CRYOGENIC ENGINEERING

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Lecture No - 7

Properties of Materials

Sr. No.	Property
1	Mechanical
2	Thermal
3	Electrical
4	Magnetic

From Mech Engg. perspective

From SC perspective

Earlier Lecture

- Introduction to material properties.
- Thermal expansion/contraction
- Specific heat of solids, Debye theory
- Thermal conductivity of solids, kdT integrals
- Electrical resistivity of solids

Outline of the Lecture

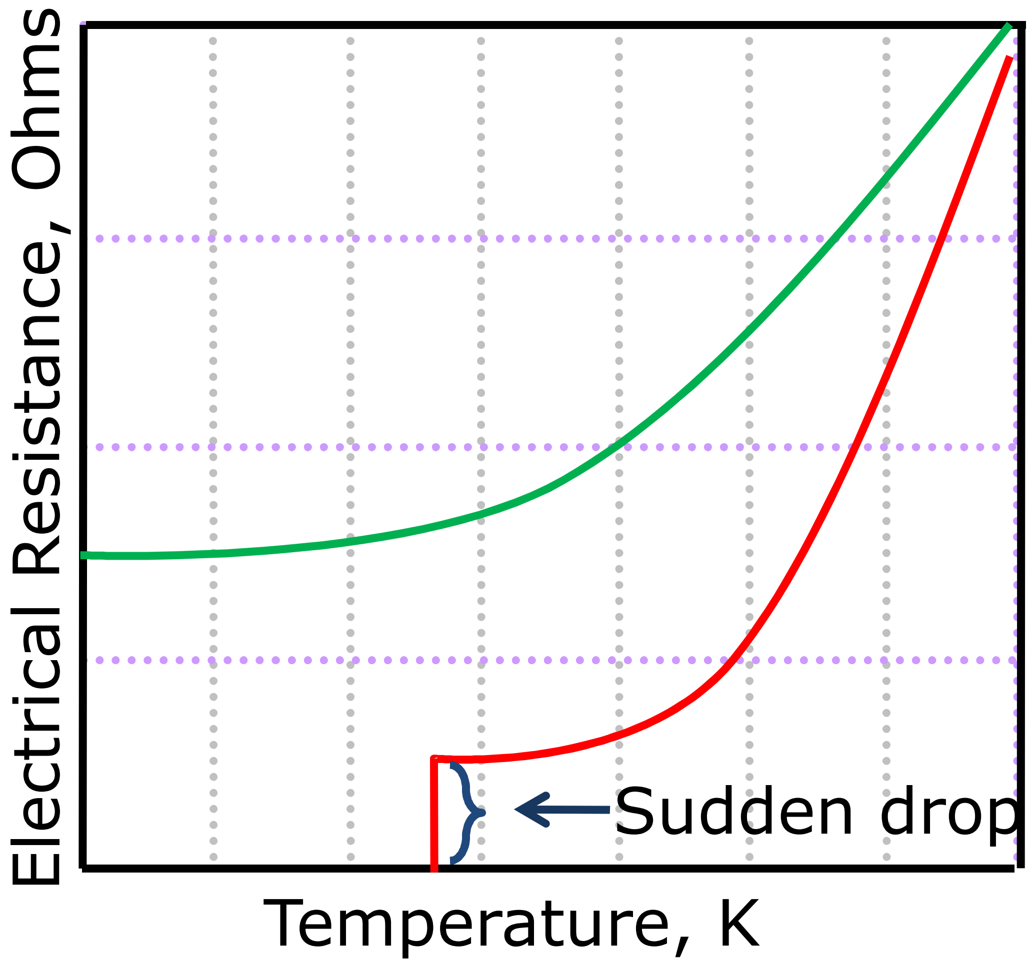
Title : Material Properties at Low Temperature (contd)

- Superconductivity
- Tutorials
- Assignments
- Conclusion

Introduction

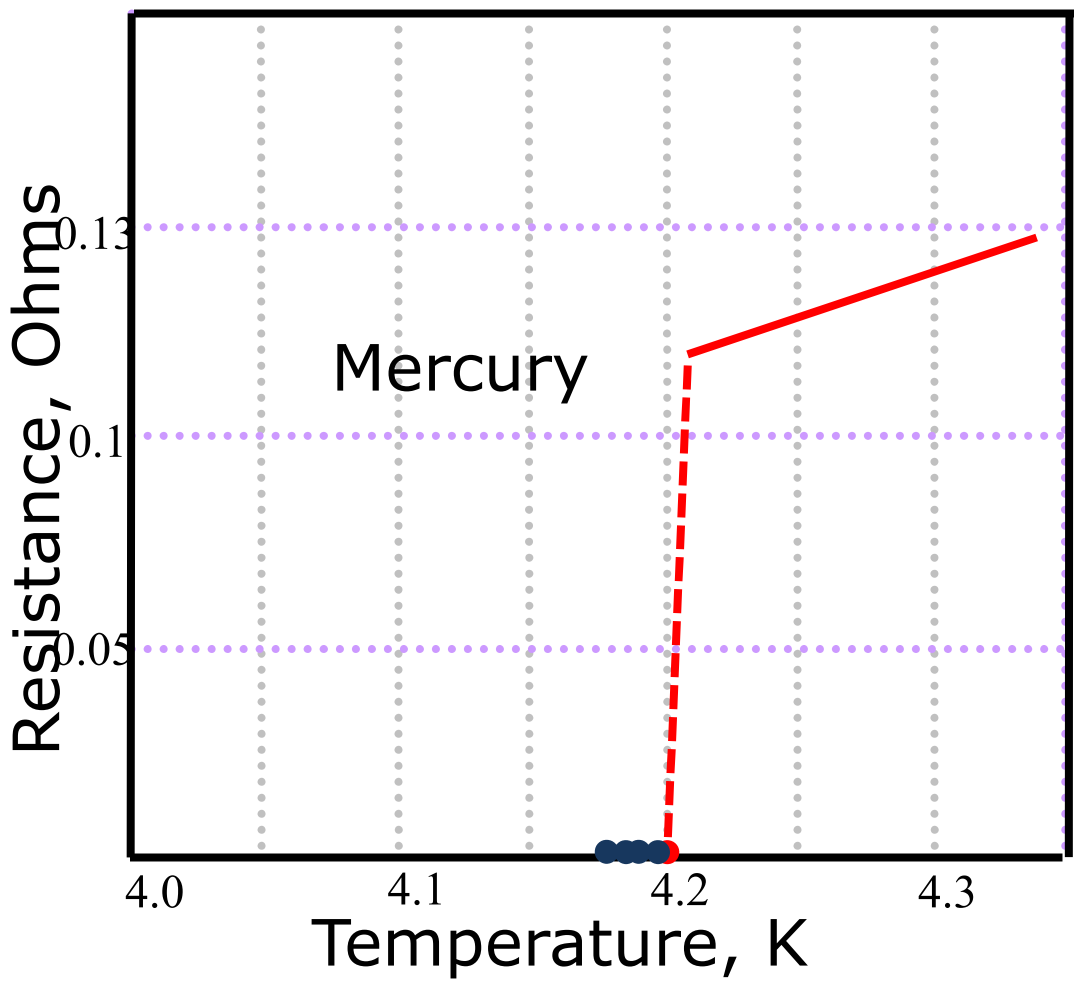
- The properties of materials change, when cooled to cryogenic temperatures (demo video).
- The electrical resistance of a conductor decreases as the temperature decreases.
- Wires made of materials like Nb – Ti, exhibit zero resistance when subjected to LHe temperatures (superconductivity).

Superconductivity



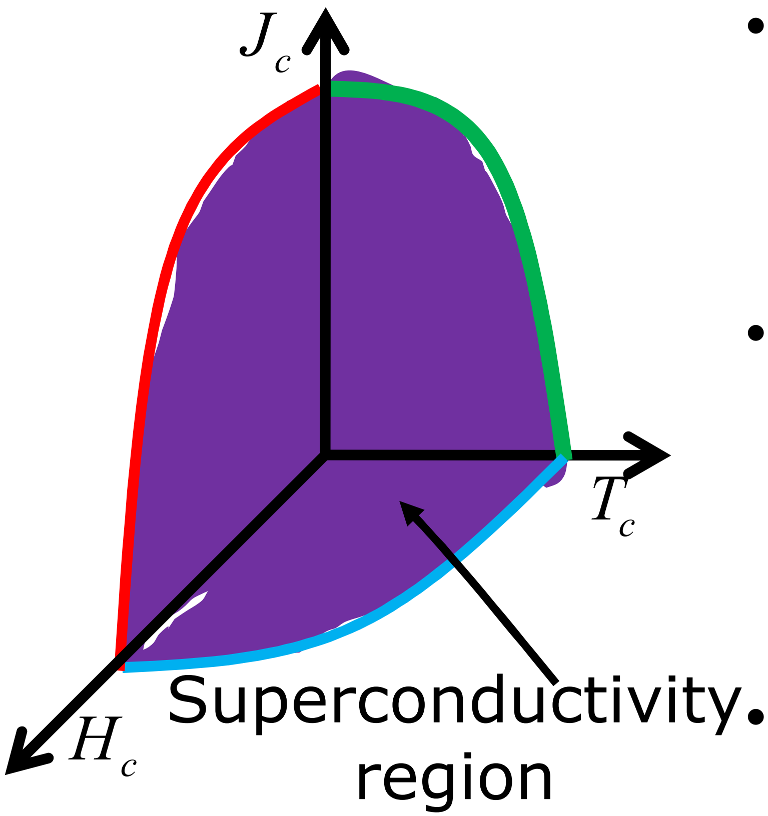
- The electrical resistance of a material decreases with the decrease in the temperature.
- Few of the materials, when cooled to lower temperatures, the resistance suddenly drops to zero at a particular temperature.

Superconductivity



- In 1911, Onnes discovered the phenomenon of Superconductivity.
- During his investigation on mercury, he observed that the resistance dropped to zero at 4.2 K.

Superconductivity



- The state of the SC is governed by three parameters.
- They are Temperature (K), Current Density (A/mm^2) and Magnetic Field (Tesla) as shown in the figure.
- The blue region in the figure is enclosed by the critical values of T_c, J_c and H_c.

Superconductivity

- The electrical resistance is due to the scattering of electron motion through the lattice imperfections like the presence of impurity and dislocations.

- The first imperfection, that is, the presence of impurity is a temperature independent factor.

- But the scattering phenomena occurring due to the lattice imperfections decreases with the decrease in the temperature.

- As a result, the electrical conductivity is more at low temperatures.

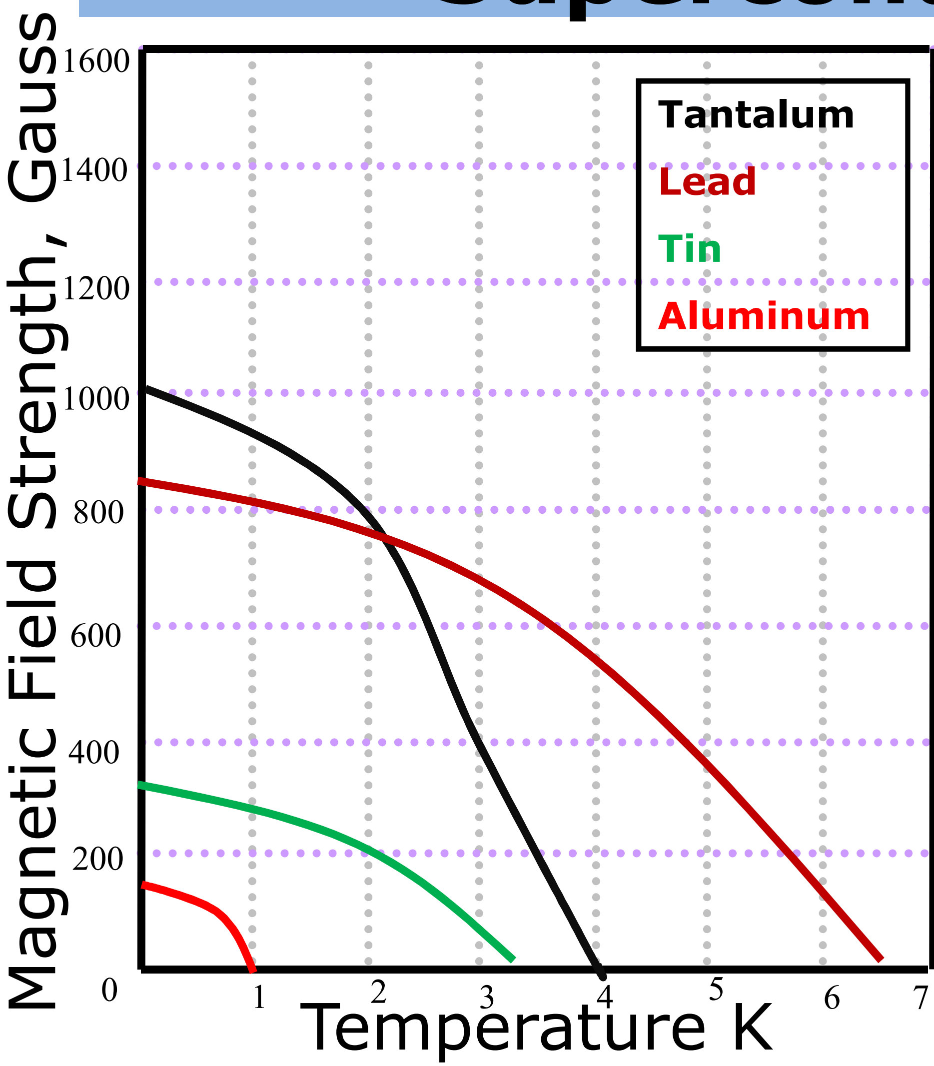
Bardeen-Cooper-Schrieffer Theory

- Electron being a negatively charged particle, moves easily through the space between the adjacent rows of positively charged ions.
- This motion is assisted by the electrostatic force which pulls the electrons inward.
- In SC state, the electrons interact with each other and form a pair. This interaction is a very low energy process (0.1 eV) called as phonon interaction.

Bardeen-Cooper-Schrieffer Theory

- The electron pair so formed moves easily and the second electron follows the first electron during the motion. As a result, this electron pair travelling together, encounters less resistance.
- This electron pair is called as a Cooper Pair.
- This theory was first explained by Bardeen, Cooper, Schrieffer in BCS Theory in the year 1957.
- They are awarded Nobel Prize in the year 1972 for this theory.

Superconductivity



- Threshold Field (H_T) is related to absolute temperature (T) as given below.

$$H_T = H_0\left[1-\left(\frac{T}{T_0}\right)^2\right]$$

- where, H_0 is the critical field at zero K and T_0 is the critical temperature at zero H.

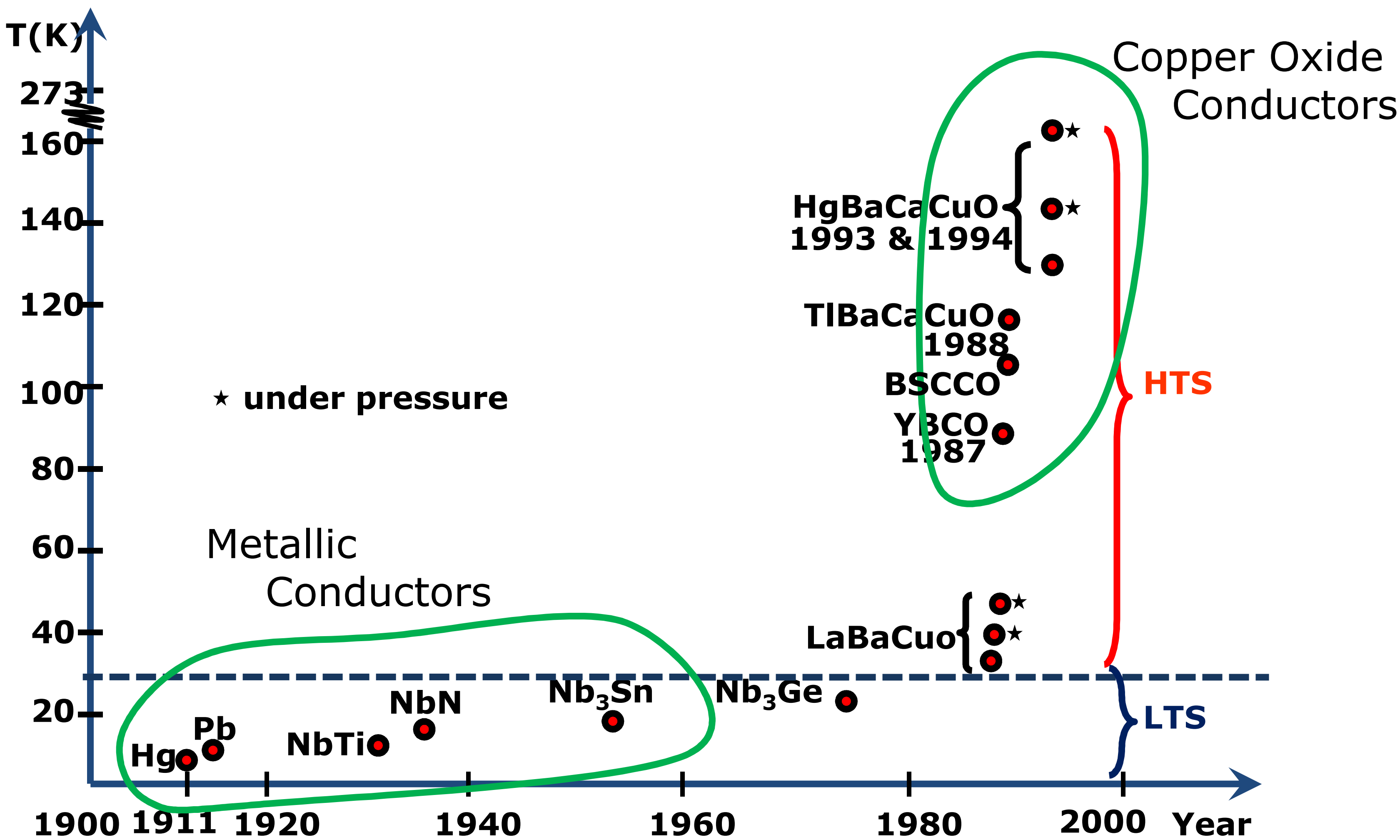
High T_c and Low T_c Materials

- Superconducting materials are distinguished depending upon the critical temperature they exhibit.

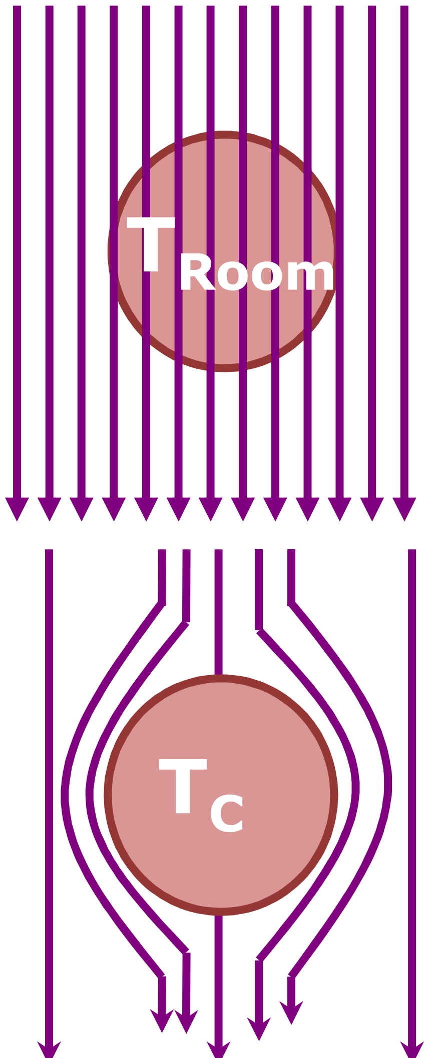
- Earlier, the materials having transition temperature above 30 K are called as High T_c or HTS materials.

- Recently this value has been changed to 77 K, due to easy availability of LN_2.

Development of SCs



Meisner Effect

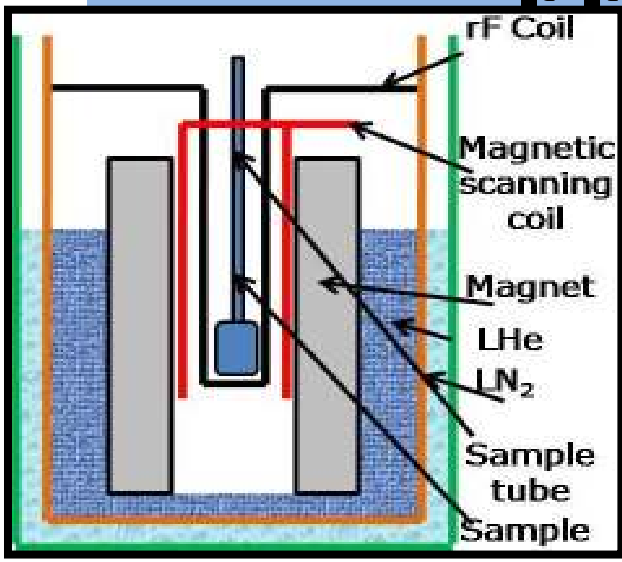


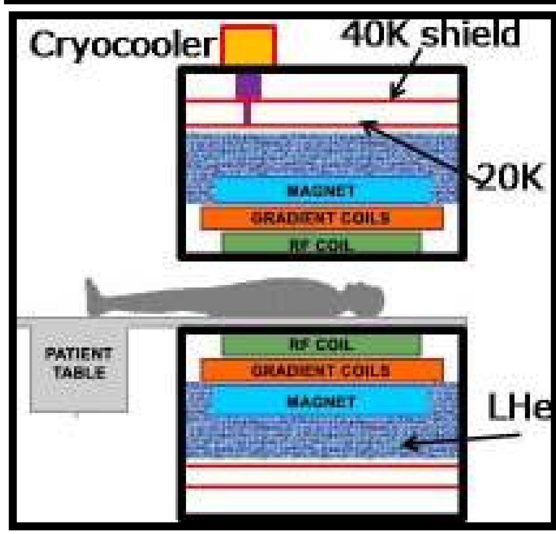
- At room temperature, if a material is subjected to a magnetic flux, the flux lines of force penetrate through the material.
- As soon as the material becomes superconducting, it repels the magnetic flux lines.
- This phenomenon is called as Meisner Effect and was first discovered by Meisner and Robert in the year 1933.

MAGLEV

- Maglev Train runs on the principle of Magnetic Levitation.
- When YBCO is cooled to temperatures less than 90 K, it turns diamagnetic.
- Proper balancing of the vessel as shown in the video levitates it from the magnetic track.
- Using the same principle, MAGLEV train gets levitated from the guide way.
- This results in no contact motion and therefore no friction.

Applications of SC





- The Nuclear Magnetic Resonance (NMR) is used by the drug industry to study the molecular structure.
- It has a SC magnet (10 T ~25 T).
- The Magnetic Resonance Imaging (MRI) machines used for body scanning have SC magnets cooled by LHe.

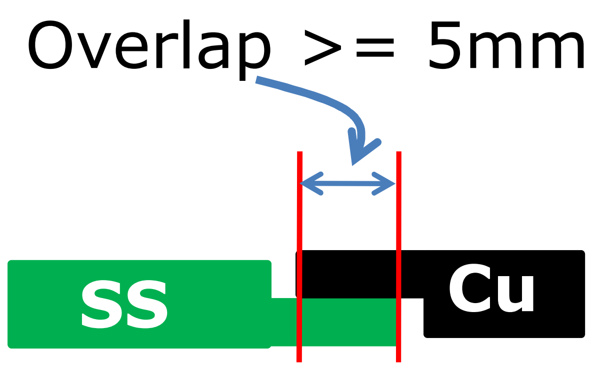
Tutorials

- There are four tutorial problems in the forthcoming slides.

1. Thermal expansion/contraction – 1 tutorial.
2. Estimation of C_v using the Debye Theory – 2 tutorials.
3. Thermal conductivity of materials – 1 tutorial.

Tutorial – 1

Calculate the overlap length of a brazed butt joint formed by SS 304 (L_0=1m) and Copper (L_0=0.5m). It is desired that the minimum overlap should be greater than 5mm. The joint is subjected to a low temperature of 80 K. Use the following data for the calculations.



	SS $\frac{\Delta L}{L_0}.10^5$	Copper $\frac{\Delta L}{L_0}.10^5$
300 K	304	337
80 K	13	26

- This condition should be verified at 80 K.

Tutorial – 1

SS 304

- Mean linear expansion in SS 304 butt

$$\frac{\Delta L_{SS}}{L_0} = \left(\frac{L_{T1}}{L_0} - \frac{L_{T2}}{L_0} \right) .10^{-5}$$

$$\frac{\Delta L_{SS}}{L_0} = (304 - 13).10^{-5}$$

L_0=1m, $\Delta L_{SS} = 2.91 mm$

Cu

- Mean linear expansion in Cu butt

$$\frac{\Delta L_{Cu}}{L_0} = \left(\frac{L_{T1}}{L_0} - \frac{L_{T2}}{L_0} \right) .10^{-5}$$

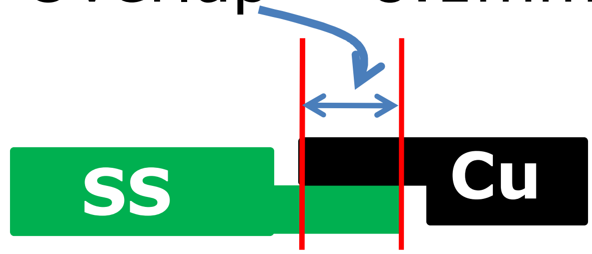
$$\frac{\Delta L_{Cu}}{L_0} = (337 - 26).10^{-5}$$

L_0=1m, $\Delta L_{Cu} = 3.11 mm$
L_0=0.5m, $\Delta L_{Cu} = 1.55 mm$

Tutorial – 1

- The greater of the two expansions is dL_{SS}
- The safe Butt joint should be more than dL_{SS} + 5 = 7.91mm.

Overlap = 8.1mm (say)



- When this joint is cooled to 80 K, the butt width in Cu after shrinkage is 6.55mm. Similarly, the butt width in SS after shrinkage is 5.19mm.

- Hence, the overlap being more than 5mm is a good design.

Debye Theory

- The expression for C_v, given by Debye theory is

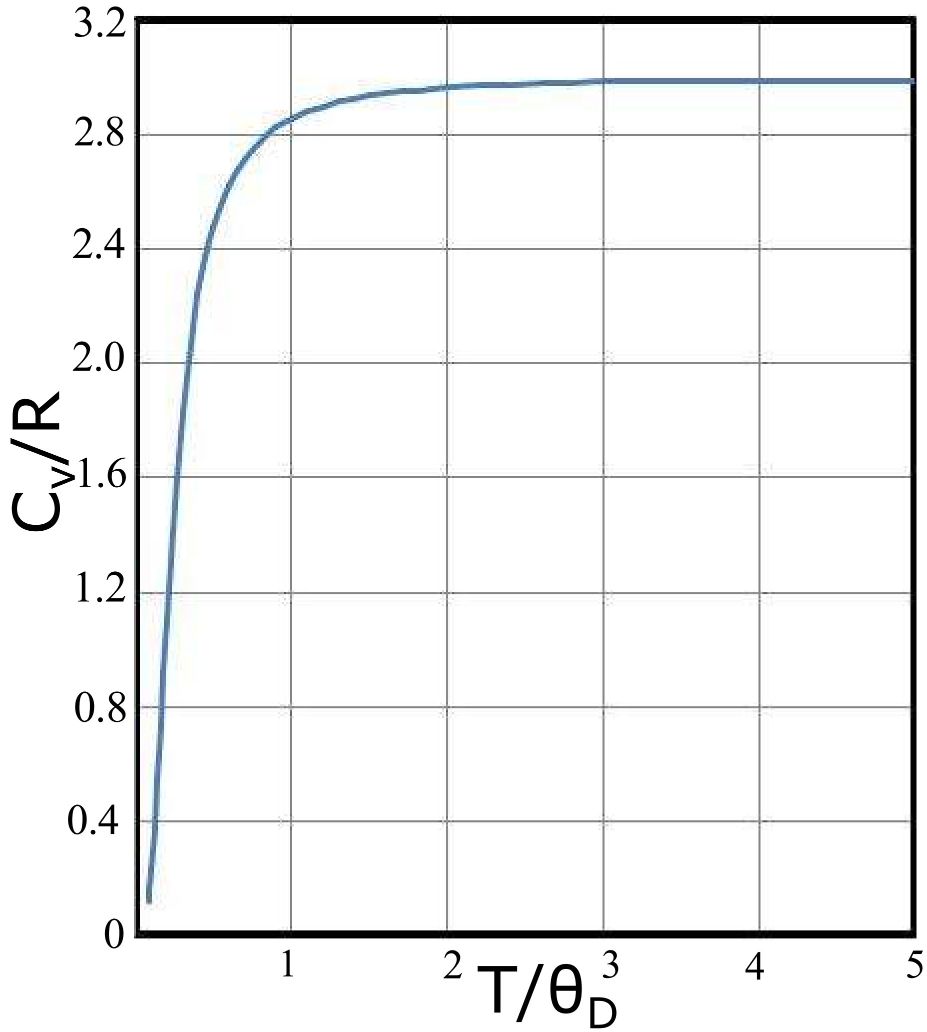
$$C_v = 3R\left(\frac{T}{\theta_D}\right)^3 D\left(\frac{T}{\theta_D}\right)$$

- θ_D is called as Debye Characteristic Temperature.
- At $(T > 2\theta_D)$, C_v approaches 3R. This is called as Dulong and Petit Value.
- At $(T < \theta_D/12)$, C_v is given by following equation.

$$c_v = \frac{12\pi^4 R}{5}\left(\frac{T}{\theta_D}\right)^3$$

- Also, D(0) is given a constant value of $4\pi^4/5$.

Specific Heat Curve



- The variation of C_v/R with T/θ_D is as shown.
- θ_D for few materials.

Material	θ_D
Aluminum	390
Lead	86
Nickel	375
Copper	310
Silver	220
α-Iron	430
Titanium	350

Tutorial – 2

Determine the lattice specific heat of copper at 100 K. Given that the molecular weight is 63.54 g/mol.

- Step 1:
- Calculation of T/θ_D ratio.

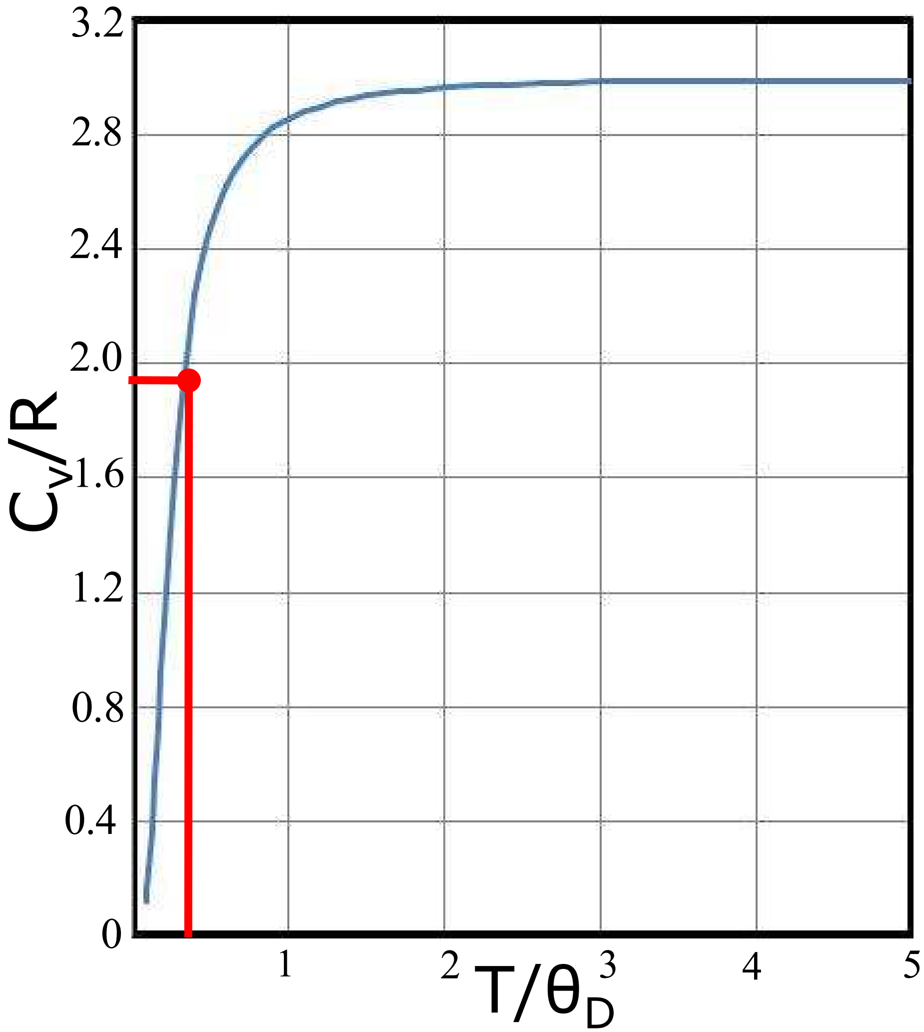
Material	θ_D
Aluminum	390
Lead	86
Nickel	375
Copper	**310**
Silver	220
Titanium	350

T = 100 K
θ_D = 310 K

$$\frac{T}{\theta_D} = \frac{100}{310} = 0.3225$$

- The value of T/θ_D is greater than 1/12 (0.0833).

Tutorial – 2



- The value of T/θ_D = 0.3225.
- From the graph, C_v/R = 1.93.

$$R = \frac{8.314}{0.06354} = 130.85$$

$$C_v = 130.85 X 1.93$$

$$= 252.534$$ **J/kg-K**

Tutorial – 3

Determine the lattice specific heat of Aluminum at 25 K. Given that the molecular weight is 27 g/mol.

- Step 1:
- Calculation of T/θ_D ratio.

Material	θ_D
Aluminum	**390**
Lead	86
Nickel	375
Copper	310
Silver	220
Titanium	350

T = 25 K

θ_D = 390 K

$$\frac{T}{\theta_D} = \frac{25}{390} = 0.0641$$

- The value of T/θ_D is less than 1/12 (0.0833).

Tutorial – 3

- Since, the T/θ_D ratio is less than 1/12, the equation to calculate the specific heat is as given below.

$$c_v = \frac{12\pi^4 R}{5}\left(\frac{T}{\theta_D}\right)^3$$

$$R = \frac{8.31434}{0.0270} = 307.9$$

$$c_v = \frac{233.78 R T^3}{\theta_D^3}$$

$$= 18.958 \text{ J/kg-K}$$

Thermal Conductivity Integrals

- The Fourier's Law of heat conduction is

$$Q = -k(T)A(x)\frac{dT}{dx}$$

- To make calculations less difficult and to account for the variation of k_T with temperature, Q is expressed as $Q = -G(\theta_2 - \theta_1)$
- kdT is taken as an integral called as Thermal Conductivity Integral evaluated w.r.t a datum.

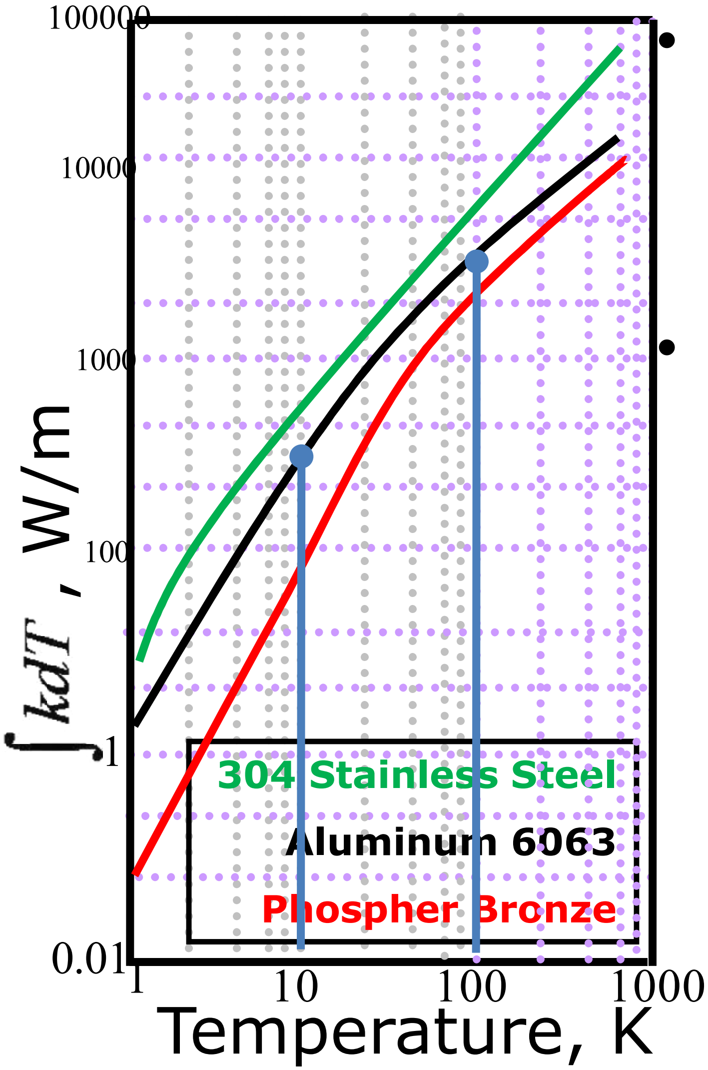
$$\theta_1 = \int_{T_d}^{T_1} k(T)dT$$

For Example

$$T_d = 0 \, or \, 4.2$$

- If A_{cs} is constant, G is defined as $G = A_{cs} / L$

Thermal Conductivity Integrals

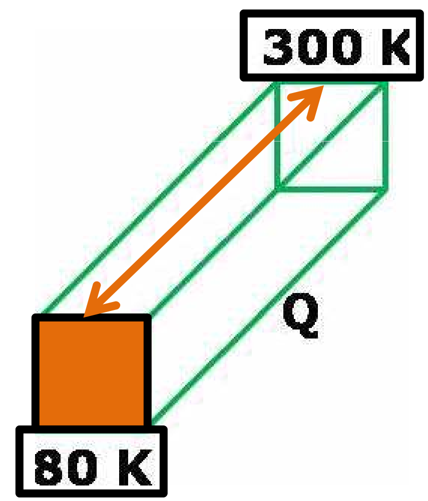


- The variation of kdT for few of the commonly used materials is as shown.
- In the calculations, the actual temperature distribution is not required, but only the end point temperatures.

$$\int_{10}^{100} kdT = \int_{0}^{100} kdT - \int_{0}^{10} kdT$$

Tutorial – 4

Determine the heat transferred in an copper slab of uniform cross section area 1cm^2 and length of 0.1m, when the end faces are maintained at 300 K and 80 K respectively. Compare the heat transferred by k_{avg} and kdT methods.

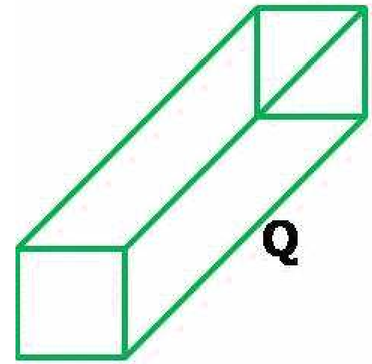


Given

- Area of cross section : 10^{-4} m^2
- Length of specimen: 0.1 m
- T_1 = 300 K
- T_2 = 80 K

Tutorial – 4

k_{avg} Method



$$Q = -k_{avg} A \frac{dT}{dx}$$

$$Q = k_{avg} A \left(\frac{T_1 - T_2}{L} \right)$$

$$Q = 57.75 X 10^{-4} \left(\frac{300 - 80}{0.1} \right)$$

$Q = 18.958$ **W**

k_{300} = 78.5 W/m K
k_{80} = 37.0 W/m K

k_{avg} = 57.75 W/m K

Tutorial – 4

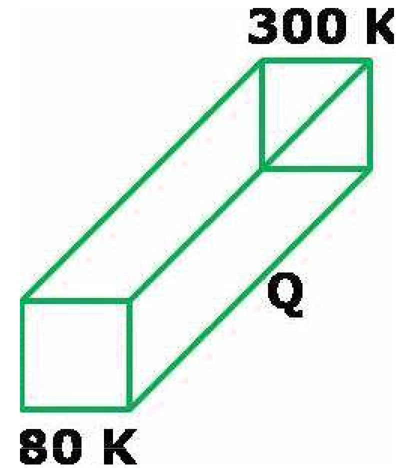
kdT Method

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

$$\theta_1 = \int_{4.2}^{300} k(T)dT = 15000$$

$$\theta_2 = \int_{4.2}^{80} k(T)dT = 1600$$

$$G = \frac{A_{cs}}{L} = \frac{10^{-4}}{0.1}$$



$$Q = -\frac{10^{-4}}{0.1}(1600 - 15000)$$

$Q = 13.4$ **W**

Comparison

k_{avg}	kdT
18.98	13.4

- K_{avg} is more than the kdT method.

Assignment

1. Determine the specific heat of Titanium at 20 K, if the specific heat is given by Debye function.

2. For Diamond the specific gas constant is 693 J/kg-K. Determine the energy required to warm a diamond of mass 20gm from 100 K to 185 K.

3. Determine the specific heat of aluminum at 60 K. given that the atomic weight is 27g/mol.

- Please check the standard properties for answers.

Assignment

4. Determine the heat transferred in an Aluminum slab of uniform cross section area 10cm^2 and length of 0.5m, when the end faces are maintained at 250 K and 80 K respectively.

$$\theta_1 = \int_{4.2}^{250} k(T)dT = 51300$$

$$\theta_2 = \int_{4.2}^{80} k(T)dT = 16700$$

5. Calculate the overlap length of a brazed butt joint formed by Copper (L_0=0.6m) and SS (L_0=1.5m). It is desired that the minimum overlap should be greater than 4mm. The joint is subjected to a low temperature of 100 K. Use the standard data form previous lecture.

Conclusion

- The properties of materials change, when cooled to cryogenic temperatures.

- Stainless steel is the best material for the cryogenic applications from strength point of view.

- Carbon steel cannot be used at low temperature as it undergoes a Ductile to Brittle Transition (DBT).

- Ultimate and Yield strength, fatigue strength of any material increase at lower temperature while impact strength, ductility decrease at lower temperature.

Conclusion

- PTFE (Teflon) can be deformed plastically at 4 K as compared to other materials.
- The coefficient of thermal expansion decreases with the decrease in temperature.
- For pure metals, k_T remains constant above LN_2 temperature. Below LN_2, it reaches a maxima and then after decreases steadily.
- For impure metals, k_T decreases with decrease in temperature. Integral kdT is used to calculate Q.

Conclusion

- Electrical conductivity of the metallic conductors increases at low temperature.
- k_e and k_t are correlated by Wiedemann–Franz Law.
- The sudden drop in the resistance when a particular material is cooled to lower temperatures is called as Superconductivity.
- This state is governed by three parameters namely Temperature (K), Current Density (A/mm^2) and Magnetic Field (Tesla).

Conclusion

- SC materials are distinguished into HTC and LTC depending upon the critical temperature they exhibit.

- Meisner Effect, Maglev, SC Magnets are some of the applications of the Superconductivity.

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Thank You!