CRYOGENIC ENGINEERING

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Lecture No - 33

Earlier Topics

- Introduction to Cryogenic Engineering
- Properties of Cryogenic Fluids
- Properties of Materials at Cryogenic Temperature
- Gas Liquefaction and Refrigeration Systems
- Gas Separation
- Cryocoolers

Current Topic

Topic : Cryogenic Insulation

- Why Insulation?
- Different types of Cryogenic Insulations
- A comparative study
- Applications

- The current topic will be covered in 3 lectures.
- Tutorials and assignments are included at the end of each lecture.

Outline of the Lecture

Topic : Cryogenic Insulations

- Why Insulation?
- Types of Insulation
- Expanded Foam and Powder Insulations
- Radiation Fundamentals

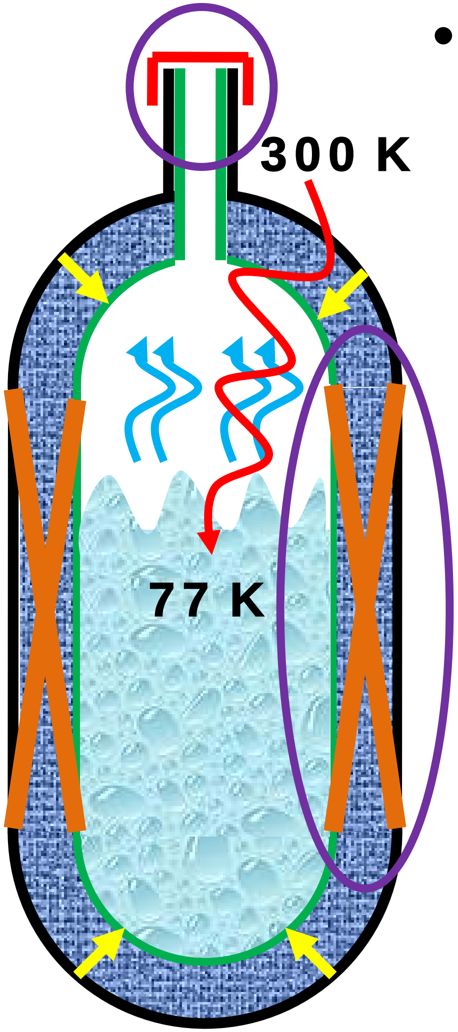
Introduction

- Storage of a cryogen (say, **LN_2**) is difficult, as there is a continuous boil off due to heat in leaks.
- These vessels cannot be sealed as boil off generates huge volumes of vapour, resulting in large pressure rise. This may lead to bursting.
- For example, vapor to liquid volume ratio for a general cryogen is 175 (1600 for water).
- To avoid the pressure rise, the need of insulation is vital. Insulation or a combination of insulations, minimize all these modes of heat transfer.

Heat Transfer

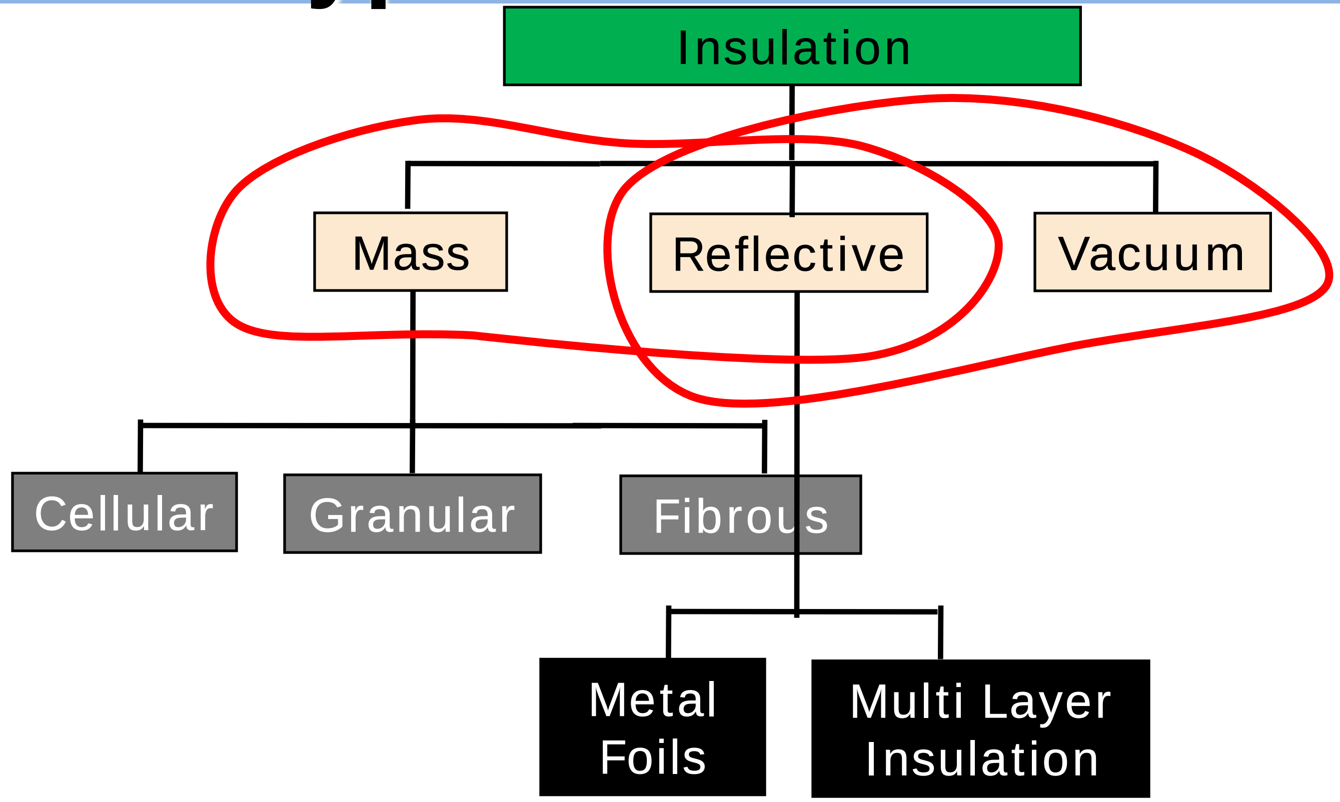
- Consider a **LN2** container as shown in the figure.
- The inner vessel is housed inside an outer vessel and these vessels are separated by some form of insulation.
- Also, the inner vessel is supported using lateral beams as shown.
- The liquid boils off continuously due to the various modes of heat transfer.

Heat Transfer



- Different modes of heat transfer are
  - **Conduction**: The heat is conducted through lateral beams, neck and residual gas conduction.
  - **Convection**: The air between inner and outer vessels convect heat into the liquid.
  - **Radiation**: The radiation heat transfer from 300 K outer vessel to 77 K inner vessel.

Types of Insulation



Types of Insulation

- Expanded Foam – Mass
- Gas Filled Powders & Fibrous Materials – Mass
- Vacuum alone – Vacuum
- Evacuated Powders – Mass + Vacuum
- Opacified Powders – Mass + Vacuum + Reflective
- Multilayer Insulation – Vacuum + Reflective

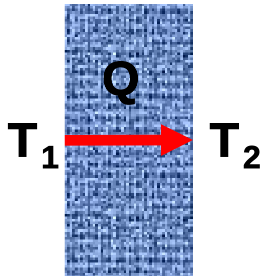
Types of Insulation

- The choice of insulation for a particular application is a compromise between the following factors.
  - Thermal Conductivity
  - Temperature
  - Effectiveness of Insulation
  - Cost
  - Ease of application
  - Weight and reliability
- A combination of insulations is used to prevent different modes of heat transfer.

Apparent Thermal Conductivity

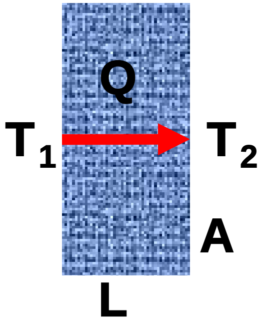
- As seen earlier, the different modes of heat transfer are Gas and Solid Conductions, Convection and Radiation.

- Consider an element of insulation, separated by two temperatures (**T_1 > T_2**) as shown below.



- Let **Q** be net heat transferred across this element by all possible modes of heat transfer mentioned above.

Apparent Thermal Conductivity



- If **A** and **L** be the area of the cross section and length of the element respectively, the apparent thermal conductivity (**k_A**) is defined as

$$k_A = \frac{QL}{A\left(T_1 - T_2\right)}$$

- In other words, this apparent thermal conductivity is calculated based on all possible modes of heat transfer.

Expanded Foams

- Expanded foam is a low density, cellular structure which is formed by evolving gases during the manufacturing process.
- Gases that are generally used are $\mathbf{CO_2}$ and Freon.
- In other words, it is a solid – gas matrix with void spaces. The solid connections together with gas trapped in cellular spaces form a continuous path.
- The heat is transferred only by conduction (solid conduction). The contribution by convection and radiation are negligible.

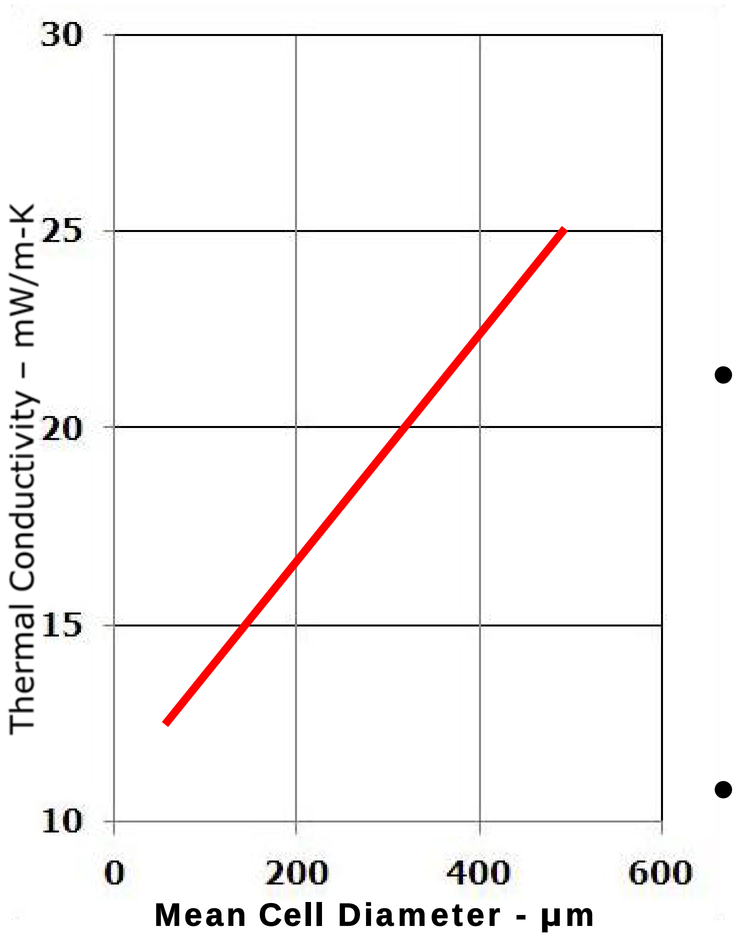
Expanded Foams

- Examples are polyurethane foam, polystyrene foam, rubber, silica glass foam.

- k_A and density are as shown below. The operating temperature is between **77 K** to **300 K**.

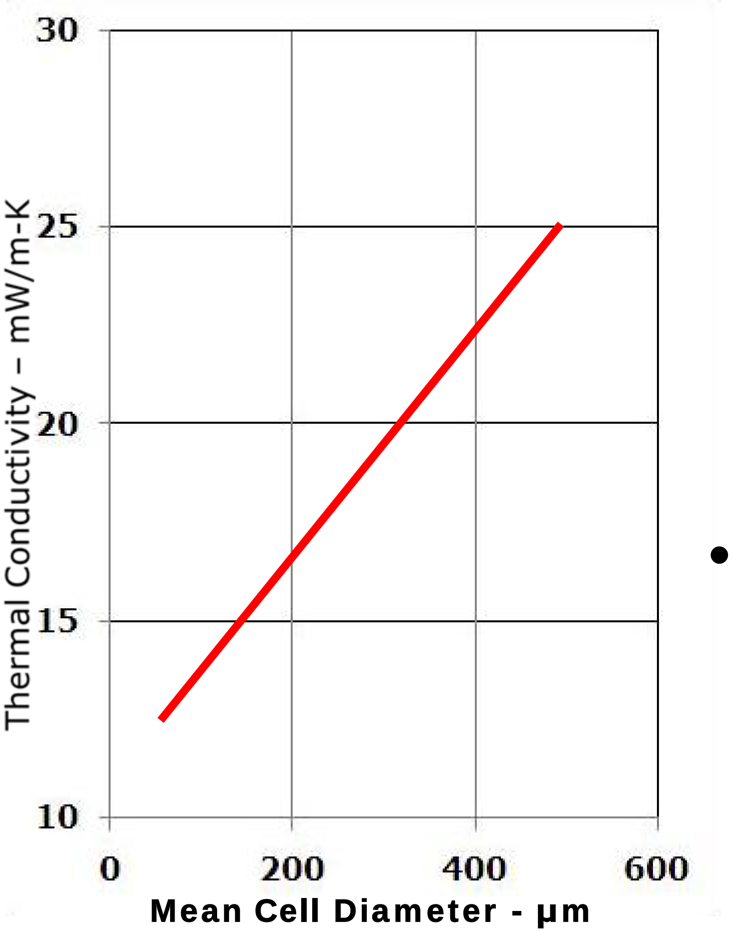
Foam	ρ (kg/m³)	k (mW/mK)
Polyurethane	11	33
Polystyrene	39	33
	46	26
Rubber	80	36
Silica	160	55
Glass	140	35

Expanded Foams



- The $\mathbf{k_A}$ of the foam depends on the type of gas used and also the temperature of the insulation.
- For a given gas, the performance of the foam is improved by varying the void size and bulk density.
- The adjacent figure shows the variation of $\mathbf{k_A}$ with the mean cell diameter.

Expanded Foams

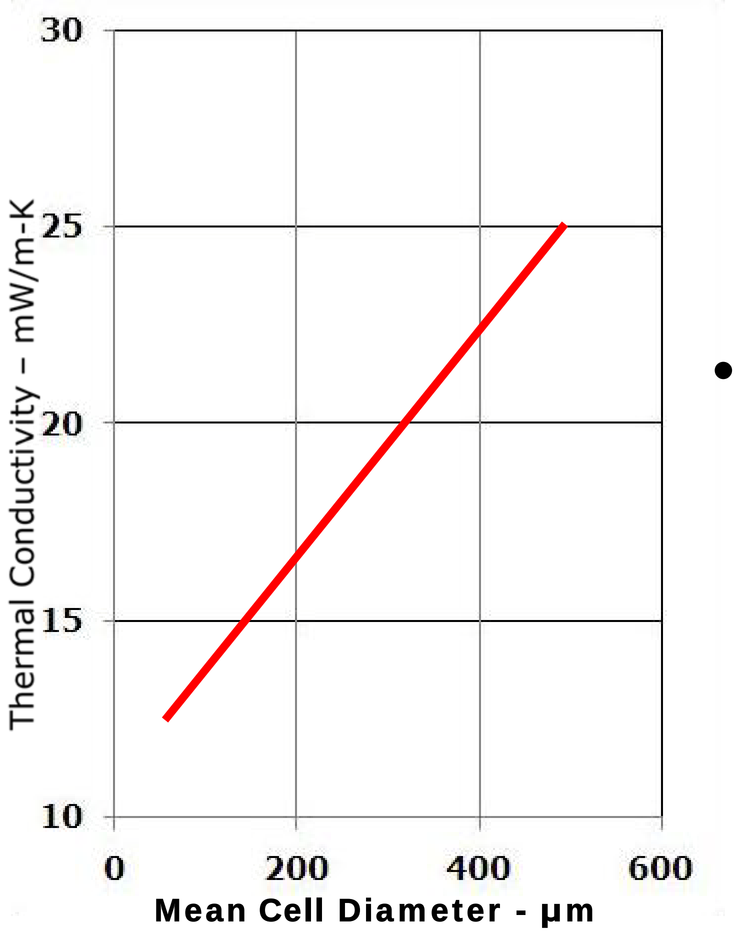


- With the decrease in the mean cell diameter, the solid conduction path increases in the foam insulation.

$$k_A = \frac{QL}{A(T_1 - T_2)}$$

- From the above equation, the **Q** decreases and hence the $\mathbf{k_A}$ decreases.

Expanded Foams



- At the same time, with the decrease in the mean cell diameter, the bulk density of the foam increases.

- Therefore, $\mathbf{k_A}$ is also a function of bulk density and it increases with the increase in bulk density.

Expanded Foams

- The major advantage of an expanded foam is that it offers an ease of fabrication.

- The foam is directly blown onto the surface of the vessel to be insulated. It forms a self supporting structure.

- The cost of this insulation is also low as compared to other types of insulations.

Expanded Foams

- Exposure of a **CO_2** expanded foam to **LN2** temperatures, increases the thermal conductivity.

- At **LN2** temperature, the vapor pressure of **CO_2** is less. As a result, most of **CO_2** is condensed within the insulation and caters for the heat transfer.

- Also over a period of time, air, hydrogen or helium diffuse into foam from external atmosphere.

- The **k_A** of the foam increases due to increase in the gas conduction at room temperature.

Expanded Foams

- Expanded foams have large thermal contractions, which pose a major disadvantage.

- A rigid foam has a large thermal contraction between -30^{o}C to +30^{o}C.

- For example, coefficients of linear expansion are
  - $\alpha_{Polystyrene\ Foam}$: 7.20 x 10^{-5}/^{o}C
  - $\alpha_{Carbon\ Steel}$: 1.15 x 10^{-5}/^{o}C

- The foam when closely fitted around a **LN2** vessel, crack due to difference in shrinkages.

Gas Filled Powder & Fibrous Insulations

- A gas filled powder or a fibrous insulation reduces or eliminates the gas convection due to the small size of voids within the material.

- This is because, the distance between the powder particles within the insulation is much smaller than the gas mean free path.

- As a result, the gaseous conduction mechanism shifts from continuum to free molecular conduction decreasing the apparent thermal conductivity, $\mathbf{k_A}$.

Gas Filled Powder & Fibrous Insulations

- The commonly used insulations of this type are Fiber Glass, Perlite (Silica Powder), Santocel, Rockwool, Vermichlitine.

- **k_A** and density are as shown below. The operating temperatures are between **77 K** to **300 K**.

Insulation	ρ (kg/m³)	k (mW/mK)
Perlite	50	26
Silica Aerogel	80	19
Fiber glass	10	25
Rockwool	160	35

Gas Filled Powder & Fibrous Insulations

- The advantages of a gas filled powder are low thermal conductivity, low density and low particle distribution to minimize the vibration effects.

- The insulation can either be evacuated or non – evacuated. Heat transfer by residual gas is further minimized by low vapor pressure of the gas.

- Finely divided particulate materials make solid conduction paths disjointed and discontinuous.

Gas Filled Powder & Fibrous Insulations

- The disadvantage is that moisture and air diffuse through the material to the cold surface unless a vapor barrier is used. **N_2** purging is used.
- Fill – gas should be unreactive and compatible with powder material.
- Powder tends to settle and packs due to vibrations, thermal contraction and expansion.
- This creates increased solid conduction.

Gas Filled Powder & Fibrous Insulations

- Nusselt & Bayer developed the following expression for $\mathbf{k_A}$ for a gas filled powder.

$$k_A = \left[\frac{V_r}{k_s} + \left[\frac{k_g}{(1 - V_r)} + \frac{4\sigma T^3 d}{V_r} \right]^{-1} \right]^{-1}$$

- $\mathbf{V_r}$ – Ratio of solid particulate to total volume.
- $\mathbf{k_s}$ & $\mathbf{k_g}$ – Thermal conductivity of Solid and Gas.
- **T** – Mean temperature.
- **d** – Mean diameter of fiber or powder.

Gas Filled Powder & Fibrous Insulations

$$k_A = \left[\frac{V_r}{k_s} + \left[\frac{k_g}{(1-V_r)} + \frac{4\sigma T^3 d}{V_r} \right]^{-1} \right]^{-1}$$

- At cryogenic temperatures, two assumptions are made
  - $\mathbf{T^3}$ term is very small relative to $\mathbf{k_g}$ term.
  - $\mathbf{k_s >> k_g}$
- Therefore, the equation is $k_A = \frac{k_g}{(1-V_r)}$

Gas Filled Powder & Fibrous Insulations

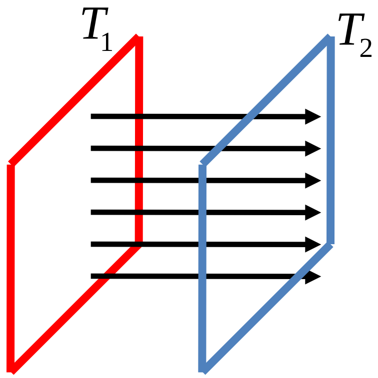
$$k_A = \frac{k_g}{\left(1 - V_r\right)}$$

- Therefore, as $\mathbf{V_r}$ tends to zero, $\mathbf{k_A}$ approaches $\mathbf{k_g}$.

- This is the lowest possible thermal conductivity of this insulation.

Radiation – Fundamentals

- Consider two flat surfaces maintained at different temperatures (**T_1 > T_2**) as shown in the figure.

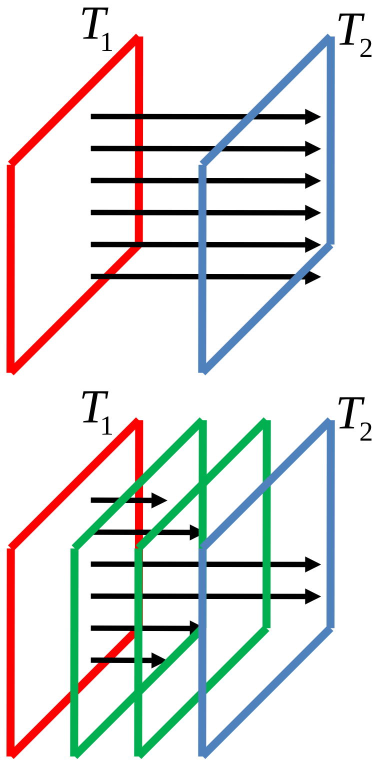


- There is continuous heat transfer between the two plates due to the radiation.
- This mode of heat transfer does not require any medium and is given by the following equation.

$$Q = F_e F_{1\to 2} \sigma A_1 \left(T_2^4 - T_1^4 \right)$$

Radiation – Fundamentals

$$Q = F_e F_{1\rightarrow 2} \sigma A_1 \left(T_2^4 - T_1^4\right)$$



- In the above equation, it is clear that for a given $\mathbf{A_1}$, $\mathbf{T_1}$, $\mathbf{T_2}$, $\mathbf{F_{1\rightarrow 2}}$, **Q** is directly proportional to the emissivity factor $\mathbf{F_e}$.
- The $\mathbf{F_e}$ is reduced by introducing the radiation shields in the path of radiation heat transfer as shown.
- The effect of these shields is as explained in the next slide.

Radiation Shields

- The effective emissivity factor $\mathbf{F_N}$ after introduction of **N** shields is as given below.

$$\frac{1}{F_N}=\left(\frac{1}{e_1}+\frac{1}{e_s}-1\right)+\left(N-1\right)\left(\frac{2}{e_s}-1\right)+\left(\frac{1}{e_2}+\frac{1}{e_s}-1\right)$$

- For the sake of understanding, let the values of $\mathbf{e_1}$, $\mathbf{e_2}$, and $\mathbf{e_s}$ be 0.8, 0.8, 0.05 respectively.

- Students are advised to calculate and compare $\mathbf{F_N}$ for following cases.
  - Case 1: N=0
  - Case 2: N=10

Radiation Shields

- Case 1 : N=0 – $F_N = 0.667$
- Case 2 : N=10 – $F_N = 0.00255$
- It is clear that the $\mathbf{F_N}$ decreases drastically with the introduction of radiation shields.
- These shields are aluminum foils with a very high reflectivity.

Summary

- Cryogenic vessels need insulation to minimize all modes of heat transfer.
- The apparent thermal conductivity is calculated based on all possible modes of heat transfer.
- Expanded foam is a low density, cellular structure. The heat is transferred only by solid conduction.
- With the decrease in the mean cell diameter, the $\mathbf{k_A}$ decreases. With the increase in the bulk density, the $\mathbf{k_A}$ also increases.

Summary

- A gas filled powder or a fibrous insulation reduces gas convection due to the small size of voids. The heat is transferred by free molecular conduction.
- Fill – gas should be unreactive and compatible with powder material.
- Radiation heat transfer does not require any medium. It is reduced by introduction of radiation shields.
- These shields are aluminum foils with a very high reflectivity.

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Self Assessment

1. The vapor to liquid volume ratio for a general cryogen is ____.
2. The liquid boils off continuously due to ______.
3. _________ is calculated based on all possible modes of heat transfer.
4. In an expanded foam, gases that are used are ___.
5. In an expanded foam, the heat is transferred only by ______.
6. With the decrease in mean cell diameter, the solid conduction path ______in the foam insulation.
7. In a Gas – Filled powder insulation, fill – gas should be ______.
8. _____ does not require any medium.

Answers

1. 175
2. Heat in leaks
3. Apparent thermal conductivity
4. CO_2 and Freon
5. Conduction
6. Increases
7. Unreactive
8. Radiation

Thank You!