Lecture 7
Thermal Insulation & Cryostat Basics

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Goals

- Introduce conduction, convection & radiation heat transfer as they apply to cryogenics
- Describe design techniques to reduce heat transfer into cryogenic devices
- Allow the estimating and scaling of heat leaks into cryogenic devices
- Discuss the basics of cryostat design
- Warning! Not a full description of heat transfer
  - Many topics (boiling, detailed convection calculations, complicated geometries in radiation heat transfer etc) won't be covered
  - Should, however, be a good example of how heat transfer theory can be applied to practical problems.

Three Ways to Transfer Heat

- Conduction
  - Heat transfer through solid material
- Convection
  - Heat transfer via a moving fluid
    - Natural or free convection – motion caused by gravity (i.e. density changes)
    - Forced – motion caused by external force such as a pump
- Radiation
  - Heat transferred by electromagnetic radiation/photons
- There is no such thing as a perfect insulator – though we can design systems with very small heat leaks
- All matter above 0 K radiate heat
  - Remember we can't get to 0 K – 3rd Law of Thermodynamics though we can get vanishingly close
- Heat flows from high temperature to low
  - Heat leaks in, cold doesn't leak out

Conduction Heat Transfer

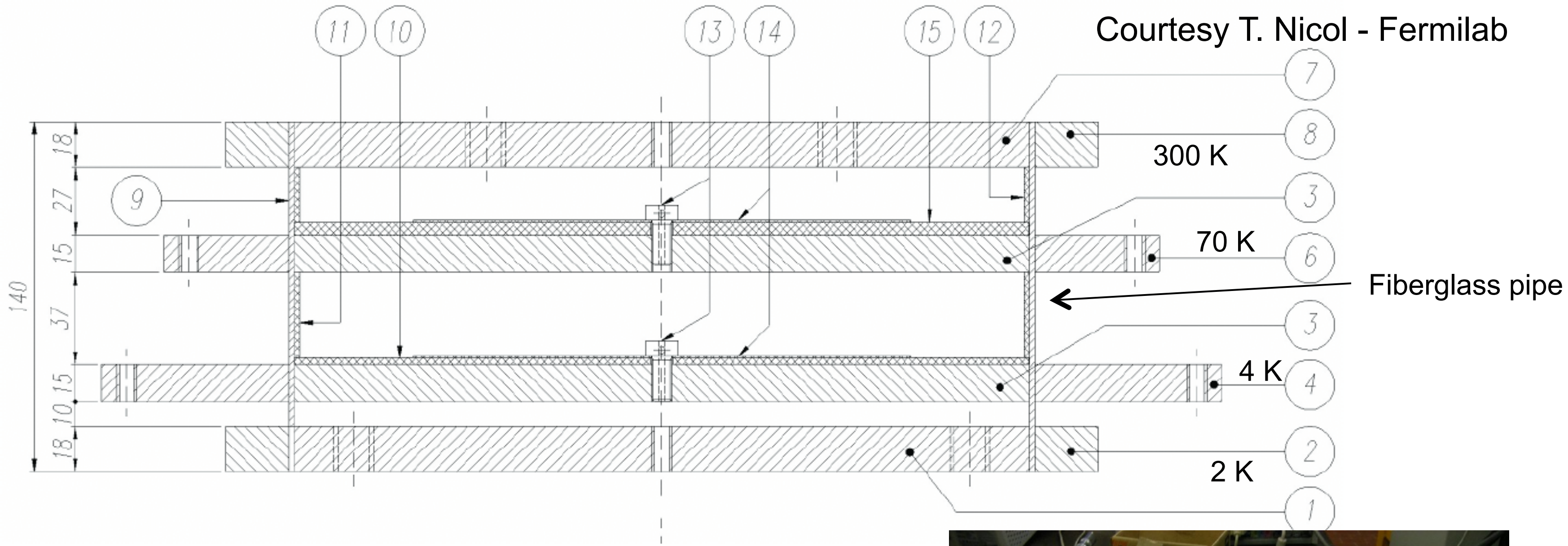
- Fundamental Equation – The Fourier Law in one dimension

$$Q = -K(T)A(x)\frac{\partial T}{\partial x}$$

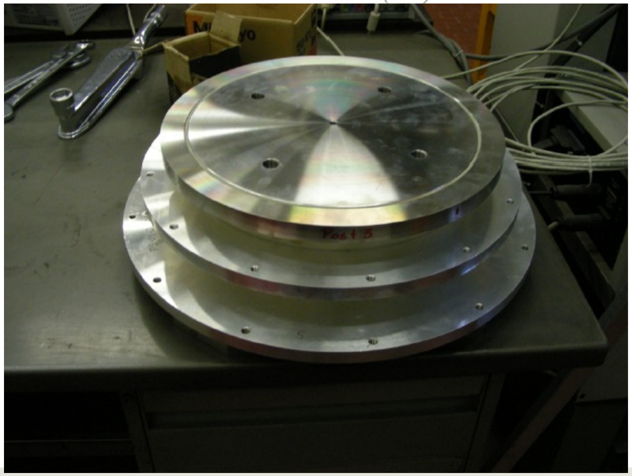
- If we assume constant cross section we get: $$Q = -A/L\int_{T_C}^{T_H} K(T)\,dT$$

- Reduce conduction heat leak by:
  - Low conductivity material: make K(T) small
  - Reduce cross sectional area: make A small
  - Increase length: make L large
  - For a given T_C make T_H smaller: i.e. use intermediate temperature heat intercepts
    - » You still have heat leak from 300 K to this intermediate temperature but remember Carnot, It's more thermodynamically efficient to remove heat at higher temperatures

Design Example
ILC Cryomodule Support Post



Courtesy T. Nicol - Fermilab



- Total Heat Leak (conduction & radiation)
  - 70 K - 10.5 W
  - 5 K - 0.9 W
  - 2 K - 0.03 W
- Can support up to 50 kN

Conduction Heat Transfer

- Conduction heat leaks may be estimated by the use of Thermal Conductivity Integrals (Lecture 4)

$$Q = -G(\theta_1 - \theta_2)$$

Convection Heat Transfer

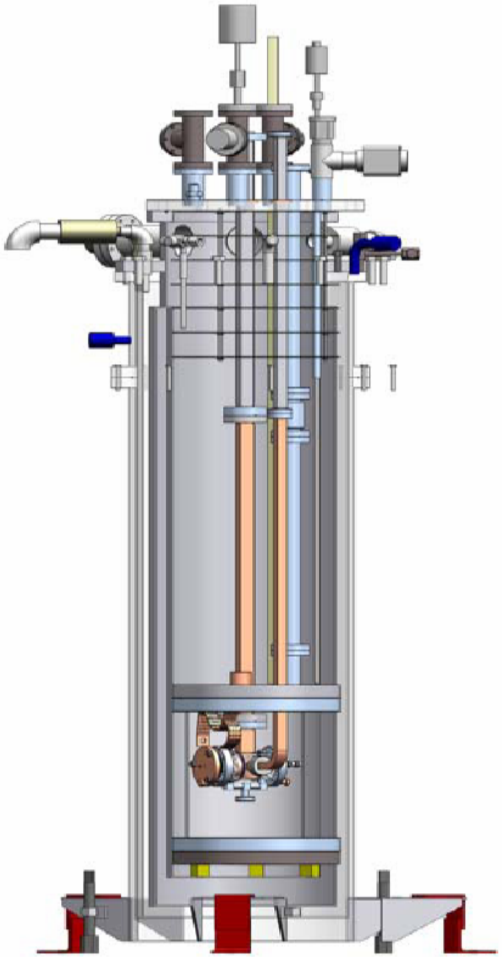
- Fundamental Equation: Newton's law of cooling

$$Q = hA(T_{surface} - T_{fluid})$$

where h is the heat transfer coefficient and is a function of Re, Pr, geometry etc depending on the situation

- In cryogenics we eliminate convection heat leak in cryogenic systems by "simply" eliminating the fluid – vacuum insulation
- Using vacuum insulation to create vessels capable of storing cryogenic liquids was first done by James Dewar – who liquefied hydrogen
  - Such vessels are frequently called dewars – though not always, more later
  - Thermos bottles are a simple example of this approach

Design Example
Vacuum Insulated Test Cryostat



- Contains 3 Vacuum Spaces
  - 1 between 300 K wall and LN_2 bath
  - 1 between LN_2 bath and LHe bath
  - 1 between LHe bath and experiment

Vacuum Insulation

- How much vacuum is enough?
  - This of course depends on the heat leak requirements but generally we want to be below 10^{-5} torr If we maintain this level or better we can generally neglect the convection heat leak for most applications.
    - » Cryogenic Engineering, Flynn (1997) has a good discussion of calculating heat leak due to residual gas pressure
- Cryopumping
  - At cryogenic temperatures almost all common gases condense and freeze onto the cold surface. Typically, we'll see that once surface are cooled to ~ 77 K the isolation vacuum will drop to the 10^{-8} torr or better range if the system is leak tight and doesn't have significant outgassing
  - But don't just start cooling with everything at room pressure
    - » Heat leak will likely be too high
    - » Safety hazards due to enrichment of LOX on cold surfaces
    - » Large amounts of condensed gases in vacuum space can lead to other problems including rapid pressure rise upon warming and possible solid conduction
    - » Best practice is to be at least 10^{-3} torr before cooling, lower pressures are better but there may be operational tradeoffs

Outgassing and Getters

- All material outgas into a vacuum. This can raise the pressure in a sealed vacuum space
- Reduce outgassing by:
  - Minimize amount of polymers, wire insulation, FRP etc – difficult
  - Keep vacuum surfaces as clean as possible. Remove any oil or cutting fluid, wear gloves etc.
- Getters: materials inserted into vacuum spaces to remove residual gas at low pressures
- In cryogenic systems, getters may be useful in removing residual gas and passively managing small leaks

Outgassing and Getters

- 3 types of getters
  - Adsorbers –gas bonds to surface
    - Activated charcoal, silica gel
    - Effectiveness increases with decreasing temperature – good for cryogenic systems
  - Chemical getters – chemical reaction between material and gas
    - Ba & other Alkali metals – not very common in cryogenics
  - Solution or absorber getters – gas is absorbed in interstitial space of metals
    - Ti, Zr, Th works well with H_2, O_2 and N_2
    - Much better at room temperature
    - Occasional use in room temperature applications in cryogenic systems

Getters, Cryogenics and Gilligan's island

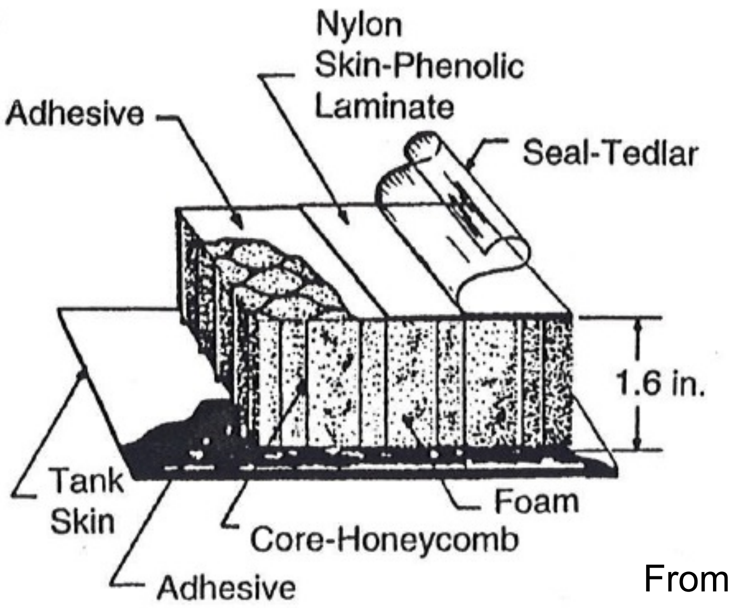
- It turns out that one of the most common and effective materials used for getters of low pressure He gas is activated charcoal made from coconut husks.
- There is a significant amount of this material in the LHC magnet cryostats

The Professor says:
"Lets look for the Higgs!"

Foam & Other Insulation Methods

- Not all cryogenic systems use vacuum insulation
- This is particularly true of storage vessels for fluids other than helium
- Reasons for using alternatives to vacuum insulation
  - Cost
  - Weight – Space shuttle main tank
  - Required hold time – related to size
  - Complex vessel shapes
- Some solutions
  - Expanded closed or open cell foams
  - Rock wool, fiberglass or other porous material
- These all require vapor barriers to prevent air from being pulled into the insulation and condensed (can cause both a safety hazard via O_2 enrichment & reduce effectiveness)

Design Example:Complex Foam Insulation System: LH_2 Tank for 2nd Stage Saturn V



From Cryogenic Engineering, Flynn

- Allows helium purging of the insulation
- Weight ~ 4.15 kg/m^2
- Performance: measured effective thermal conductivity (0.86 – 1.1 mW/cm K) at T_{av} = 144 K Note this includes conduction, convection and radiation heat transfer

Radiation Heat Transfer

- Frequently the largest source of heat leak to cryogenic systems
- Fundamental Equation: Stefan-Boltzmann Law – energy emitted from an ideal black body: $E_b = \sigma T^4$ where $\sigma = 5.67\times10^{-8}$ W/m²K⁴

- Real world Assumptions:
  - » Emissivity (ε) << 1 and independent of wavelength (grey body)
  - » Two parallel infinite plates: Radiative heat flux (W/m²)

Eq. A

$$q_r = \left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1\varepsilon_2}\right)\sigma\left(T_1^4 - T_2^4\right)$$

  - » Frequently in cryogenic systems $\varepsilon_1 \sim \varepsilon_2 << 1$ then Eq. A becomes:

Eq. B

$$q_r = \left(\frac{\varepsilon}{2}\right)\sigma\left(T_1^4 - T_2^4\right)$$

Radiation Heat Transfer

- Two long concentric cylinders or concentric spheres (1 represents the inner cylinder): the radiative heat flux (W/m^2) on the inner cylinder is

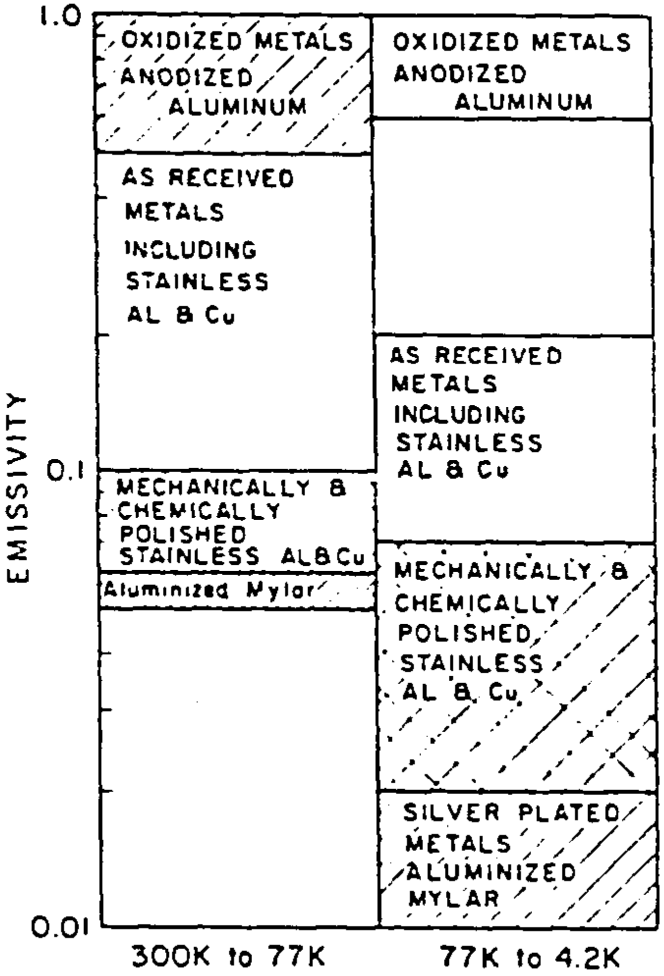
Eq. C

$$q_1 = \left(\frac{\sigma\left(T_1^4 - T_2^4\right)}{1/\varepsilon_1 + \left(A_1/A2\right)\left(1/\varepsilon_2 - 1\right)} \right)$$

- Note as is frequently the case in cryogenics, if the spacing between the cylinders is small compared to the inner radius (i.e. $A_1 \sim A_2$) Eq. C becomes Eq. A

Radiation Heat Transfer

- Looking at Eq. A, How do we reduce the radiation heat transfer?
- We could reduce the emissivity (ε)
  - This is done in some cases; using either reflective tape or silver plating
  - Better below 77 K
  - It’ s also part of MLI systems (see below)
  - We have to consider tarnishing
  - May be labor intensive



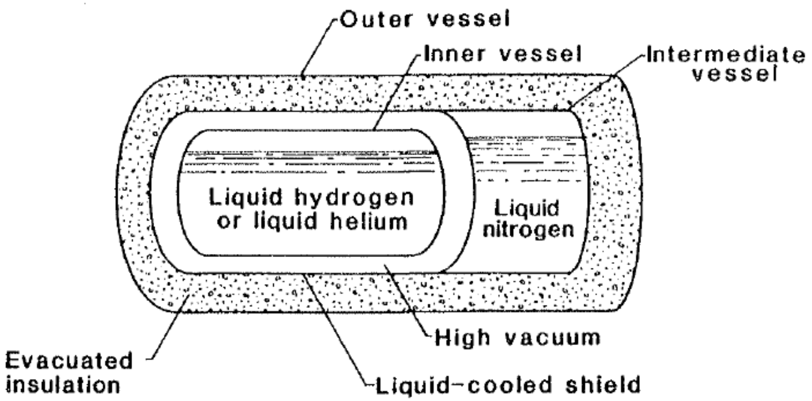
From Helium Cryogenics – S. W. Van Sciver

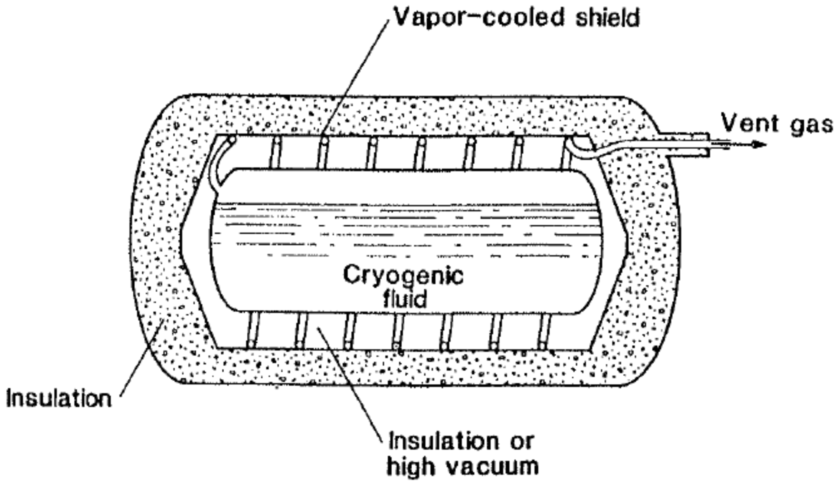
Radiation Heat Transfer

- Another way to reduce radiation heat transfer is to install intermediate actively cooled radiation shields that operate at a temperature between 300 K and the lowest cryogenic temperature. This has several advantages.
  - It greatly reduces the heat load to the lowest temperature level
    - » Assume parallel plates with $\varepsilon = 0.2$
    - » then from Eq. B q (300 K – 4.2 K) = 46 W/m^2 while q (77 – 4.2) = 0.2 W/m^2
  - It allows heat interception at higher temperatures & thus better Carnot efficiency
  - Such an actively cooled shield provides a convenient heat intercept for supports, wires etc to reduce conduction heat leak.
- Shields may be cooled by
  - Liquid baths (LN_2)
  - Vapor boil off from stored liquid – common in LHe storage dewars
  - Cooling flows from refrigeration plants
  - Conductive cooling via small cryocoolers

Examples of Cooled Radiation Shields

- LN_2 bath surrounds inner LHe or LH_2 bath
- Baths are separated by a vacuum insulation space
- Shield is cooled by boil off gas from stored cryogen
  - Spacing of cooling tubes on shield may be calculated by: $\Delta T = qL^2/2kt$
    - » ΔT = max allowable temperature difference between any point on shield and tube
    - » q = heat flux on shield
    - » k = shield thermal conductivity
    - » L = ½ max tube spacing
    - » t = shield thickness





From Cryogenic Engineering, Flynn

Thermal Radiation Shields

- Uncooled thermal radiation shields placed in a vacuum space between the warm & cold surfaces also help reduce the thermal radiation heat leak
- It can be shown (with the grey approximation and equal emissivities) that with N shields thermal radiation heat transfer is given by:

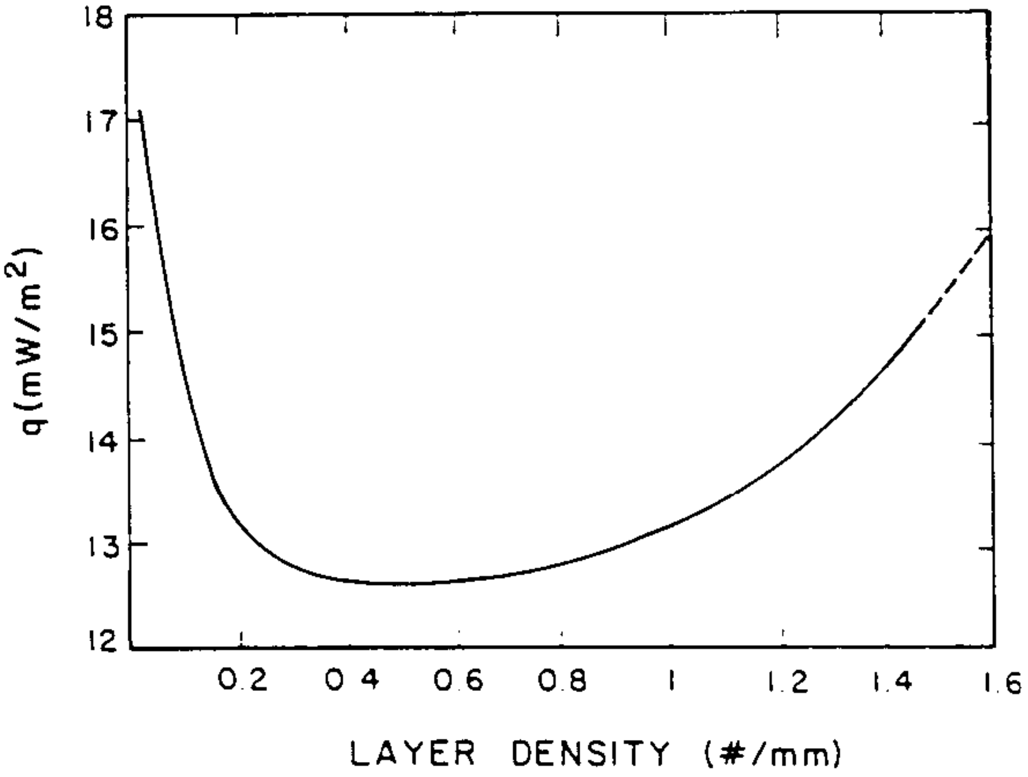
$$q = \frac{\varepsilon}{(N+1)2}\sigma\left(T_H^4 - T_L^4\right)$$

This is the motivation behind Multilayer Insulation

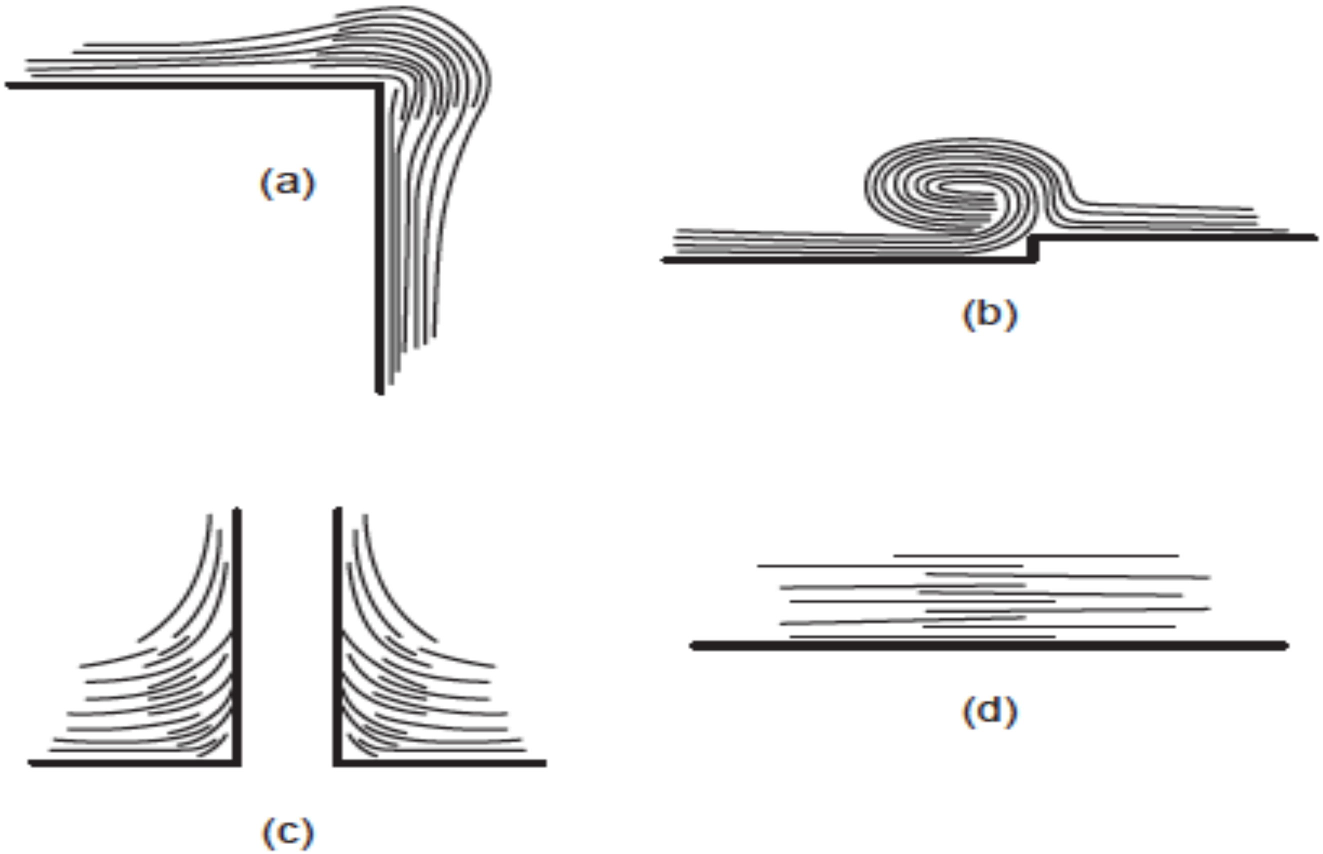
MultiLayer Insulation

- Also referred to as superinsulation
- Used in the vacuum space of many cryostats (10^{-5} torr or better for best performance)
- Consists of highly reflective thin sheets with poor thermal contact between sheets.
  - Made of aluminized Mylar (or less frequently Kapton)
  - May include separate non conducting mesh
  - May use Mylar aluminized on only one side and crinkled to allow only point contacts between sheets
  - Frequently perforated to allow for better pumping
- Can be made up into blankets for ease of installation
- Don't pack MLI too tightly. Optimal value is ~ 20 layers / inch
- Great care must be taken with seams, penetrations and ends.
  - Problems with these can dominate the heat leak

MLI



Examples of Proper MLI Installation



From “Cryogenic Engineering” in *Wiley Mechanical Engineer’s Handbook*

MLI Example from LHC cryostats

"SERIES-PRODUCED HELIUM II CRYOSTATS FOR THE LHC MAGNETS: TECHNICAL CHOICES, INDUSTRIALISATION, COSTS"
A. Poncet and V. Parma
Adv. Cryo. Engr. Vol 53

Porous Insulation

- Radiation heat transfer may also be reduced by filling the vacuum space between 300 K and cryogenic temperatures with other materials that are low conductivity and block line of sight
- Such materials include:
  - Glass beads or microspheres
  - Perlite powder (made from a volcanic rock)
  - Opaciated powders – copper or other metallic flakes mixed in with other powders to further reduce radiant heat transfer
  - Aerogel
- Advantages:
  - Cheaper
  - Easier to install in complex shapes
  - Better performance than MLI in poor or no vacuum
- Frequently used in large storage and transport dewars

Porous Insulation

The total heat transfer through porous insulation between 2 spheres may be estimated by:

$$W = \frac{\bar{k}\left(T_2 - T_1\right)}{t}\sqrt{A_1 A_2}$$

- Where
  - t = thickness of Insulation
  - $\bar{k}$ = the mean thermal conductivity
  - 1 = inner vessel and 2 = outer vessel

- Mean thermal conductivities may be found in references such as

<u>Cryogenic Engineering</u> by Flynn

Comparison of Thermal Insulation Approaches (6 inch thick insulation in all cases)

	Total Heat Flux (W/m^2)	
Type of Insulation	**300 K to 77 K**	**77 K to 20 K**
Polystyrene Foam (2 lb/ft^3)	48.3	5.6
Gas Filled Perlite powder (5 – 6 lb/ft^3 filled with He)	184.3	21.8
Perlite powder in vacuum (5 – 6 lb/ft^3)	1.6	0.07
High Vacuum (10^{-6} torr $\varepsilon = 0.02$)	9	0.04
Opacified powder (Cu flakes in Santocel)	0.3	-
MLI	0.03	0.007

↓ Increasing Cost & Complexity

Note better performance of evacuated Perlite over high vacuum between 300 K & 77 K

From Cryogenic Systems – Barron
For rough estimates only

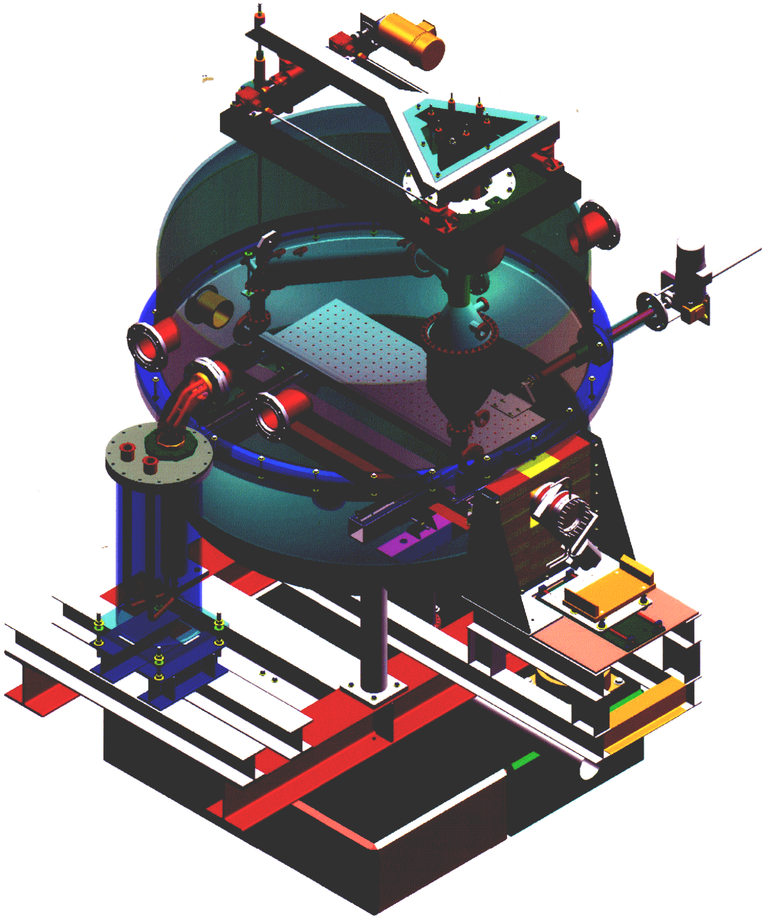
Cryostat Design

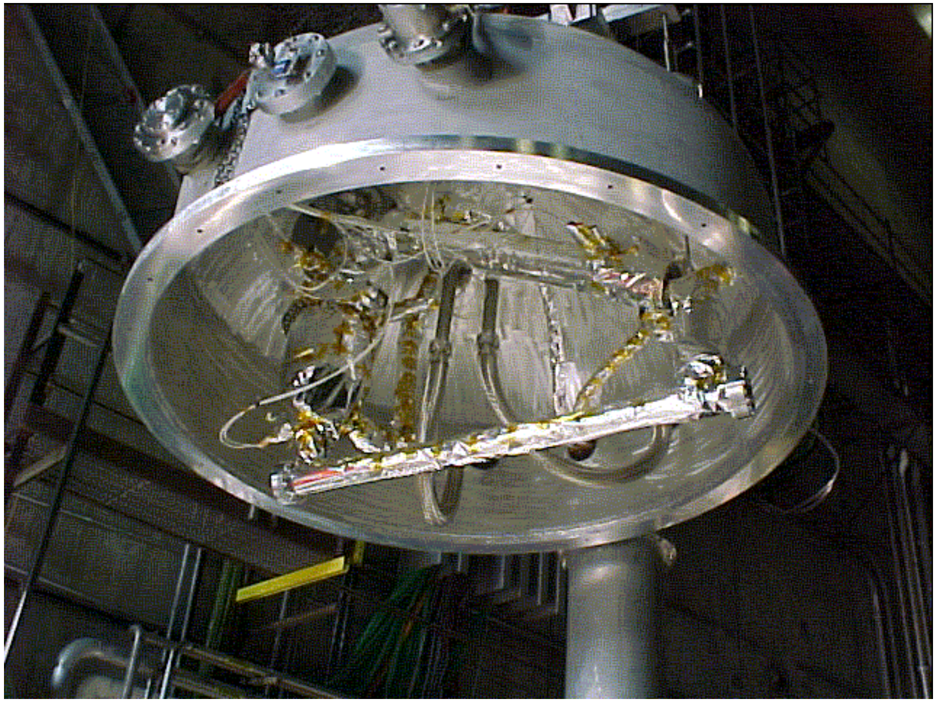
- What is a cryostat?
  - A device or system for maintaining objects at cryogenic temperatures.

- Cryostats which contain superconducting RF systems are traditionally called cryomodules (term originally coined by Jlab)

- Cryostats whose principal function is to store cryogenic fluids are frequently called Dewars. Named after the inventor of the vacuum flask and the first person to liquefy hydrogen

E158 LH_2 Target Cryostat





Cryostat Design

- Cryostats are one of the technical building blocks of cryogenics
- Cryostat design involves many subtopics:
  - Development of requirements – covered here
  - Materials selection – already covered
  - Thermal insulation - already covered
  - Support systems – covered here
  - Safety – covered in a future lecture
  - Instrumentation – covered in a future lecture
- One of the best ways to learn about cryostat design is through examples (see next 2 talks)
- There are many different types of cryostats with differing requirements
  - The basic principles of cryostat design remain the same
  - Before we can do anything else we have to define our requirements

Cryostat Requirements

- Maximum allowable heat leak at various temperature levels
  - This may be driven by the number of cryostats to be built as well as by the impact of large dynamic heat loads (SCRF or target cryostats)
- Alignment and vibration requirements
  - Impact of thermal cycles
  - Need to adjust alignment when cold or under vacuum?
  - Alignment tolerances can be quite tight (TESLA :
  +/- 0.5 mm for cavities and +/- 0.3 mm for SC magnets)
- Number of feed throughs for power, instrumentation, cryogenic fluid flows, external manipulators

Cryostat Requirements

- Safety requirements (relief valves/burst discs)
  - Design safety in from the start. Not as an add on
- Size and weight
  - Particularly important in space systems
- Instrumentation required
  - Difference between prototype and mass production
- Ease of access to cryostat components
- Existing code requirements (e.g. TUV or ASME)
- Need, if any, for optical windows
- Presence of ionizing radiation

Cryostat Requirements

- Expected cryostat life time
- Will this be a one of a kind device or something to be mass produced?
- Schedule and Cost
  - This should be considered from the beginning

All Design is Compromise