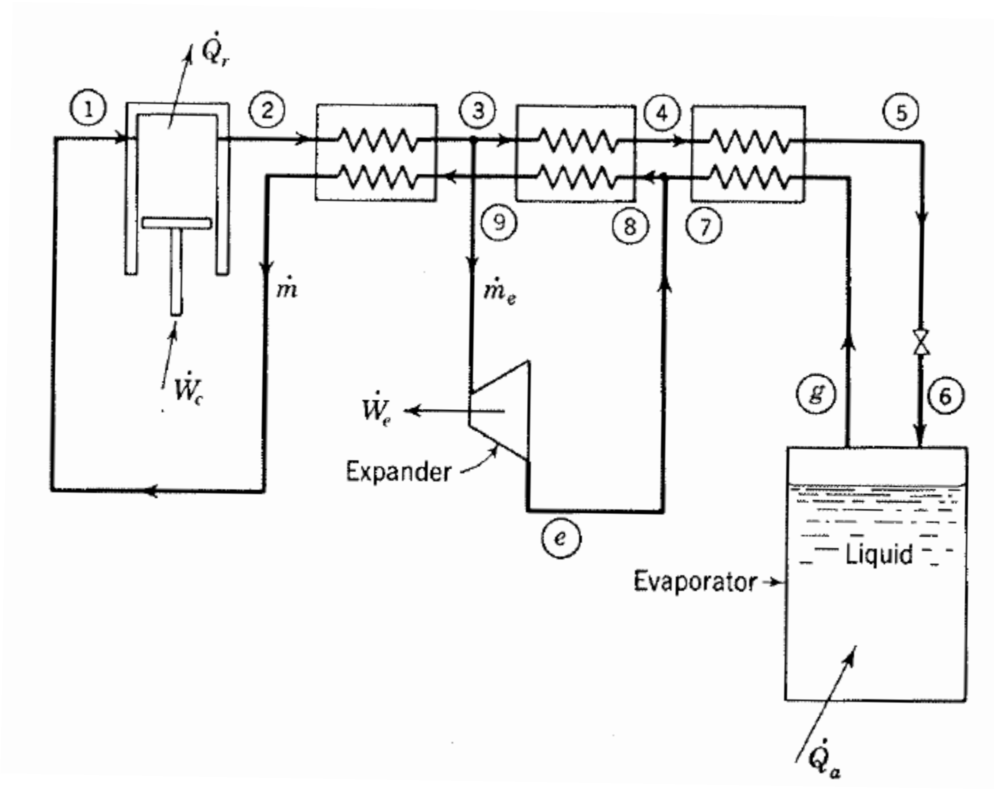
From Cryogenic Systems
R. Barron

- Simple
- Mainly used for cryocoolers (more later) and not for large plants
- Also known as a Linde-Hampson Refrigerator

Practical Large Scale Helium Refrigerators (at last)

- Modern large scale helium refrigerators/liquefiers use a variation of the Claude cycle known as the Collins cycle
- The key difference between these cycles and the JT cycle is the addition of expansion engines (pistons or turbines) that the fluid does work against and thus cools
- The process through these expansion engines may be idealized as Isentropic (s = constant) expansion
  - Cooling occurs at any temperature
  - ΔT for a given ΔP is much larger than for isenthalpic expansion
- Claude cycle = 1 expansion engine, Collins cycle = multiple expansion engines
  - The post WW II development of the Collins liquefier revolutionized laboratory research in cryogenics

Claude Cycle



From Cryogenic Systems
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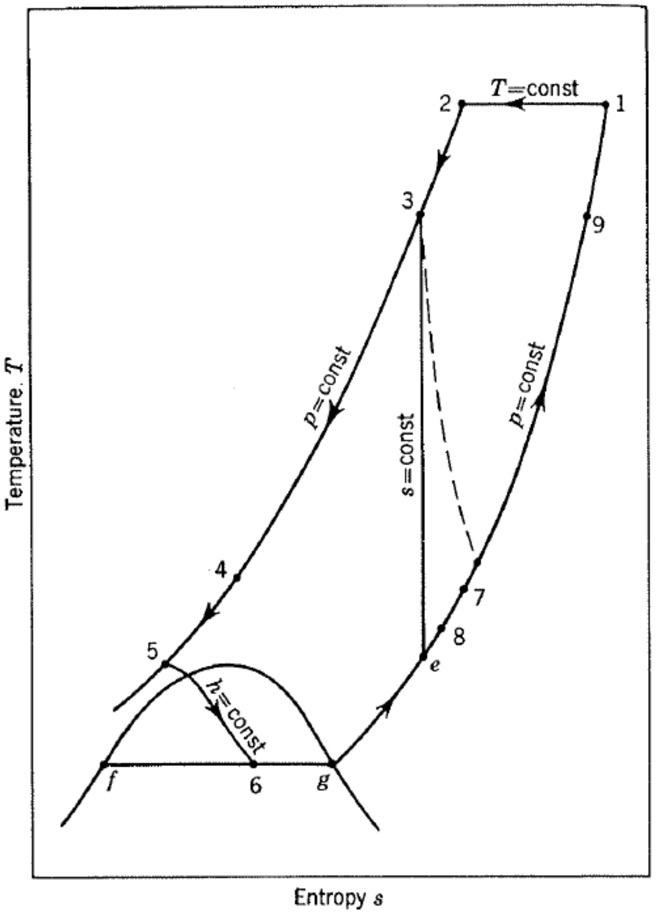

Collins Cycle

- Cycle consists of :

1) Compression to ~ 16 Bar with cooling back to 300 K + oil removal
2) Cooling of high pressure gas with LN_2 or expansion turbine flow
3) Isentropic expansion via 2 or more expansion turbines
4) Cooling of high pressure gas by the cold returning low pressure stream
5) Isenthalpic expansion through JT valve
6) Return of gas to compressors at just above 1 Bar

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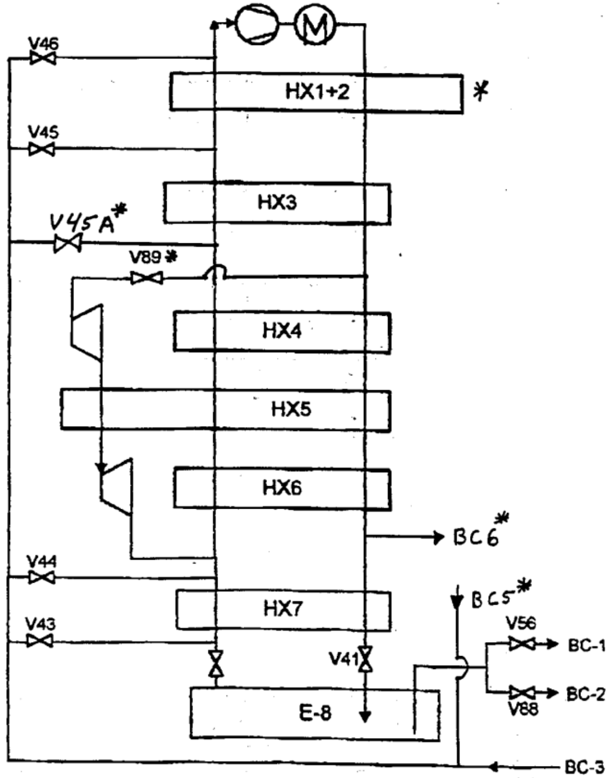
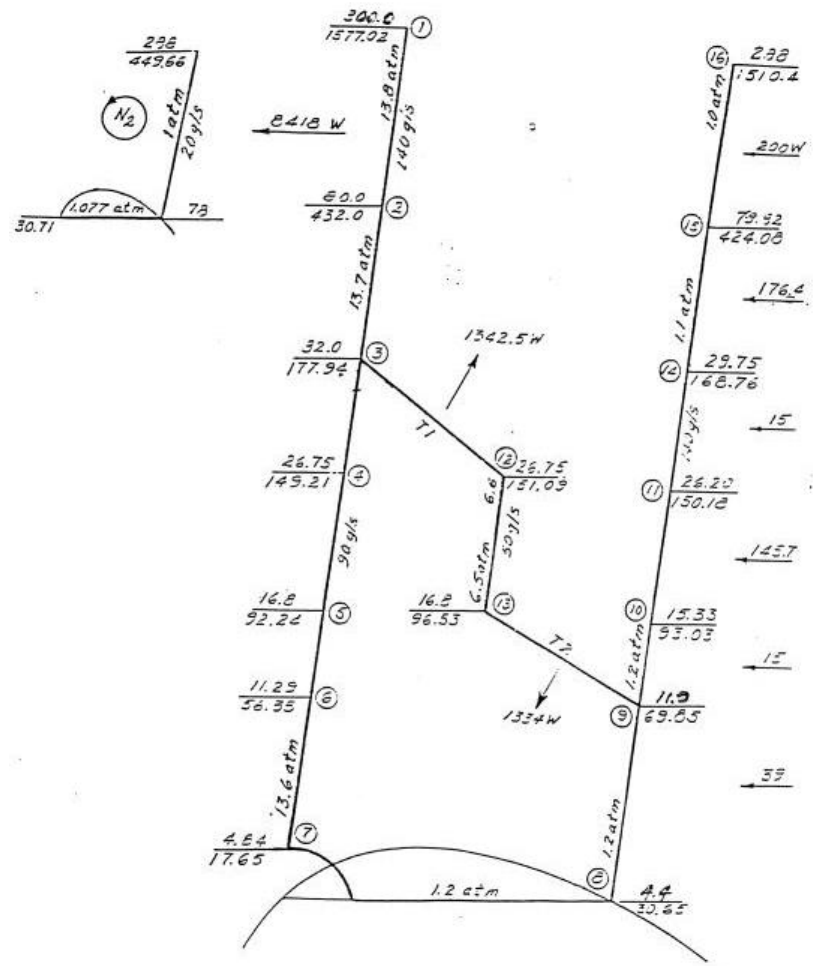
CTI 4000 Refrigerator (early 80's vintage ~ 1.2 kW @ 4.5 K)

EUROPEAN SPALLATION SOURCE

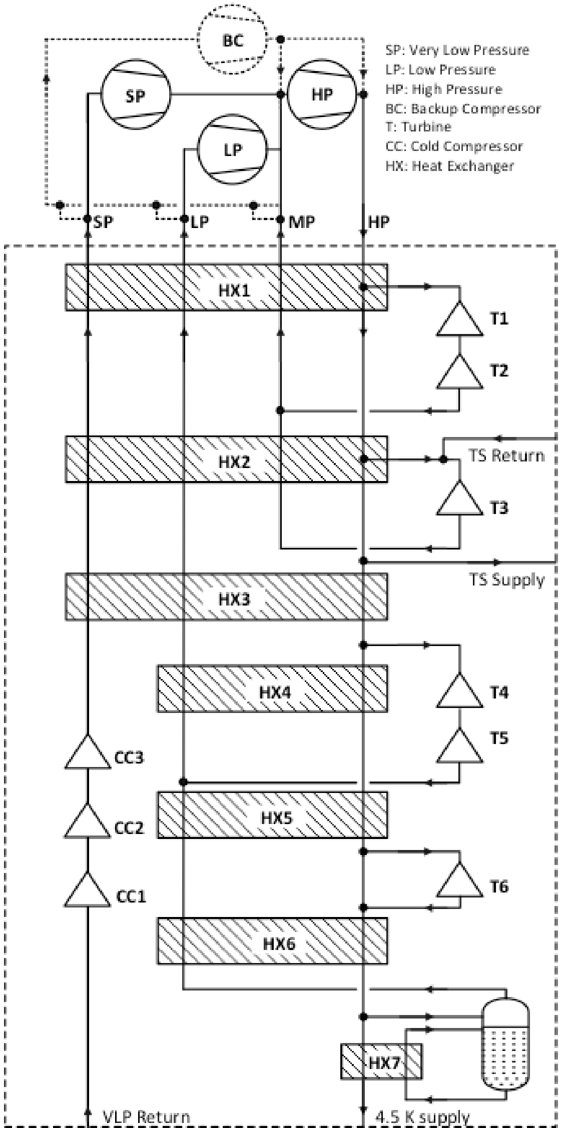


CTI 4000 Upgrade 12 / 2 / 99

* Indicates new or changed component



ESS Accelerator Cryoplant (2016) up to 3 kW cooling at 2 K



Note:

1)No LN_2 Precooling

2)Large number of expansion turbines – some in series with HP stream

3) Intermediate temperature shield cooling

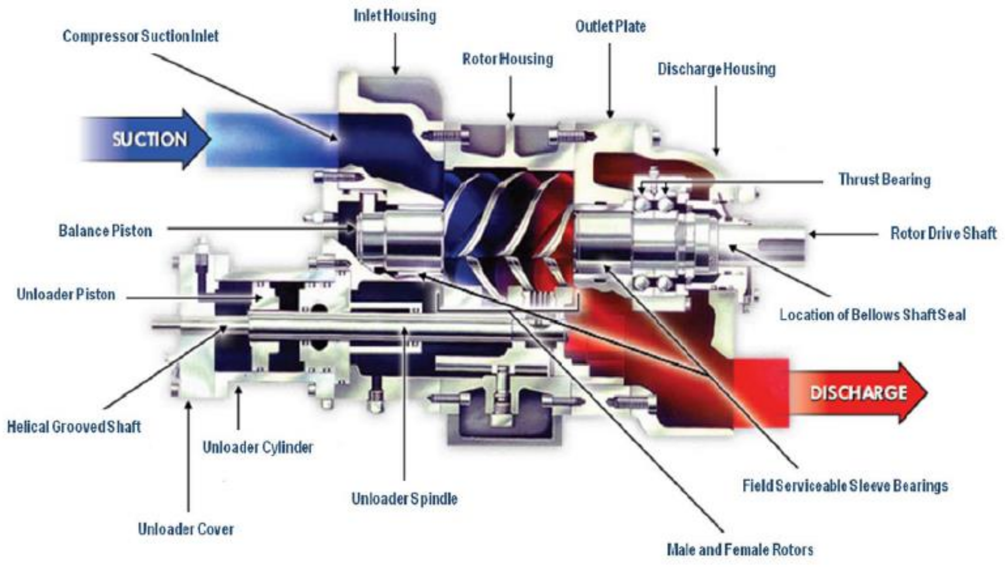
4) Medium pressure return

5) Last stage of subatmospheric pumping is warm

System uses 3 cold compressors + 1 warm sub-atmospheric compressor for 2 K cooling

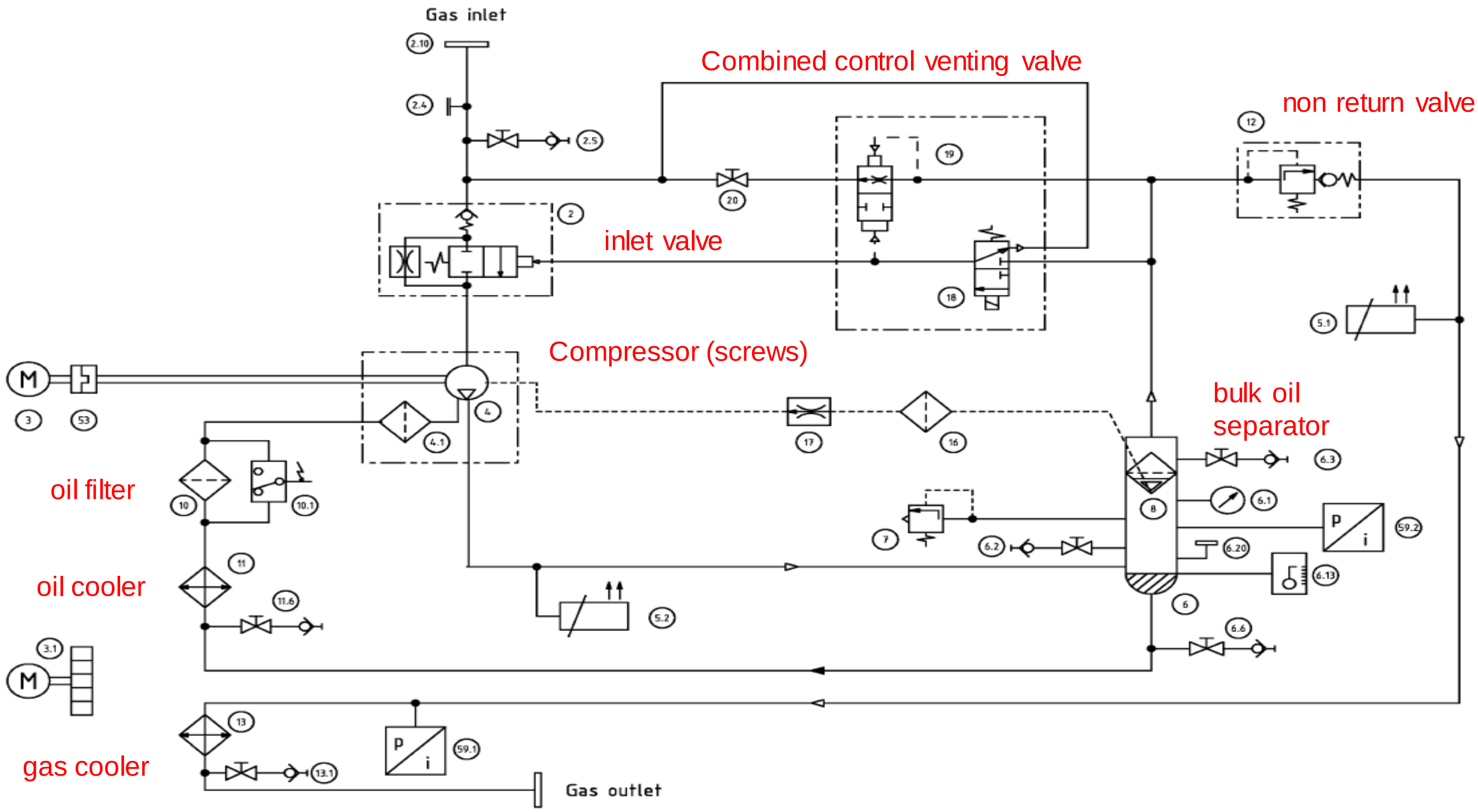
Major Components of a Helium Refrigeration Plant

- Helium Screw Compressors
  - Operate at room temperature
  - Are oil flooded – compress a mixture of He gas and special oil
  - Require water cooling to remove heat due to compression
  - Vast majority of power goes here
  - We expect the largest compressors at ESS to use 1.2MW motors



From Dunham Bush Co.

Schematic of a Helium Compressor

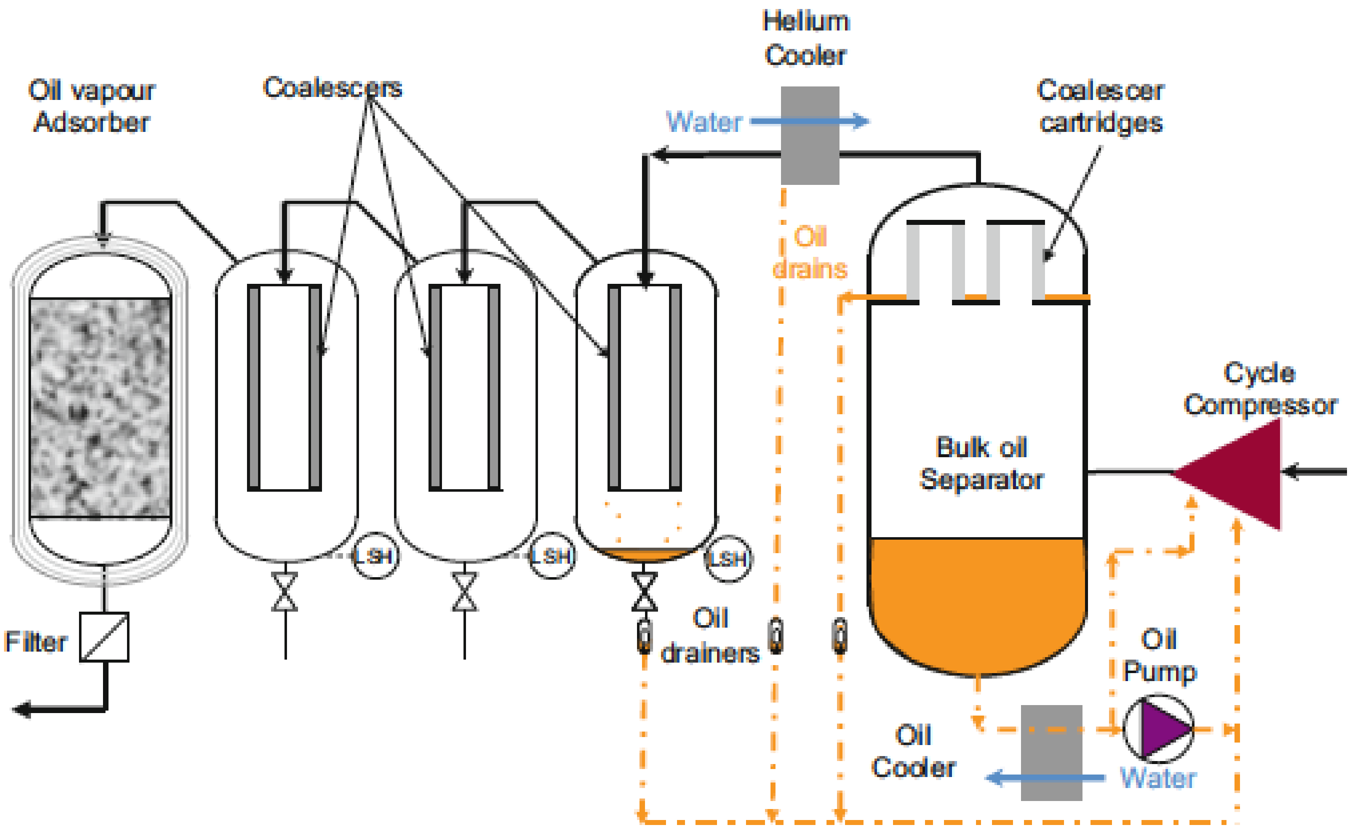


Courtesy Linde/Kaeser

Major Components of a Helium Refrigeration Plant

- Oil Removal Systems
  - Removes oil down to the ppb level – critical for proper operation of the plant
  - Bulk Oil Separators: should reduce level down to < than 250 ppm
  - Coalescers: two or more in series reduce oil level down to < 10 ppm
  - Absorbers:
    - contain activated charcoal
    - Are redundant
    - Reduces level down to < 1 ppb
    - Can be regenerated via warm $N_{2\ gas}$

Typical Oil Separation System
(from G. Gistau Cryogenic Helium Refrigeration)

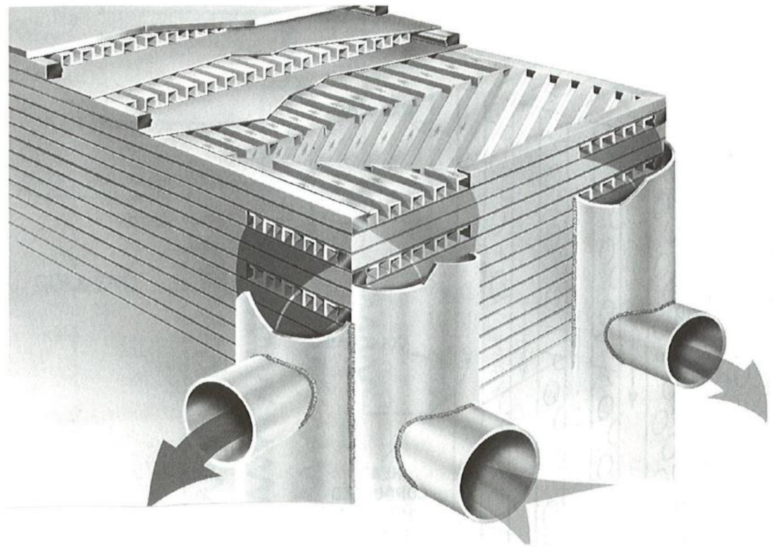


ESS ACCP Compressor System

TMCP Warm Compressor and Oil Removal Skids in Compressor Hall

Brazed Plate Fin Heat Exchangers

- All aluminum
- Vacuum brazed
- Very compact
- High efficiency
- Can handle multiple streams
- Standard for cryogenic plants



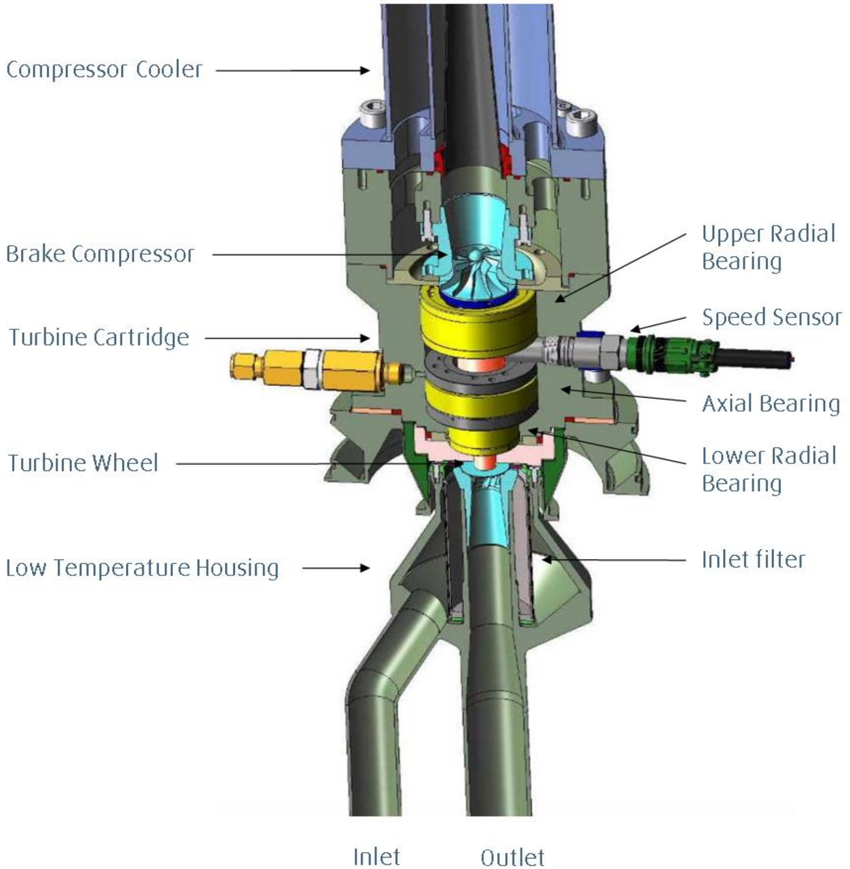
From The Handbook of Cryogenic Engineering

Courtesy Linde

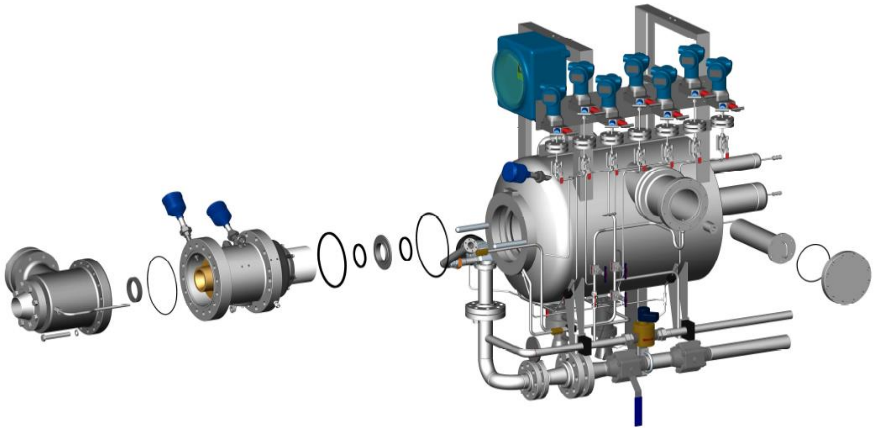
Expansion Turbines

- One of the key technologies for cryogenic plants
- Proprietary designs resulting from a significant amount of R&D
- Modern ones are quite reliable
- Water cooling is generally required to absorb work at room temperature
- May operate at speeds up to 120,000 rpm
- Two primary suppliers: Air Liquide and Linde

Examples of Expansion Turbines

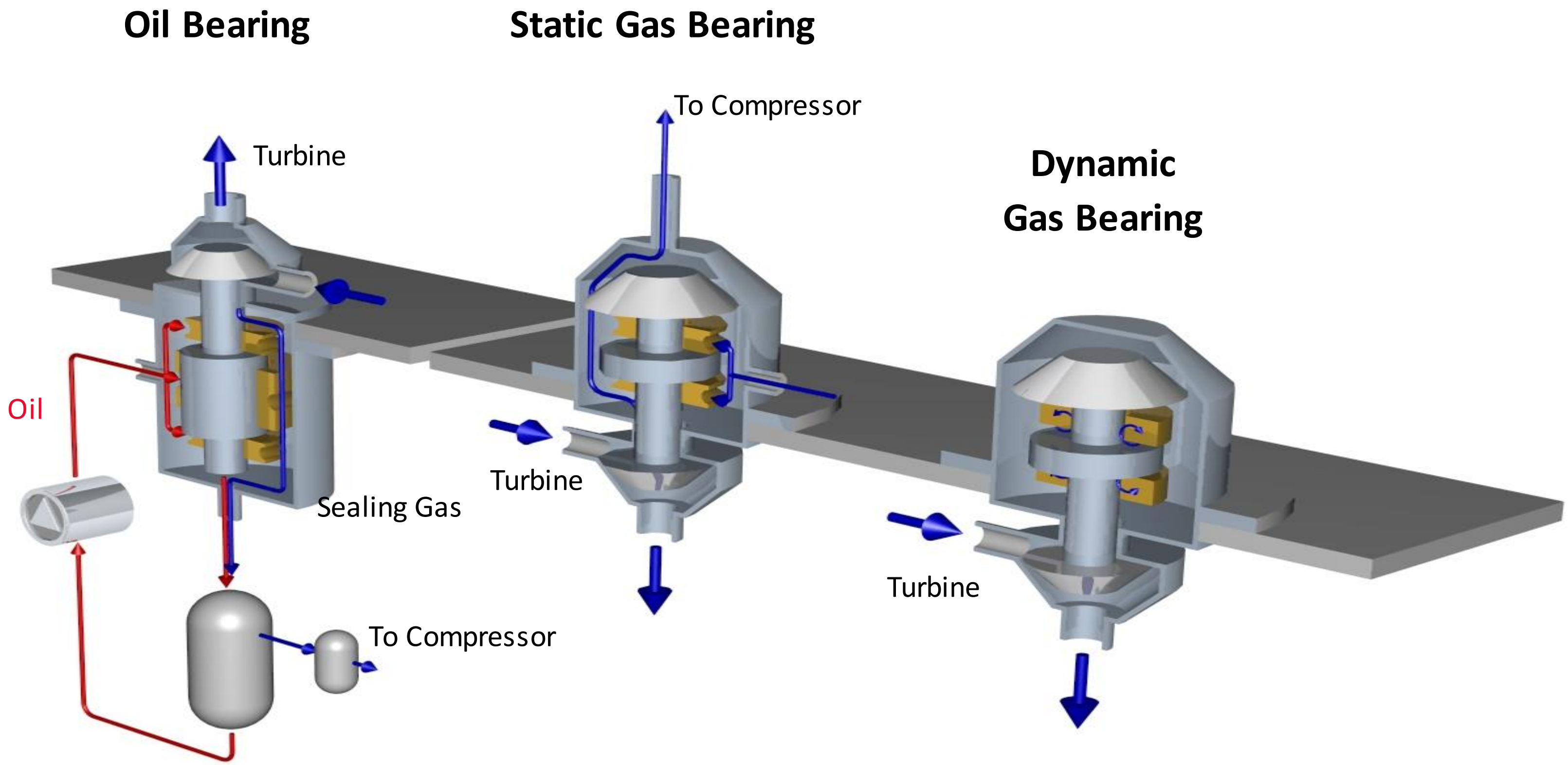


Courtesy Linde



Courtesy Air Liquide

Expansion Turbine Bearing Options (Gas bearings are the most common now)

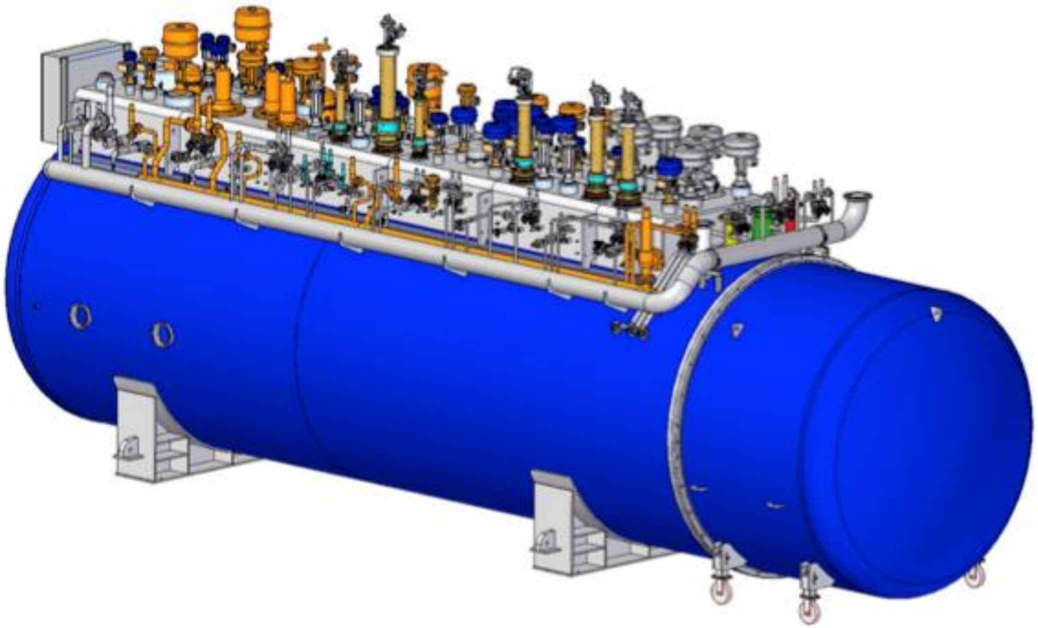


Courtesy Linde

Major Components of a Helium Refrigeration Plant

- Cold Box
  - Contains cryogenic components
    - Heat exchangers
    - Valves
    - Expansion Turbines
    - Piping
    - Vacuum insulated

Accelerator Cryoplant Cold Box



One Coldbox comprising 6 expansion turbines, 3 cold compressors, built-in acceptance test equipment

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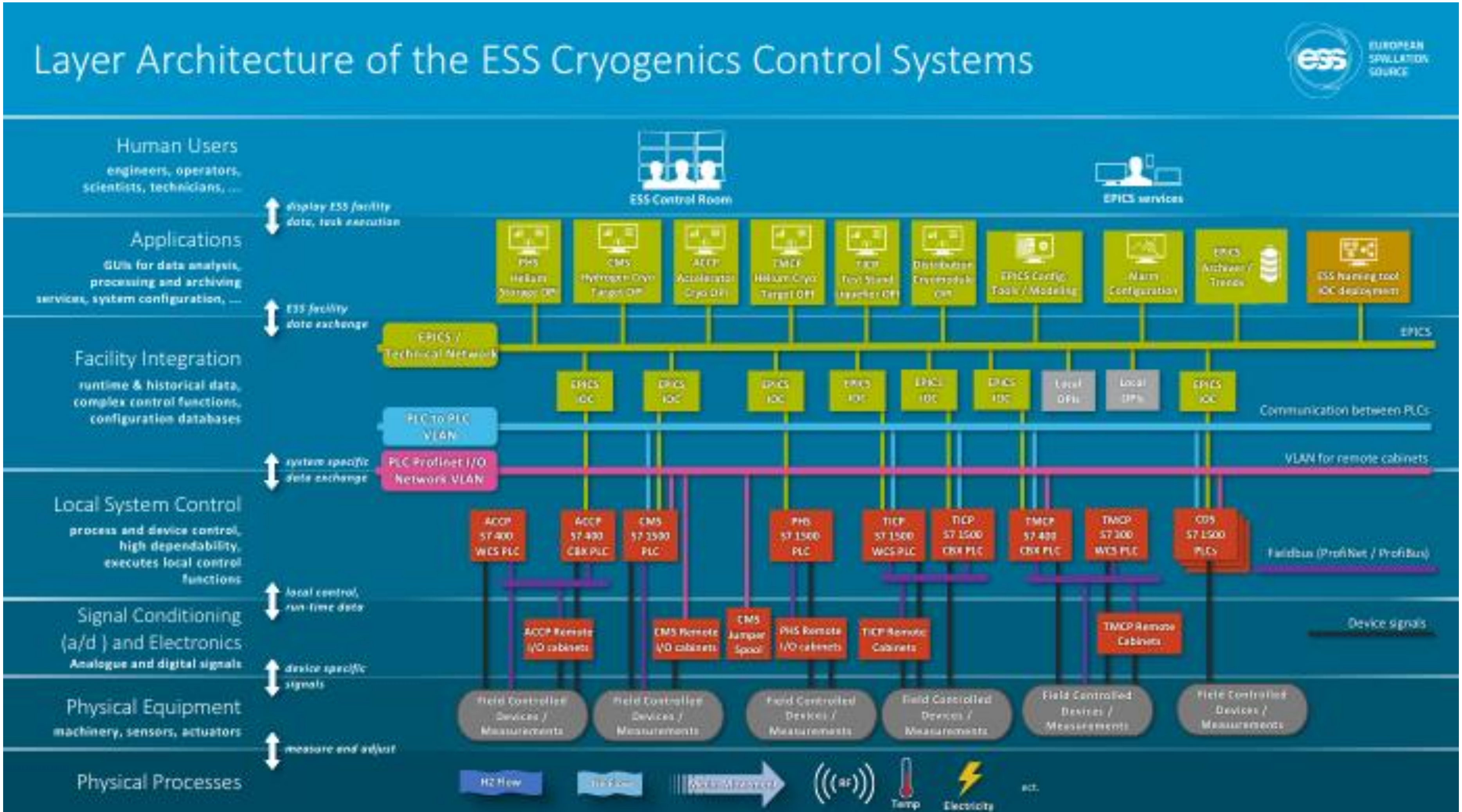
ESS Cold Boxes
Accelerator Cryoplant (Right) 3 kW @ 2 K
Target Moderator Cryoplant (Left) 30.3 kW @ 16 K

EUROPEAN SPALLATION SOURCE

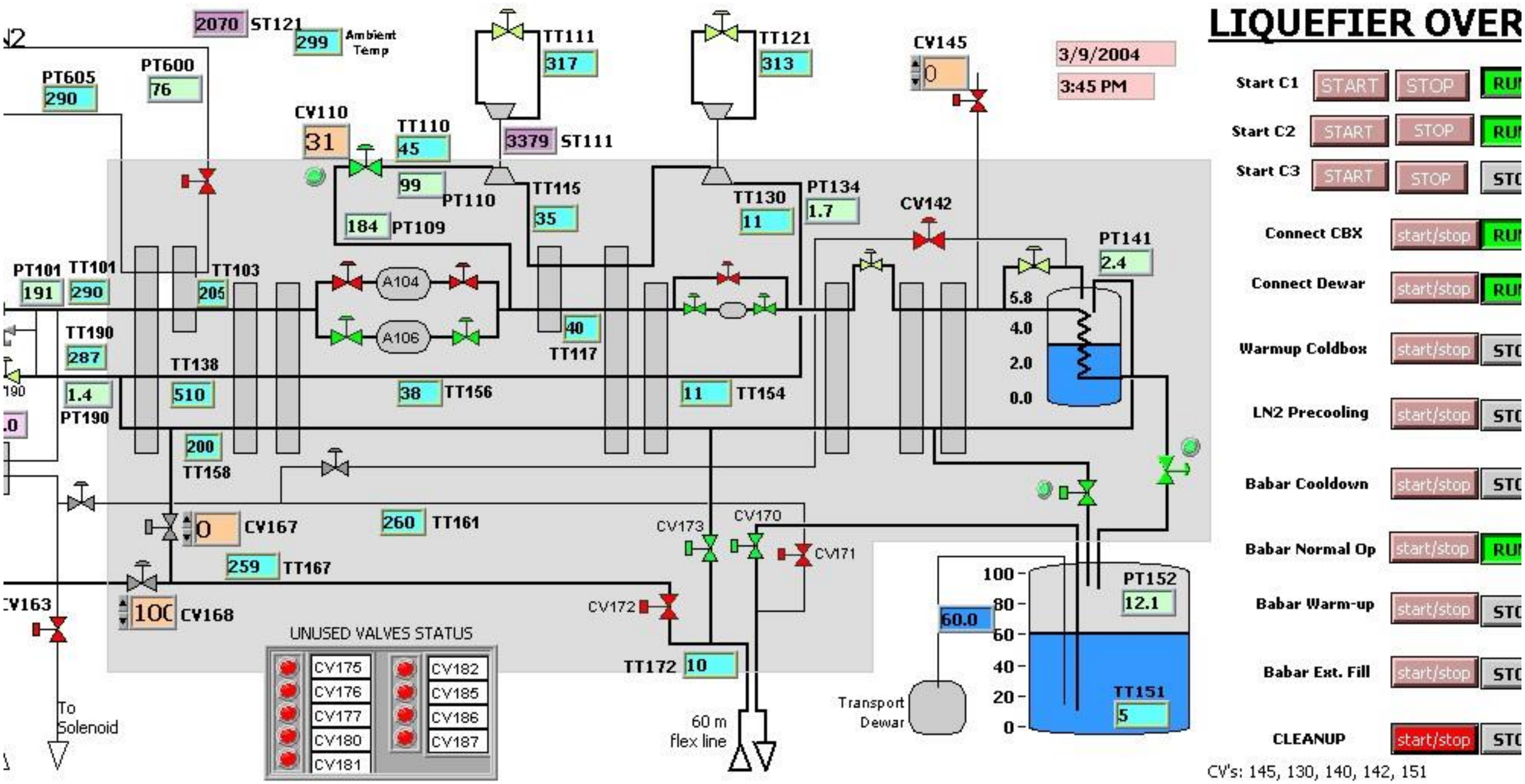
Major Components of a Helium Refrigeration Plant

- Main Distribution Box
  - Connects refrigeration plant with the distribution lines
- Storage vessels (LN2, LHe, GHe)
- Purifier: separate system that removes impurities from the helium space of the cryogenic system, including piping and items being cooled
  - Contamination control is very important to reliable operation
- Control System
  - Generally PLC based with a higher level HMI
  - Once fully commissioned, modern Helium refrigeration plants can operate autonomously 24/7

Typical Modern Cryogenic Controls System



BaBar Liquefier Control Screen
SLAC



Sizing of Cryoplants and Margin

- Given the long lead time in ordering and commissioning large cryoplants you may need to place the order or start design (if done in house) prior to knowing all the cryogenic loads.
- AT ESS we used the following to determine needed capacity
- $$C = F_o\,(F_{ud}\,Q_d + Q_b + F_{us}\,Q_s)$$
- C is the total capacity of the plant at a given temperature
- F_o is the operational safety factor. This value sets to 1.15 gives us some margin within which to control the plant as well as providing some margin for suboptimal plant performance
- F_{ud} is the safety factor for the dynamic heat loads associated with the superconducting RF (SRF) cavities. In the case of the ACCP, this value is set to 1.0 as the SRF cavity head loads are calculated assuming a fairly poor performing cavity. That is, the safety factor is already built into the estimated cavity dynamic heat load.
- Q_d is the SRF cavity dynamic heat load.
- Q_b is the heat load caused by beam losses in the accelerator. This is fixed at 1 W/m. The accelerator is not allowed to operate at higher beam losses and thus no additional safety factor is required
- F_{us} is the safety factor associated with static heat loads. This is set at 1.5. (it typically is between 1.5 – 2 depending on design maturity)
- Q_s is the static heat load

Best Practices for Cryplant Procurement

- Start early
- Optimize the overall cryogenic system and use this to define cryoplant requirements
  - Include safety venting and off nominal operations at the start of design
- Consider the use of industry studies to aid in the development of specfcations
- Put proper effort into development of technical specifications
  - Use previous specifications as models
  - Review by outside experts

Best Practices For Cryoplant Procurement

- Work closely with vendor during design, construction, installation and commissioning
  - Reviews
  - Participation of technicians in commissioning
  - Build up in house staff early to allow for this approach
- Keep in mind effort and time needed to optimize control systems
- Consider computer simulation of the final system to try out operating strategies, response to upsets etc.
- Don't underestimate the complexity of the warm portion of the He system