Lecture 7
Heat Transfer & Thermal Insulation

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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
- 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

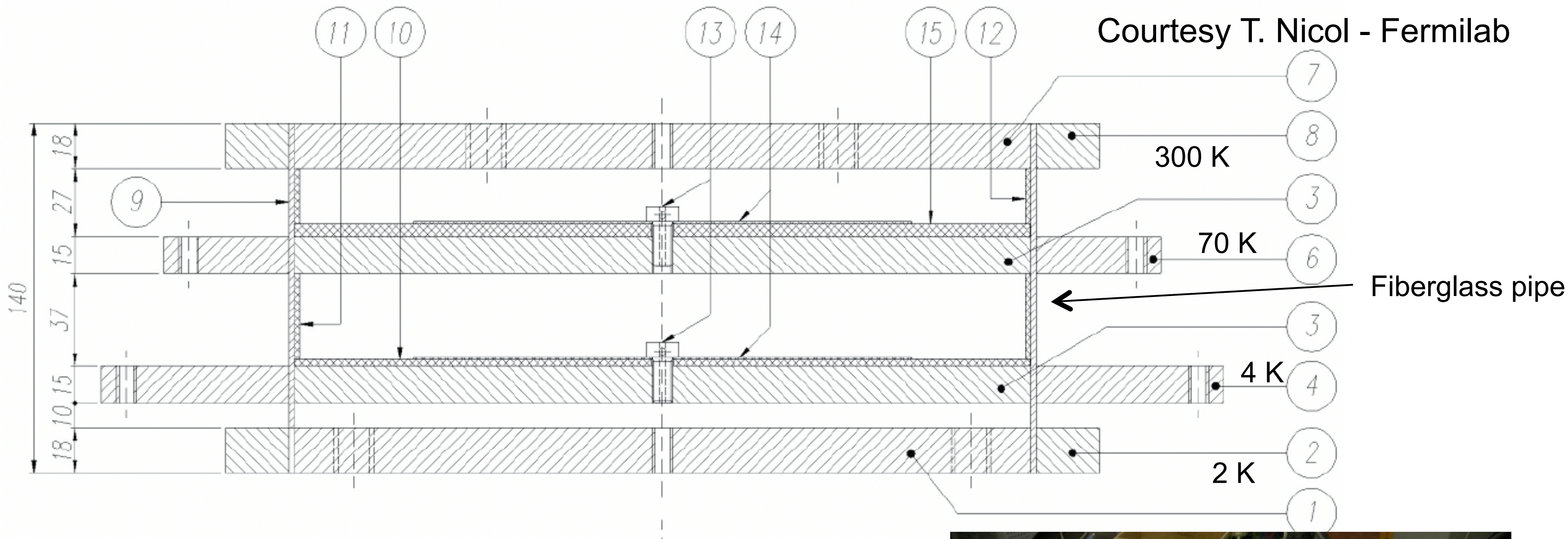
$$Q = -K(T)A(x)\frac{\partial T}{\partial x}$$

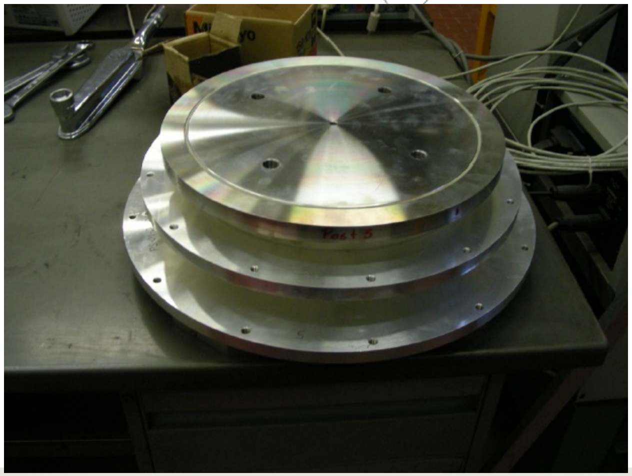
- If we assume constant cross section we get: $Q = -A/L\int_{T_C}^{T_H} K(T)\,dT$

- 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

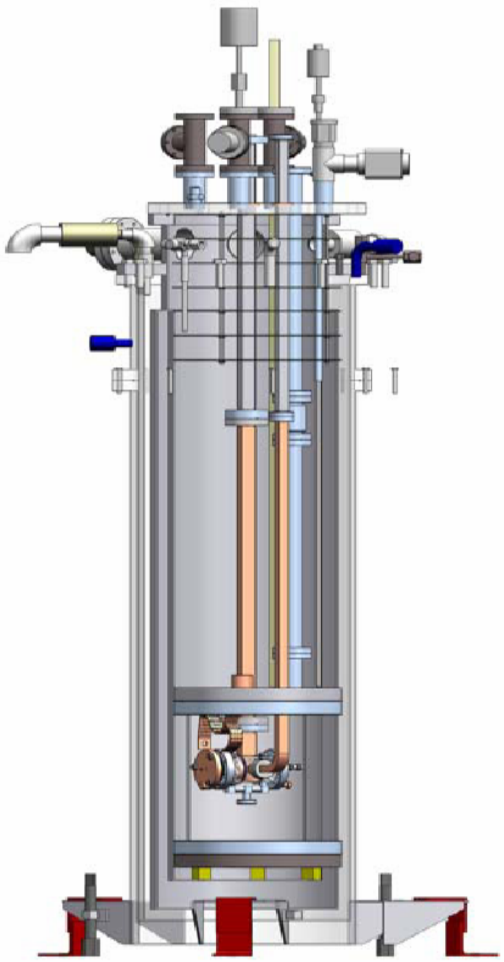
- Fundamental Equation: Newton's law of cooling

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

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

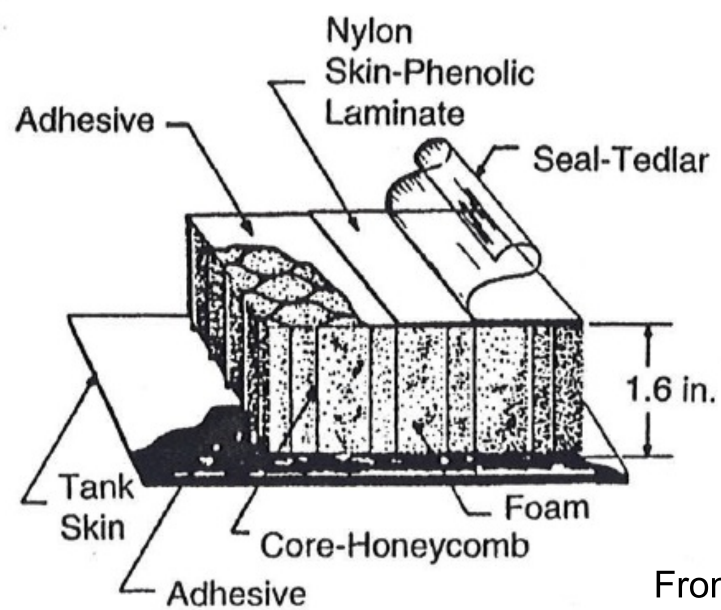
- It turns out that one of the most common and effective materials used for getters of low pressure He gas is activated charcoal made from coconut husks.
- There is a significant amount of this material in the LHC magnet cryostats

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 $\sigma = 5.67 \times 10^{-8}$ W/m^2K^4

- Real world Assumptions:
  - » Emissivity (ε) << 1 and independent of wavelength (grey body)
  - » Two parallel infinite plates: Radiative heat flux (W/m^2)

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

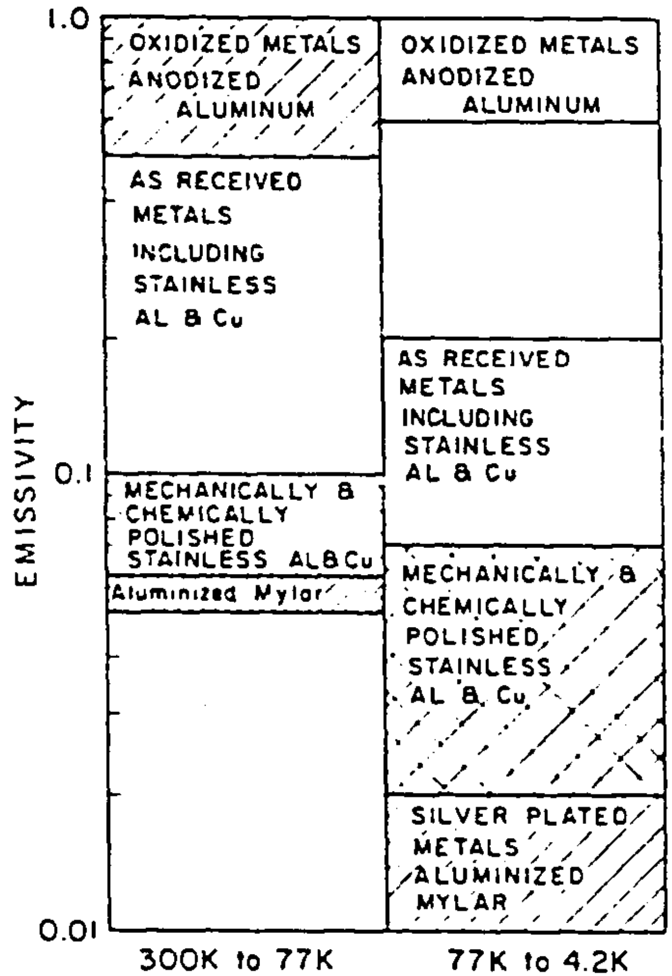
Eq. C

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

» 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



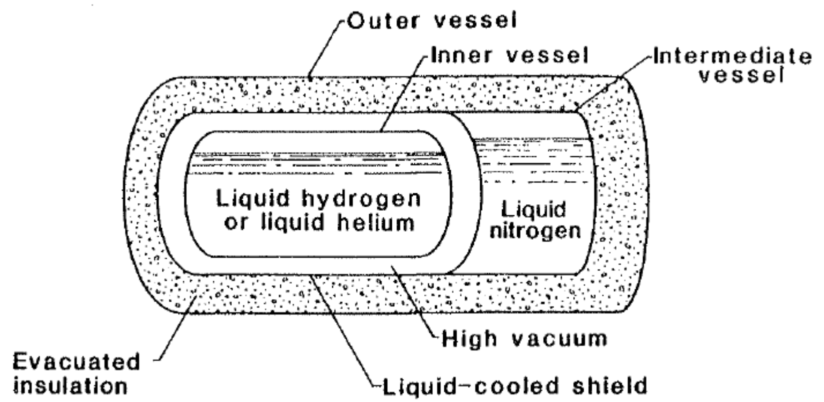
From Helium Cryogenics – S. W. Van Sciver

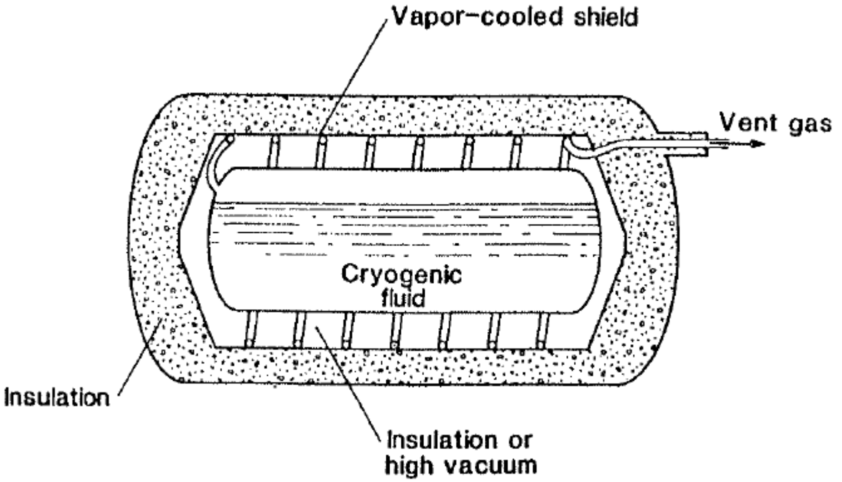
Radiation Heat Transfer

- 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