Cryogenics : Basic Thermodynamics and Liquefaction Cycles

T S Datta
Indian Institute of Technology. Kharagpur. India

The 4th Asian School on Superconductivity and Cryogenics for Accelerators
Feb. 13-19, 2023, Korea University, Sejong, Korea

Outline of my Lectures

1. **Introduction on Cryogenics**
2. **How to Produce Cryogen**

   - **Thermodynamic Process (Carnot)**
     - **Liquefaction Cycle**
     - **Performance of Cycle**

3. **Practical Helium Liquefier/ Refrigerator**
   - **Components**

4. **Properties of Matter at Cryogenic Temperature**
   (If Time Permits)

Temperature Scale

Temperature	
6000K	Sun
373K	Water Boils
300K	Room Temp
273K	Ice
263K	SO_2 -liquid
240K	NH_3- liquid
111K	CH_4 –liquid (LNG)
90K	LOX -liquid Oxygen
77K	LN2 -liquid Nitrogen
20K	LH2 -liquid Hydrogen
4.2K	LHe -liquid Helium
2.1K	Superfluid Helium

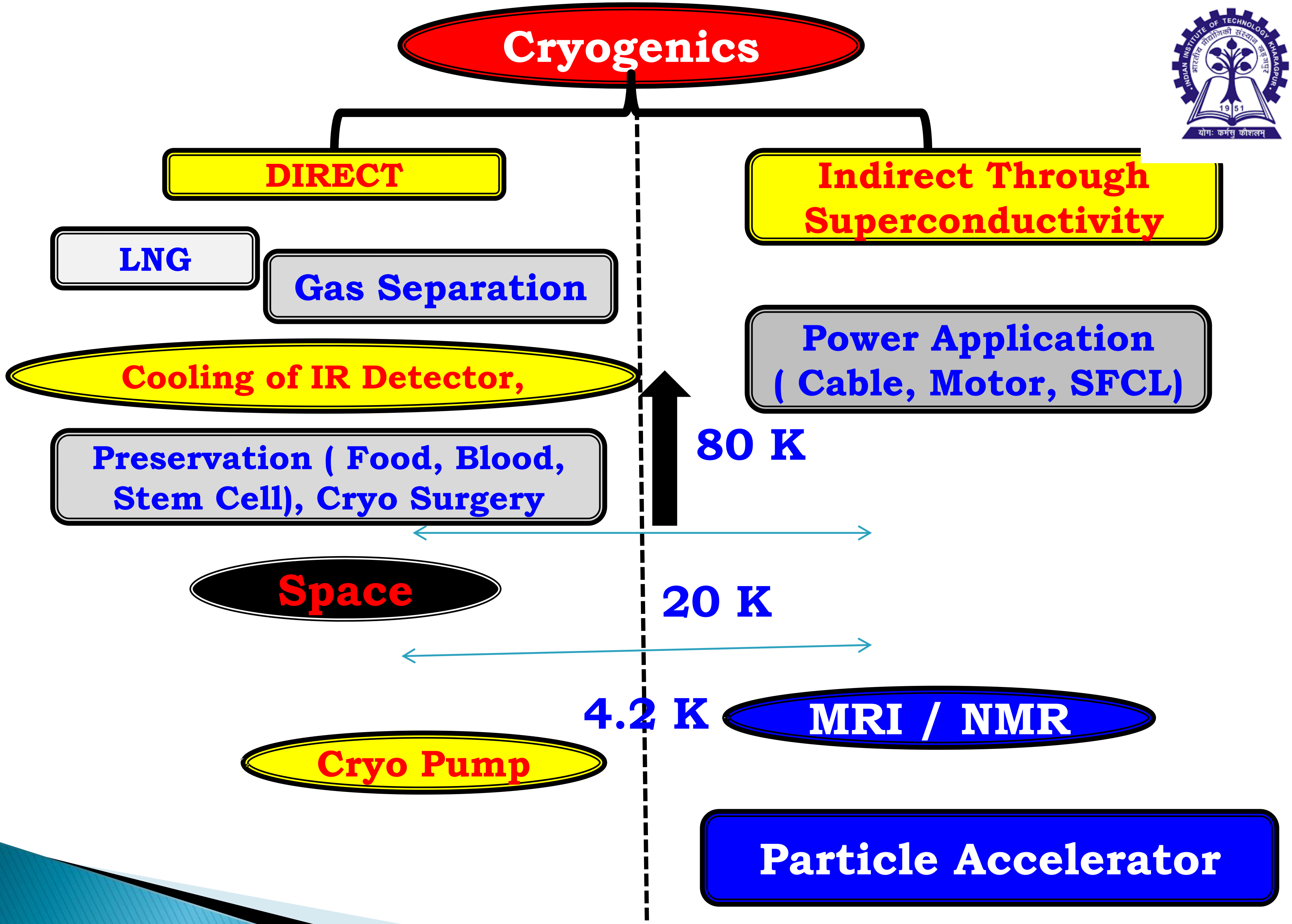
Lowest Temp: 500 pico K

Why?

120K — Cryogenics boundary

Cryogenic Temperature range

0 K - Absolute Zero

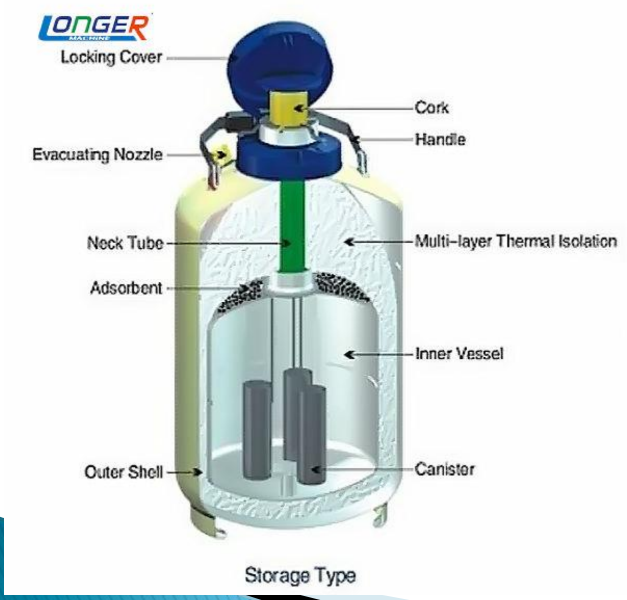

Cryogenics
DIRECT
Indirect Through Superconductivity
LNG
Gas Separation
Power Application (Cable, Motor, SFCL)
Cooling of IR Detector,
80 K
Preservation (Food, Blood, Stem Cell), Cryo Surgery
Space
20 K
4.2 K
MRI / NMR
Cryo Pump
Particle Accelerator

CRYOGEN STORAGE VESSEL

Small container 10- 60 L

100- 500L Pressurized

20,000 L Storage Vessel at IUAC



Transport Vessel

WHY STORAGE IS SO CRITICAL ?

A. LOW LATENT HEAT (L)

B. LARGE TEMPERATURE DIFFERENCE (T_r- T_b)

Property	He	N2	Water
Boiling Point	4.2K	78K	373K
Density	0.12kg/liter	0.81kg/liter	1kg/litre
Heat of Vaporisation	*20KJ/ kg*	*198*	*2250*
Liquid evaporated on 100 W Heat input	140 L/ hr	2.2 L/hr	0.16 L/hr

1 W HEAT LOAD EVAPORATES 34 LITRES LHe in ONE DAY

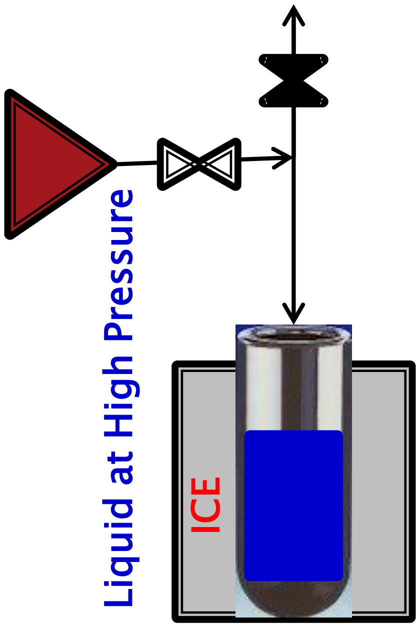
THANKS TO MLI (MULTILAYER INSULATION TECHNOGY)

EVAPORATION RATE ONLY 1 LITRES/d in 100 Litres Vessel

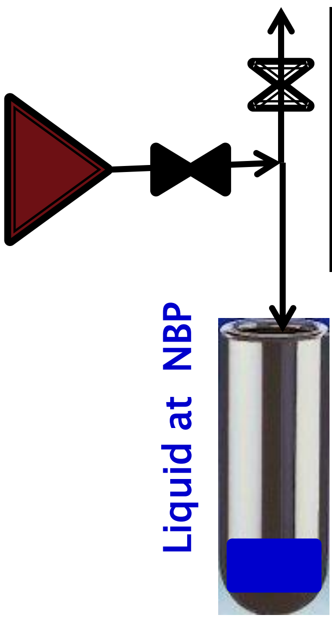
PERMENANT GASES

Laboratory techniques for reducing temperatures and Liquefaction

A. **Liquefaction of gas at high pressure in a thick-walled glass tube surrounded by ice (273 K),**
B. **A rapid expansion of the vapor phase to atmospheric pressure through a valve.**
C. **The temperature of the remaining liquid phase then dropped to its NBP.**



a) Isothermal Compression



b) Rapid Expansion

Ethylene, could be liquefied with a critical temperature of 282 K and a normal boiling point temperature of 169 K,

Methane, Nitrogen, hydrogen, Helium that could not be liquefied by this technique, even with pressures up to 40 MPa, were called “permanent”gases.

CRYOGENIC RANGE

	T(boil)	T(critical)	P(critical)
SO_2	263K	432K	79 Bar
NH_3	240K	405K	115 Bar
C_2H_4	169	282	50
CH_4	112	191K	46 Bar
O_2(LOX)	90K	155K	50 Bar
N_2 (LN2)	78K	126K	34Bar
H_2 (LH2)	20K	33K	13Bar
He(LHe)	4.2K	5.2K	2.2 Bar

Permanent Gas

Tc [SO2/NH3] > 273K (ICE temp)

gas

Pressure

liquid

Tc [N2/He] < 273 K (ICE Temp)

gas

Whatever Pressure ?

No liquid

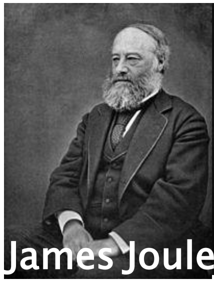
LNG & LPG ??

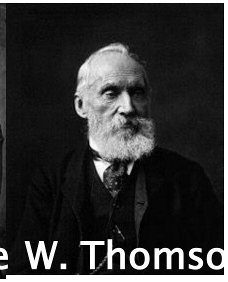
Permanent Gases

Hence they are called

Ar, N_2, O_2, Air, Ne, H_2 and He

HISTORY ON LIQUEFACTION OF PERMANENT GASES



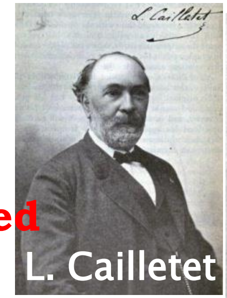


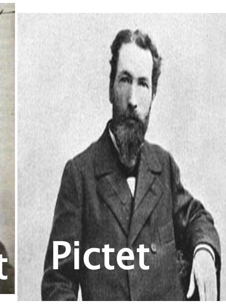
1852

JT Effect Discovered

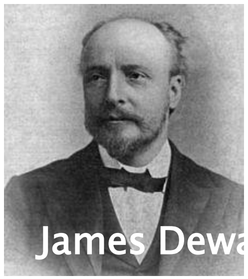
1877- 1883

Oxygen / Nitrogen Liquefied





Wroblewski and Olszewski

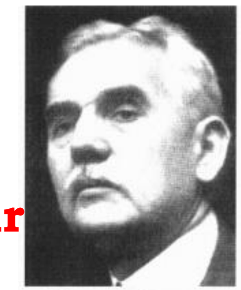


1898

Hydrogen Liquefied

1902

Expansion Engine for Air



George **Claude**

Carl **von Linde**

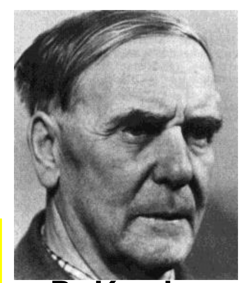
Heike
Kamerlingh Onnes

July 10, 2008

Helium Liquefaction

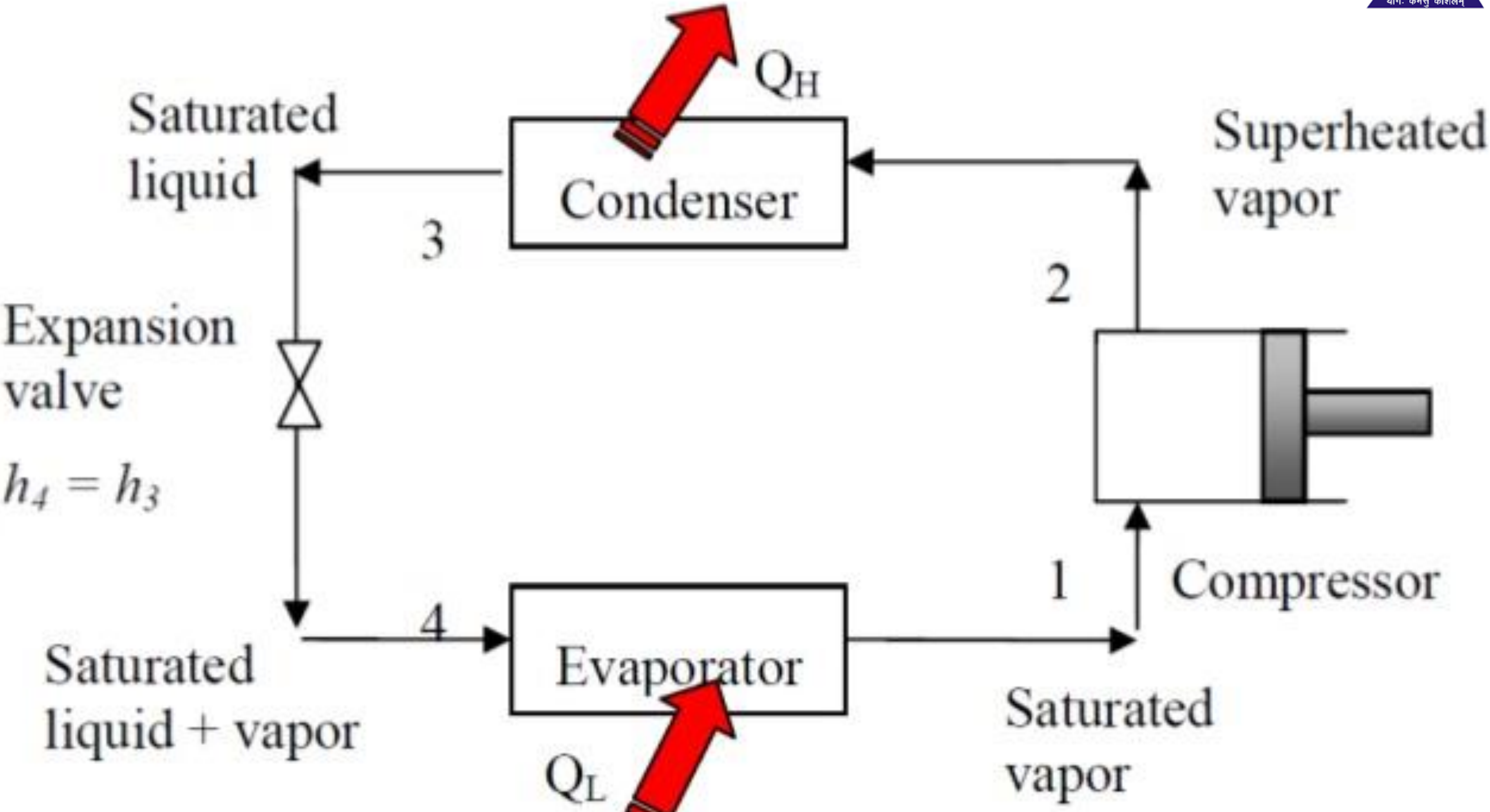
1934

Helium Liquefaction with Claude Cycle



P. Kapitsa

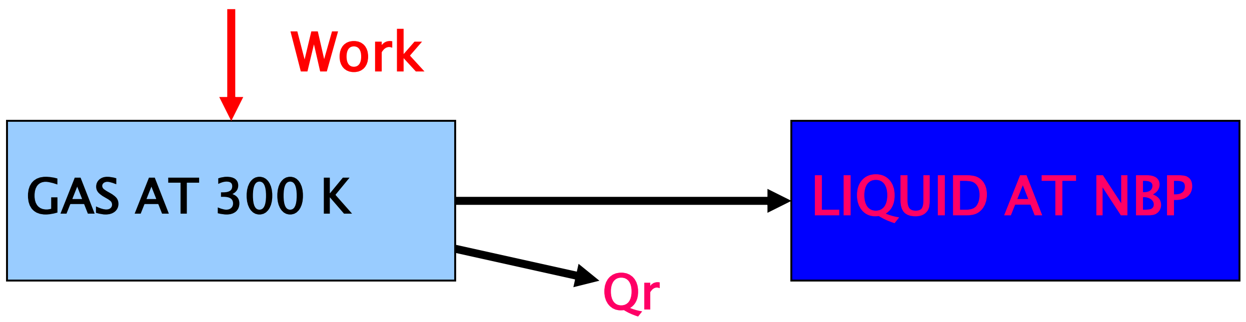
DOMESTIC REFRIGERATOR



We can not use similar principle for Cryogenic Refrigerator, because Critical Temperature of Cryogenic gases are much below Room Temperature

LIQUEFACTION OF PERMANENT GASES

Qr = Sensible Heat + Heat of Vaporisation



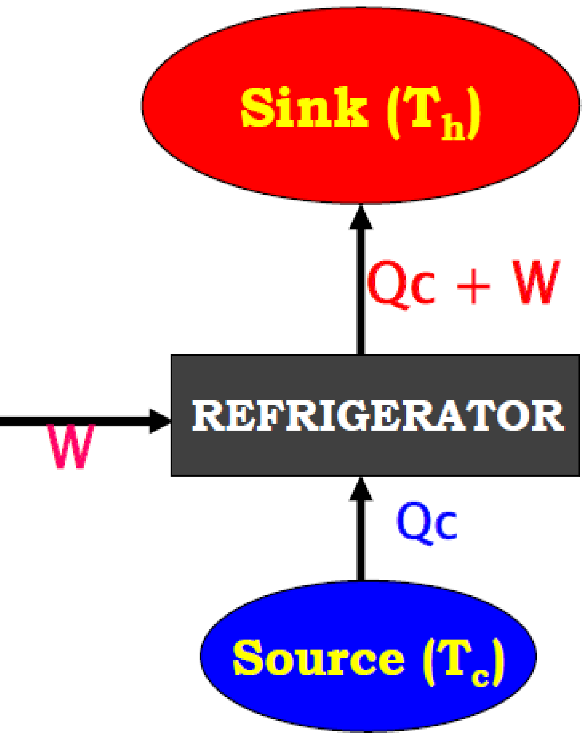
(Qr) = Nitrogen 234 J/ gm (300K to 78 K) + 199 J/gm

Helium : 1542 J/ gm (300 K to 4.2 K) + 20 J/ gm

Sensible Heat **Latent Heat**

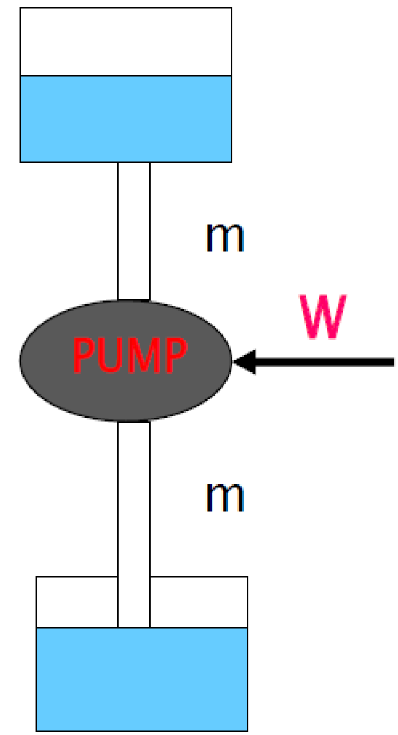
Refrigerator

To Transfer Heat from Source to Sink if Source Temp is less than Sink



Refrigerator is analogues to Water Pump to transfer Heat (Water) from Lower Temp (Lower level) to Higher Temp (Higher Level)

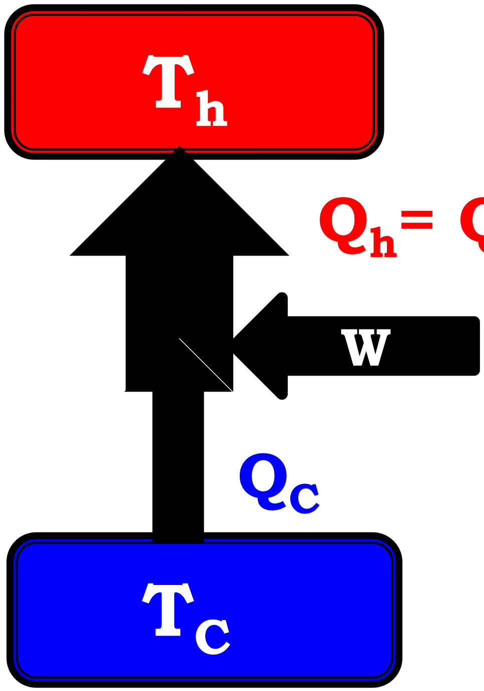
Power required or pump size depends on water capacity (Ref. Load in Watt) and the difference of level (Diff on Temp)



Transfer Amount of Heat energy is different between Source and Sink unlike pump. That embodies the concept the " Quality" of Thermal energy

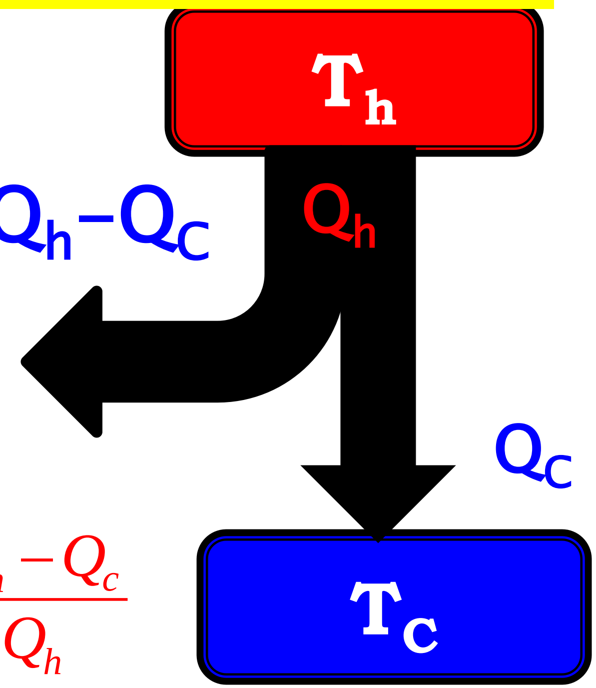
REFRIGERATOR & HEAT ENGINE

Second Law of Thermodynamics: It is impossible to extract an amount of heat Q_H from a hot reservoir and use it all to do work W .



$Q_h = Q_C + W$

$W = Q_h - Q_C$



$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h}$$

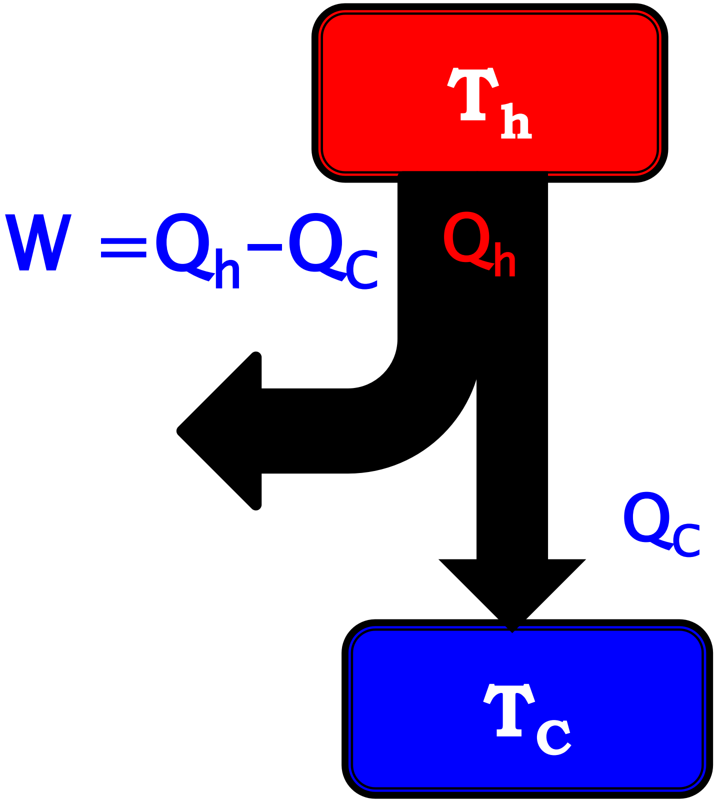
$COP_{R,Carnot} = Q_C / W$

$= T_C / (T_h - T_C)$

2nd Law of Thermodynamics: It is not possible for heat to flow from a colder body to a warmer body without any input of Work

CARNOT CYCLE is the Most Efficient Cycle to have Maximum Work

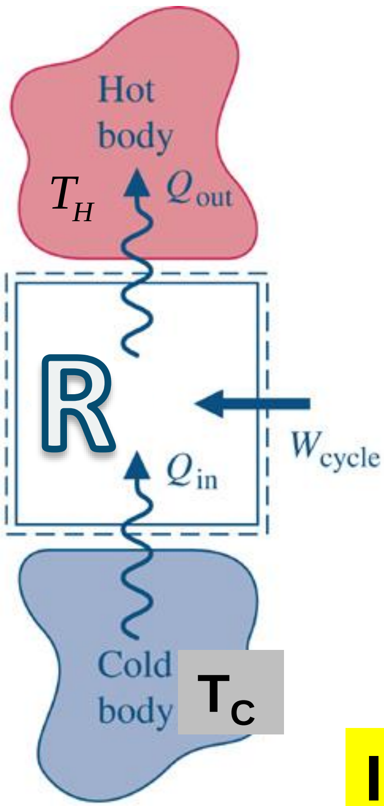
$$\eta = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = \frac{T_h - T_c}{T_h}$$



Here T_C Is fixed (300 K) and T_h Can be varied . Higher T_h Higher Efficiency.

T_h= 600, η = 50 %
T_h= 1000K , η= 70%

VCR used for Cooling



$$\eta_E = \frac{\text{energy sought}}{\text{energy that costs}} = \frac{Q_{in}}{W_{cycle}} = \mathrm{COP_C}$$

$\mathrm{COP}_{R,Carnot} = T_C/(T_h - T_C)$

Observation: η_E may be >1 $(\eta_E > 100\%)$

The concept of an efficiency being greater than 100% makes people uneasy. Therefore, the conversion efficiency for a refrigerator is called the **Cooling Coefficient of Performance ($\mathrm{COP_C}$)**. A refrigeration system that is used for cooling is called a **refrigerator**.

Inverse COP : Power required to have refrigeration of 1 W : $W/Q_c = (T_h - T_C)/T_C$

Power (W) required to extract 1 W refrigeration at Tc is : 1/ (COP) =

$$= \frac{W}{Q_c} = \frac{Q_h - Q_c}{Q_c} = \frac{T_h - T_c}{T_c}$$

T_h = 300 K T_c vary from 200 K to .000001 K

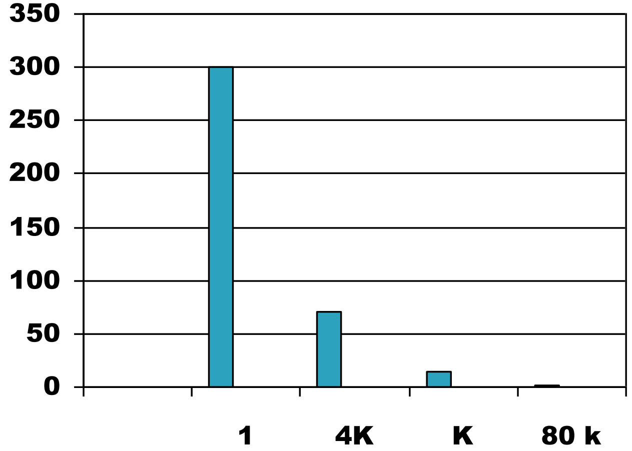
T_C=200 K , W = 0.5 W

LN_2 : T_c = 78 K , W = 1.68 W

LH_e : T_c = 4.2 K, W = 70 W

Tc= 2 K , W = 150 W

T_c = 0.01   W= 30k W



These are Theoretical minimum Power. We have to multiply first with efficiency of the Cycle and then multiply with mechanical efficiency of all Components (Compressor, Heat Exchanger, Expander of refrigerator)

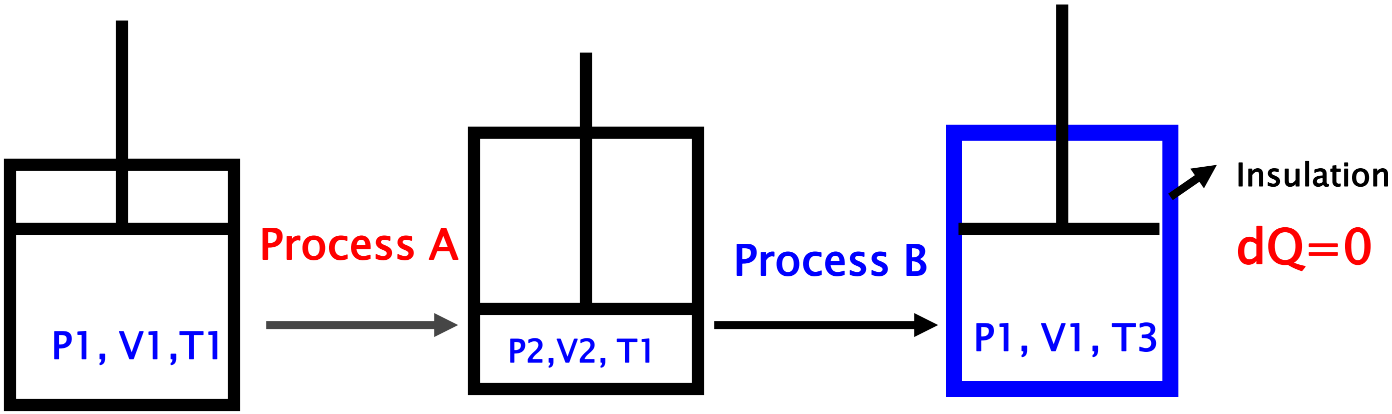
Actual work $= W_c/(\eta_{Cycle} * \eta_{Comp})$ Total efficiency may be 10 to 30 % at 4.2 K

Required Plug Power for 1 W refrigeration at 4. 2 K = 500- 225 W

Required Plug Power for 1 W refrigeration at 2K = 1000- 1500 W

BASIC THERMODYNAMIC PROCESS FOR COOLING

- A. ISOTHERMAL COMPRESSION (Compressor)
- B. ADIABATIC EXPANSION (Turbine)
- C. ISENTHALPIC EXPANSION (JT VALVE)
- D. ISOBARIC COOLING (Heat Exchanger, Precooler)



T3 < T1 (Cooling)

Isothermal compression is achieved with water/ air cooling System. W = m. T (R/ M) ln (P2/P1) .

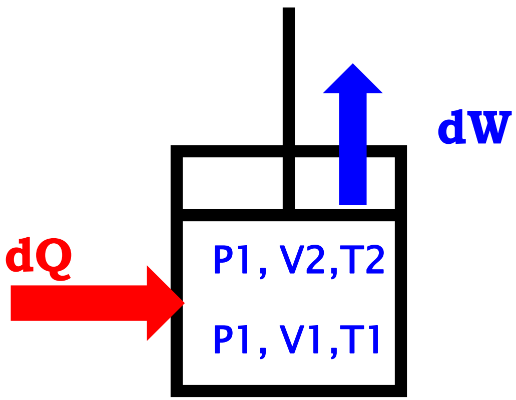
Example : 1 gm/s gas T= 300 K, P2/ P1 = 15

Helium : 1600 W (20 NM^3), N2 = 200 W (2. 8 NM^3)

Thermodynamic Parameters

Fundamental :

Pressure (P)
Temperature (T)
Volume (V)
Gas Constant (R)
Work (W)
Heat (Q)
Internal Energy (U)



$$dQ = dU + dW = C_p dT + pdV$$

Other Important Parameters

1. Entropy (S) :

$$dS = \frac{dQ}{T}$$

- **Entropy is a measure of Disorder.**
- **Second Law of Thermodynamics: In any cyclic process the entropy will either increase or remain the same.**

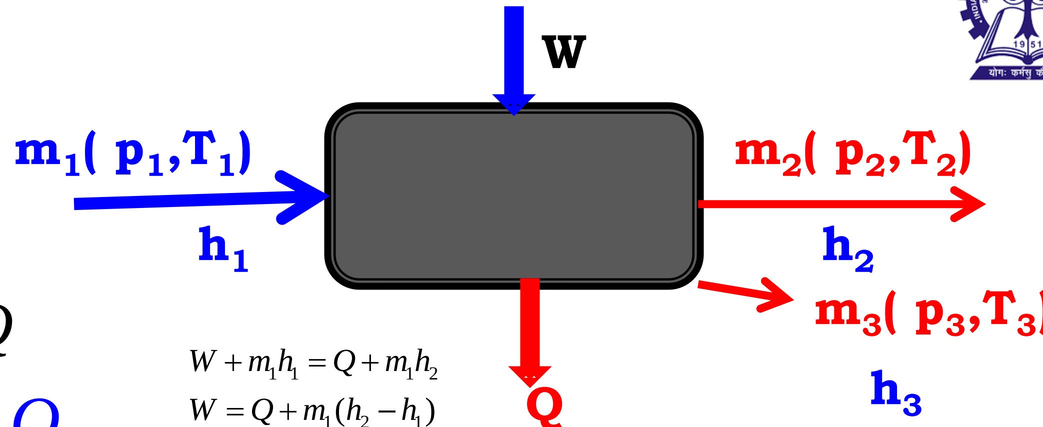
$$\oint ds = \oint \frac{dq}{T} \geq 0$$

2. Enthalpy (h)

- **equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.**

$$dh = du + pdv$$

Energy & Mass Balance



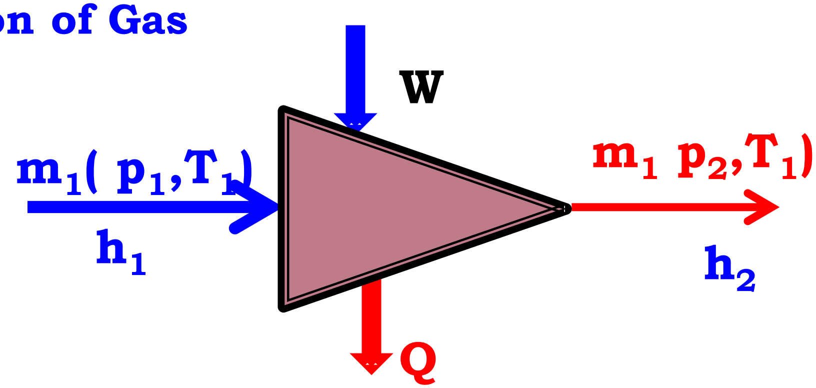
$$m_1 = m_2 + m_3$$

$$m_1 h_1 + W = m_2 h_2 + m_3 h_3 + Q$$

$$W = m_2 h_2 + m_3 h_3 - m_1 h_1 + Q$$

$$W + m_1 h_1 = Q + m_1 h_2$$
$$W = Q + m_1 (h_2 - h_1)$$
$$W = m_1 T_1 (S_2 - S_1) + m_1 (h_2 - h_1)$$

A. Example : Isothermal Compression of Gas

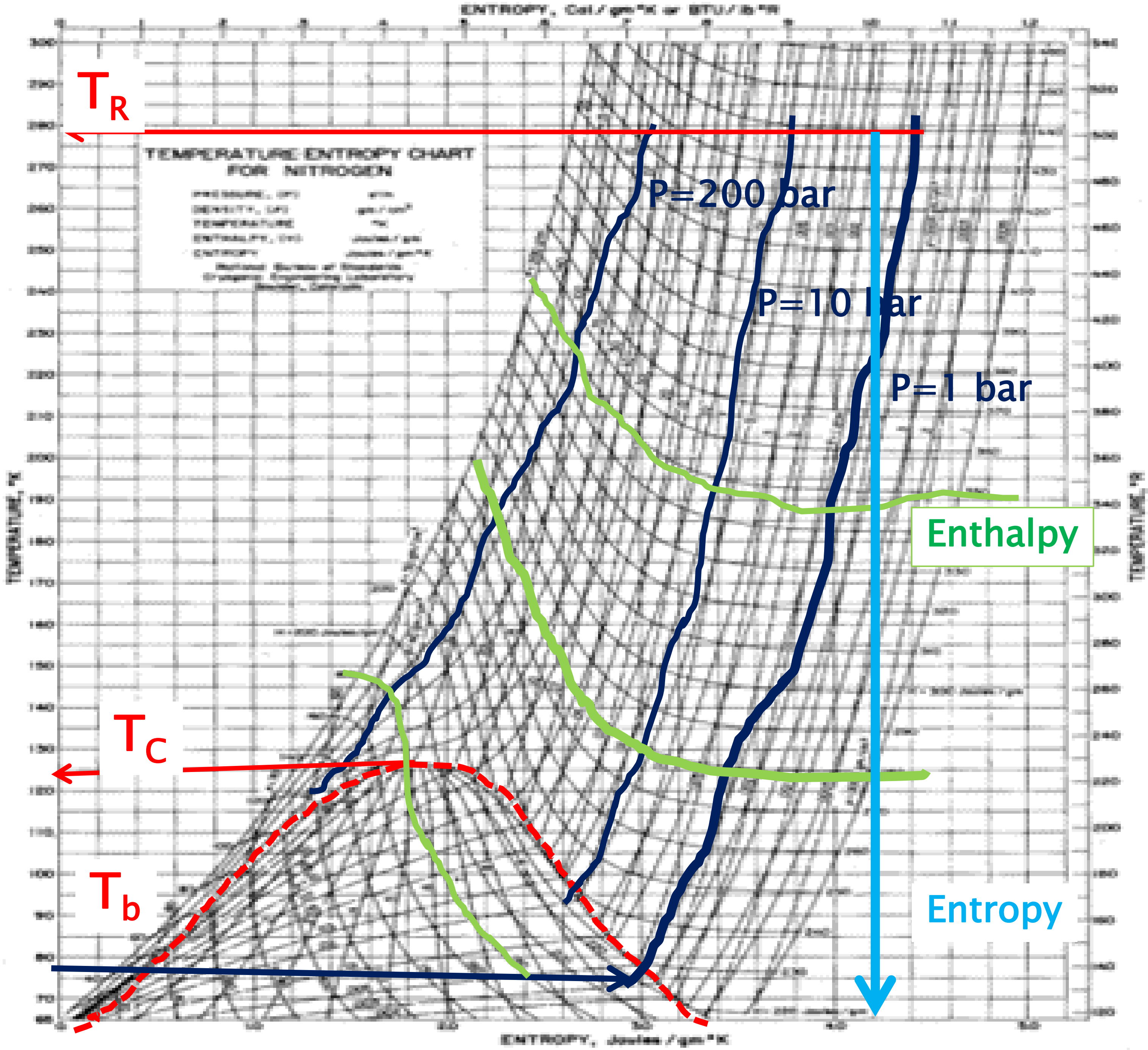


$$W + m_1 h_1 = Q + m_1 h_2$$

$$W = Q + m_1 (h_2 - h_1)$$

$$W = m_1 T_1 (S_2 - S_1) + m_1 (h_2 - h_1)$$

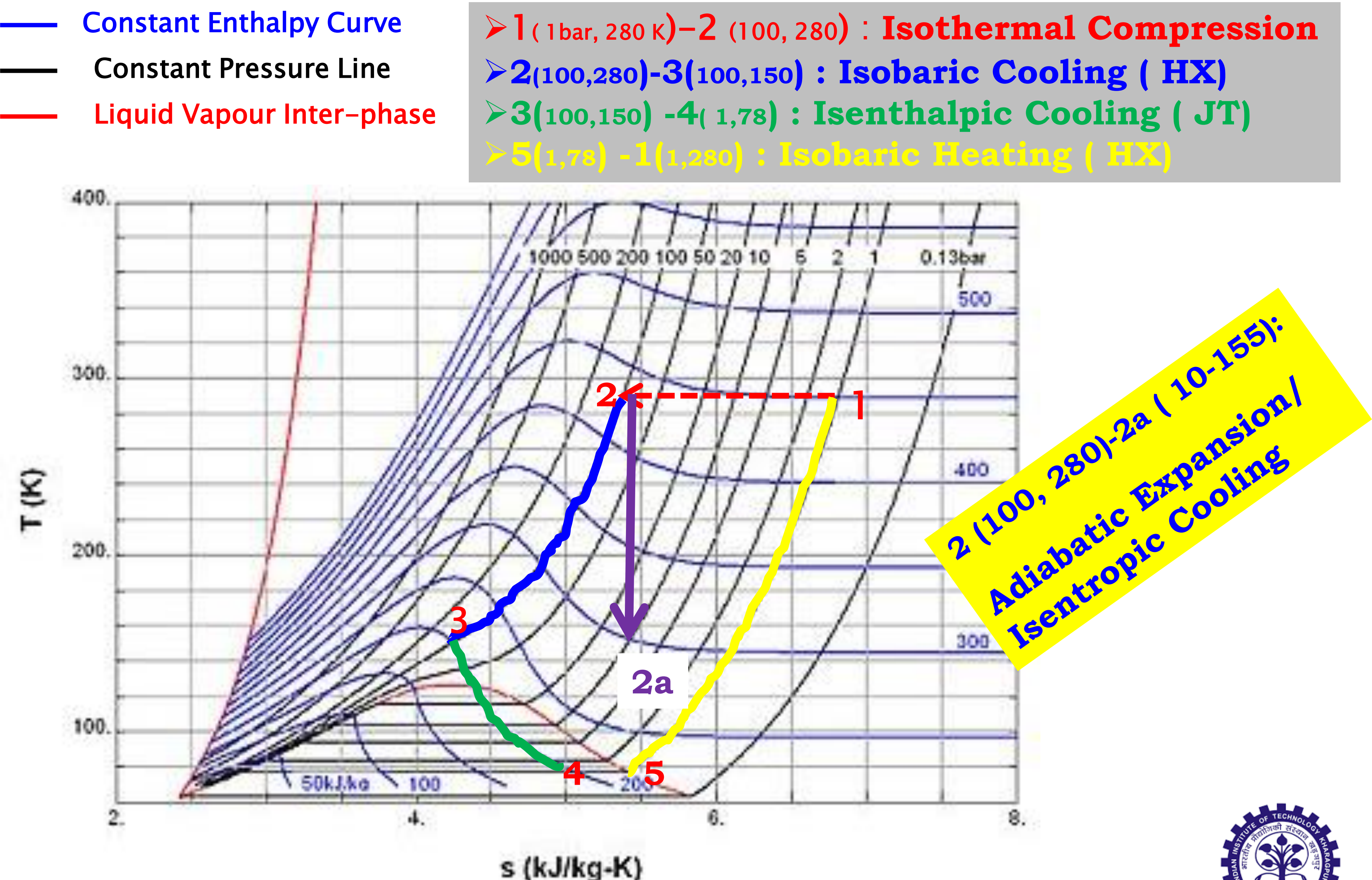
(Temperature, Entropy Chart with enthalpy)



ENTROPY, Cal / gm °K or BTU / lb °R
TEMPERATURE ENTROPY CHART
FOR NITROGEN
ENTROPY, Joules / gm °K
TEMPERATURE, °K
TEMPERATURE, °R
T_R
T_C
T_b
P=200 bar
P=10 bar
P=1 bar
Enthalpy
Entropy

SAMPLE TEMPERATURE- ENTROPY CHART FOR NITROGEN

- ➢1 (1bar, 280 K)–2 (100, 280) : **Isothermal Compression**
- ➢2(100,280)-3(100,150) : **Isobaric Cooling (HX)**
- ➢3(100,150) -4(1,78) : **Isenthalpic Cooling (JT)**
- ➢5(1,78) -1(1,280) : **Isobaric Heating (HX)**



To Liquefy Permanent Gases

Cooling

Isenthalpic (JT)

Indirectly By Other Cold Liquid/ Gas (Heat Exchanger

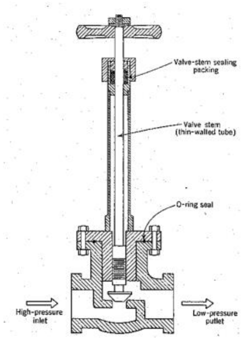
Isentropic

By JT Valve
(No External Work)

By Expansion Engine/Turbine
(Do External Work)

High Pressure to Low pressure

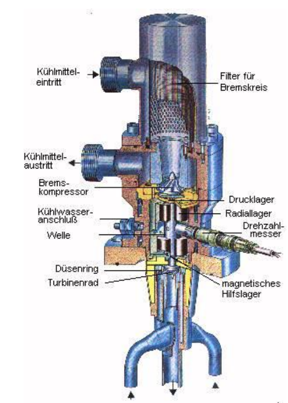
Cooling co- efficient



$$\mu_{jT} = \left(\frac{\partial T}{\delta p}\right)_h$$

$$\mu = \left({dT}/{dP}\right)_x$$

$$\mu_s = \left(\frac{\partial T}{\partial p}\right)_s$$



μ should be positive
Higher is Better

Isenthalpic /JT Cooling

$$\mu_{jT} = \left(\frac{\partial T}{\delta p}\right)_h = \frac{1}{C_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]$$

For an Ideal Gas $pv = RT, \quad \left(\frac{\partial v}{\partial T}\right)_p = R/p = v/T$

$$\mu_{JT} = 0$$

Fortunately Gas does not behave ideally

Real Gas : Vander Wall $\left(p + \frac{a}{v^2}\right)(v - b) = RT$

$$\mu_{JT} = \frac{(2a/RT)\left(1 - b/v\right)^2 - b}{C_p\left[1 - (2a/vRT)\left(1 - b/v\right)^2\right]}$$

Isenthalpic /JT Cooling

$$\mu_{JT} = \frac{(2a/RT)\left(1-\frac{b}{v}\right)^2 - b}{C_p\left[1-(2a/vRT)\left(1-\frac{b}{v}\right)^2\right]}$$

At large specific volumes

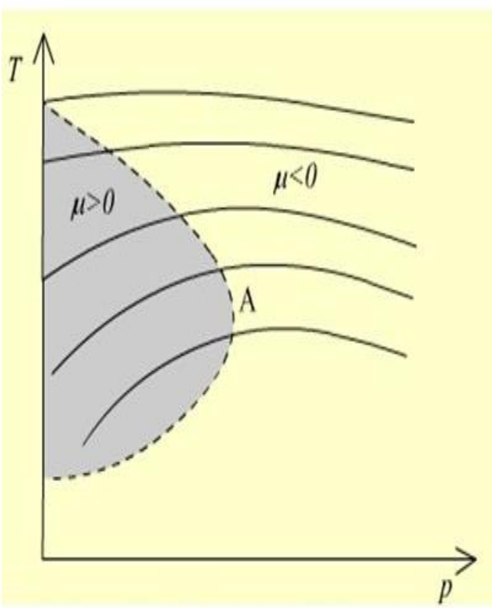
$$\mu_{JT} = \frac{1}{C_p}\left(\frac{2a}{RT} - \text{b}\right)$$

When , 2a/RT > b,
Or T < 2a/bR

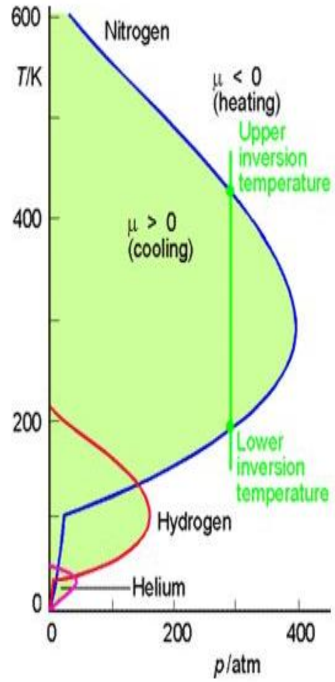
μ_{jT} is Positive , Hence Cooling

When , 2a/RT < b,

μ_{jT} is Negative , Hence Heating



Inversion curve



Inversion curve is represented by all points , where μ_{jT} =0

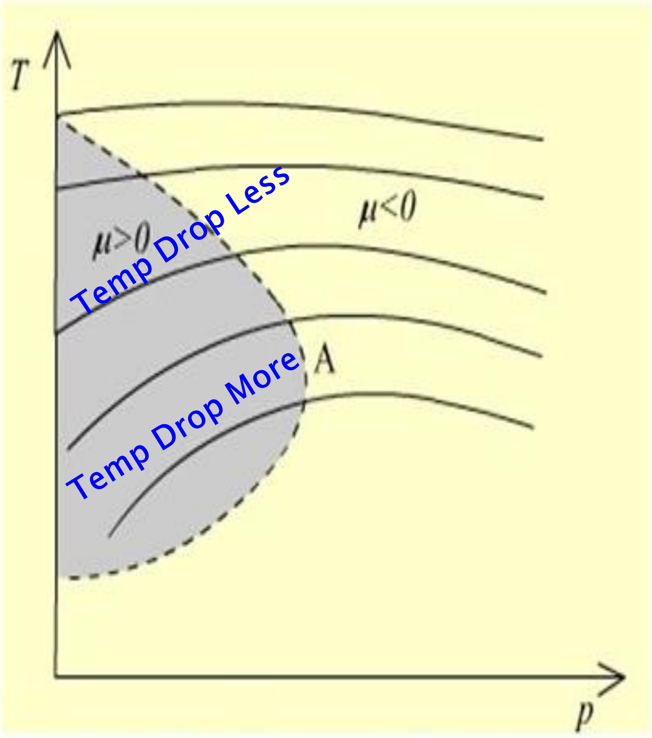
$$T_i = \frac{2a}{bR}\left(1-\frac{b}{v}\right)^2$$

Maximum Inversion Temperature
T_{imax} = 2a/bR
(at p=0 or b/v=0)

Above Max inversion temperature (T_{imax})we will not be able to cool the gas for any set of pressure combination.

Gas	He	H2	Ne	N2	Ar	O2
T_{imax} (K)	45	205	250	621	794	761

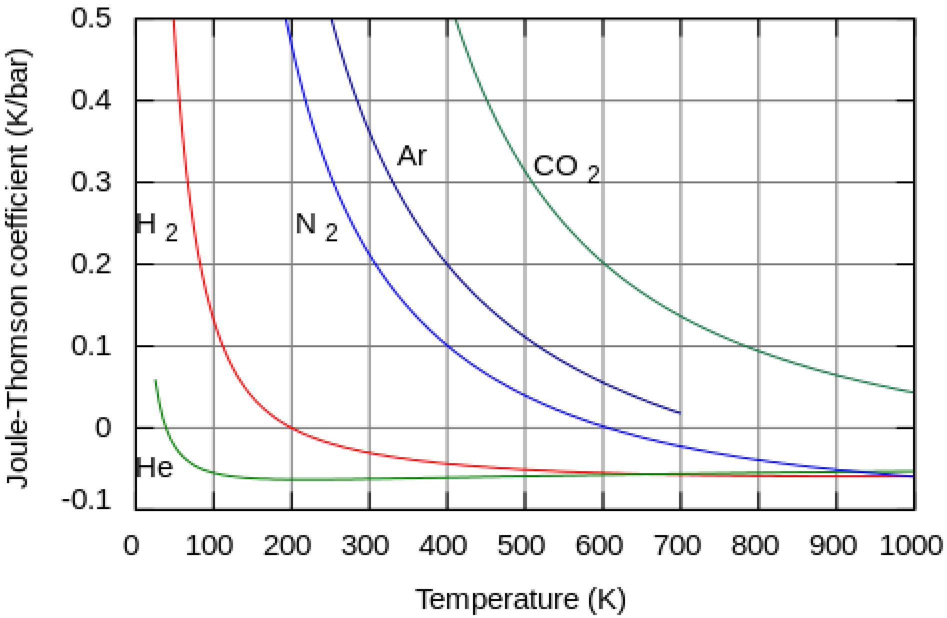
Above RT



Just below their max inversion temperature drop in temperature is not significant and temperature drop increases as we lower the inlet temperature and max above their critical temperature.

That's the reason JT is always incorporated in the last stage of liquefaction cycle. It can also handles liquid gas mixture unlike turbine

Temperature is the measure of thermal kinetic energy (energy associated with molecular motion); so a change in temperature indicates a change in thermal kinetic energy. The internal Energy is the sum of thermal kinetic energy and thermal potential energy. Thus, even if the internal energy does not change, the temperature can change due to conversion between kinetic and potential energy; this is what happens in a free expansion and typically produces a decrease in temperature as the fluid expands



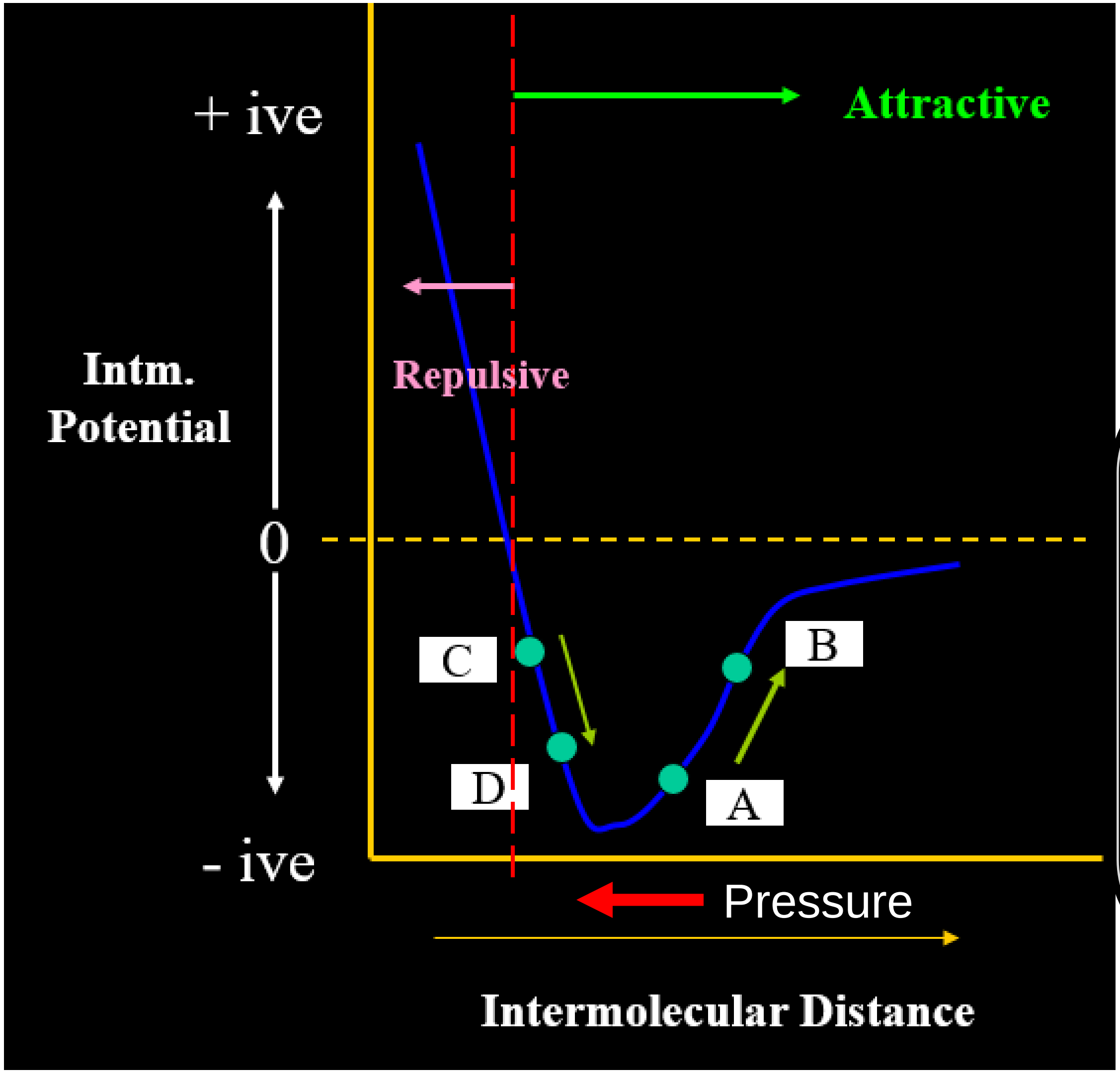
$$dh = du + pdv$$

Pdv=0 , dh=0 and hence du=0

d(KE+ PE) = 0

JT COOLING

$$dh = du + pdv$$



Pdv=0 , dh=0 and
Hence du=0

Difference (KE+ PE) = 0

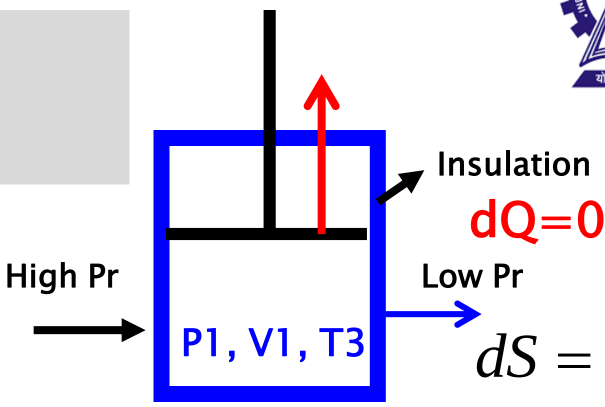
Expansion from A to B : Potential Energy increases and hence KE decreases (Temp Drop)

Expansion from C to D : Potential Energy decreases and KE increases , Temp increases

Adiabatic Expansion (Isentropic Cooling)

High Pressure Gas does an External work (Lifting Piston) and comes out at low Pressure and low temperature

$$\mu_s = \left(\frac{\partial T}{\partial p}\right)_s = \frac{T}{C_p}\left(\frac{\partial v}{\partial T}\right)_p$$



$$dS = \frac{dQ}{T}$$

$$\left(\frac{\partial v}{\partial T}\right)_p = R/p = v/T$$

$$\mu_s = {}^{v}\!/\!_{C_p}$$

dS=0 (Isentropic)

$$dQ = dU + dW = C_p dT + p dV$$

$$\mu_s > \mu_{JT}$$

- **Unlike JT Expansion, There will be always cooling effect on adiabatic expansion at any temperature and Pressure**
- **Temperature drop is much higher compared to JT Expansion**

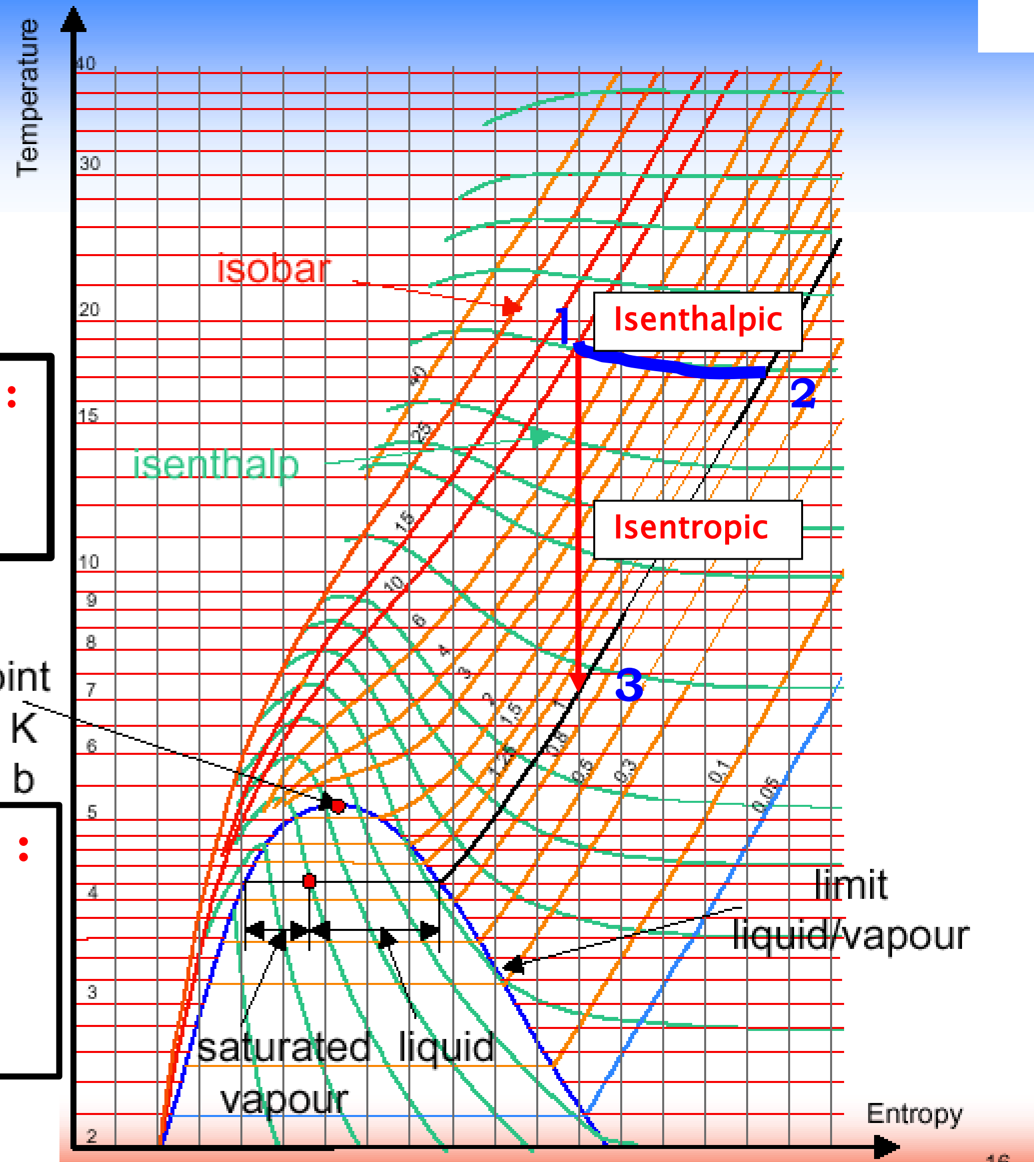
Comparison of Cooling Effect by JT & Isentropic Expansion Through T- S Chart

$(dT)_s >> (dT)_h$

HELIUM

1 (19k, 10 bar) - 2 (17 K, 1 Bar) :
JT Cooling

Drop only 2 K



Critical point
T = 5,195 K
P = 2,274 b

1 (19k, 10 bar) - 3 (7 K, 1 Bar) :
Isentropic Cooling

Drop 12 K

Adiabatic (Isentropic) Expansion

$$PV^{\gamma} = Constant \qquad \gamma = \frac{C_p}{C_v}$$

γ = 1.66 (He, Monatomic Gas)
=1.4 (N2, Diatomic Gas)

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} \qquad T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Example : If Helium Gas is Expanded from 220 Psi (p_1) to 18 Psi (p_2) at Inlet temperature (T_1) = 60 K

T_2 = 23.4 K , Actual Case it is 30K

Efficiency = 80 %

LIQUEFACTION SYSTEM PARAMETERS

- **Work Required per unit mass liquefied = W/m_f**
- **Work Required per unit Mass Gas Compressed = W/m**
- **Yield (What fraction of Compressed Gas is liquefied) , $y = m_f/m$**
- **Ideal work required per unit mass liquefied= W_i/m_f**
- **Figure of Merit : Ideal work/ Actual work for the cycle**

FOM= $(W_i/m_f)/\ (W/m_f)$: 0 to 1

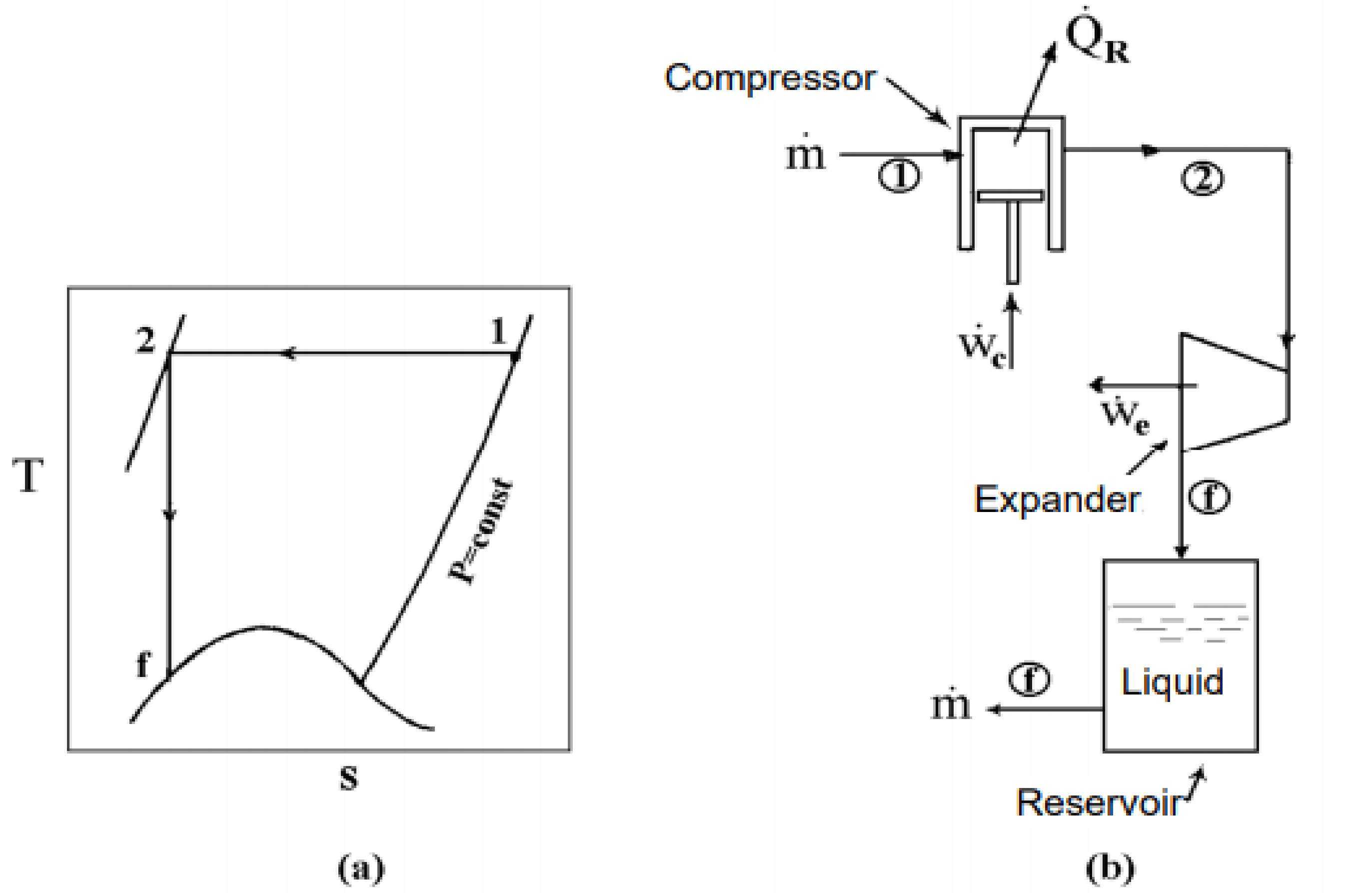
Assumptions

- ❑ Compressor and Expander Effic… 100%
- ❑Heat Exchanger Effective…
- ❑Pressure drop is neg…
- ❑Heat Transfer … …ld system from the Surrounding …

Not This Time

We … …nsider the effect of efficiency on …ycle performance in later stage

Ideal Thermodynamic Liquefaction Cycle



Ideal Thermodynamic Liquefaction System
(a) T-S diagram (b) System diagram

Ideal Thermodynamic Liquefaction Cycle

Table 3.1. Ideal-work requirements for liquefaction of gases beginning at 300 K (80°F) and 101.3 kPa (14.7 psia)

Gas	Normal Boiling Point		Ideal Work of Liquefaction, $-\dot{W}_i/\dot{m}_f$	
	K	°R	kJ/kg	Btu/lb$_m$
Helium-3	3.19	5.74	8 178	3 516
Helium-4	4.21	7.58	6 819	2 931
Hydrogen, H_2	20.27	36.5	12 019	5 167
Neon, Ne	27.09	48.8	1 335	574
Nitrogen, N_2	77.36	139.2	768.1	330.2
Air	78.8	142	738.9	317.7

- Theoretical minimum work for liquefaction of gas

$$-\frac{\dot{w}_i}{\dot{m}} = T_1 \cdot (s_1 - s_f) - (h_1 - h_f) = -\frac{\dot{w}_i}{\dot{m}_f}$$

Ideal Thermodynamic Liquefaction Cycle

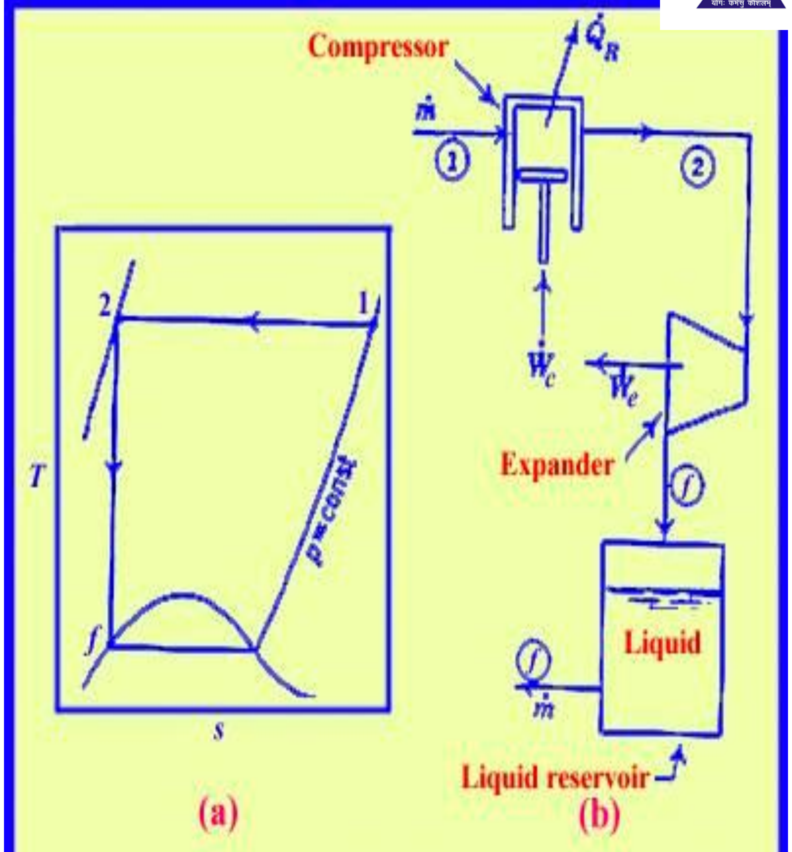
1----2 : Isothermal Compression
2----f : Isentropic Expansion

Not Possible , Why ???

For N_2, if P_1 is I bar, then P_2 must be 700000 Bar (very high pressure) to liquefy all the gases

Not Practical

Liquid Yield (Y) = m_f/m= 1



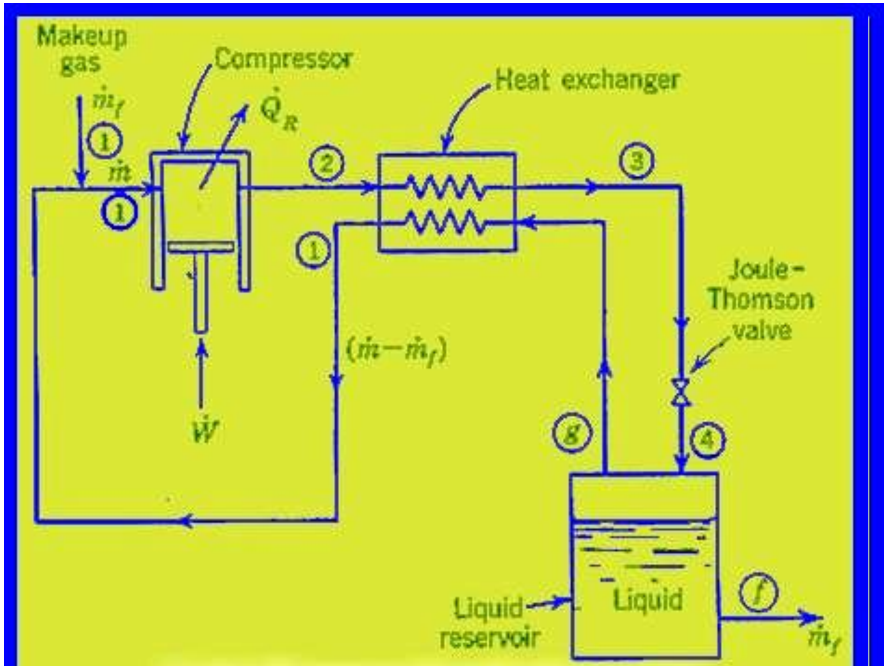
The thermodynamically ideal liquefaction system.

Ideal Work Requirement for 1 Kg Liquid Production
N2 = 768 KJ, He = 6800 KJ,

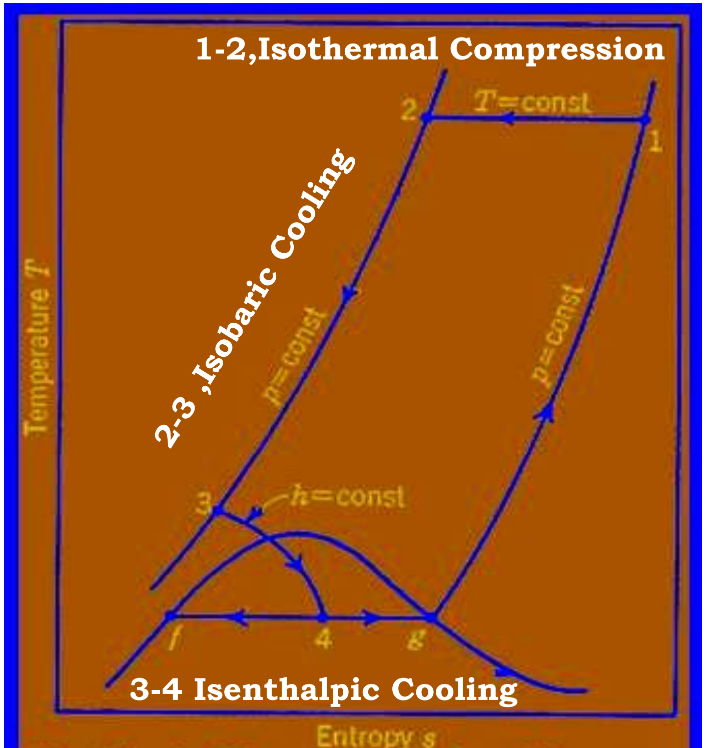
Value will be used for Comparison

Primary Practical Nitrogen Liquefier (Linde- Hampson Cucle)

It is only for those gases whose T_{imax} is above RT



Linde-Hampson liquefaction system.



The Linde-Hampson cycle. The state-points refer to the numbered points in the Linde-Hampson liquefaction system.

$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f} \quad <<1$$

Yield can be increased by Increasing Pressure (lower h2), Other parameters are fixed but at what cost ??

A simple table on liquid yield and work required per unit production of liquid nitrogen for various compressor discharge pressure is presented here

(T_1 = 300 K, P_1 = 1 bar absolute pressure, h_f = 30 J /gm. h_1 = 462 J/ gm)

$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f}$$

$$\frac{W}{m_f} = y\left[T_1\left(S_1 - S_2\right) - \left(h_1 - h_2\right)\right]$$

Pressure (P_2)	h_2	$Y = m_f / m$	W/m_f	FOM
20 bar	454	0.02	12888	0.06
50	448	0.03	9937	0.08
100	438	0.06	7200	0.11
200	425	0.09	5564	0.13

FOM = Ideal Work Required/ Actual Work

We Need Very High Pressure to have Significant Percentage of Liquid Production on this L- H Cycle

Linde-Hampson Performance

- Optimum theoretical performance realized by minimizing h_2 (P_2 such that h is on the inversion curve)
- P_2 is typically ~ 100 atm.
- Theoretical performance with P_2 = 20 atm.(from Barron):

Table 3.3. Performance of the Linde-Hampson system using different fluids. p_1 = 101.3 kPa (14.7 psia); p_2 = 20.265 MPa (200 atm); $T_1 = T_2$ = 300 K (80°F); heat-exchanger effectiveness = 100 percent; compressor overall efficiency = 100 percent

Fluid	Normal Boiling Point		Liquid Yield $y = \dot{m}_f/\dot{m}$	Work per Unit Mass Compressed		Work per Unit Mass Liquefied		Figure of Merit FOM = $\dot{W}_i/\dot{W}$
	K	°R		kJ/kg	Btu/lb$_m$	kJ/kg	Btu/lb$_m$	
N_2	77.36	139.3	0.0708	472.5	203.2	6673	2869	0.1151
Air	78.8	142	0.0808	454.1	195.2	5621	2416	0.1313
CO	81.6	146.9	0.0871	468.9	201.6	5381	2313	0.1428
A	87.28	157.1	0.1183	325.3	139.8	2750	1182	0.1741
O_2	90.18	162.3	0.1065	405.0	174.1	3804	1636	0.1671
CH_4	111.7	201.1	0.1977	782.4	336.4	3957	1701	0.2758
C_2H_6	184.5	332.1	0.5257	320.9	138.0	611	262	0.5882
C_3H_8	231.1	416.0	0.6769	159.0	68.4	235.0	101.0	0.5976
NH_3	239.8	431.6	0.8079	363.1	156.1	449.4	193.2	0.7991

No Helium??

Analysis on Linde- Hampson Cycle

Pressure	Yield mf/m	W/mf (J/ Kg)
100 Bar	0.06	7200

For 10 litre/ hr (8 kg/hr) liquid nitrogen production : Compressor capacity required at 100 bar discharge pressure

$m = m_f \times y$ = 8 kg/hr/0.06 = 133 kg/hr = 106 M^3/hr

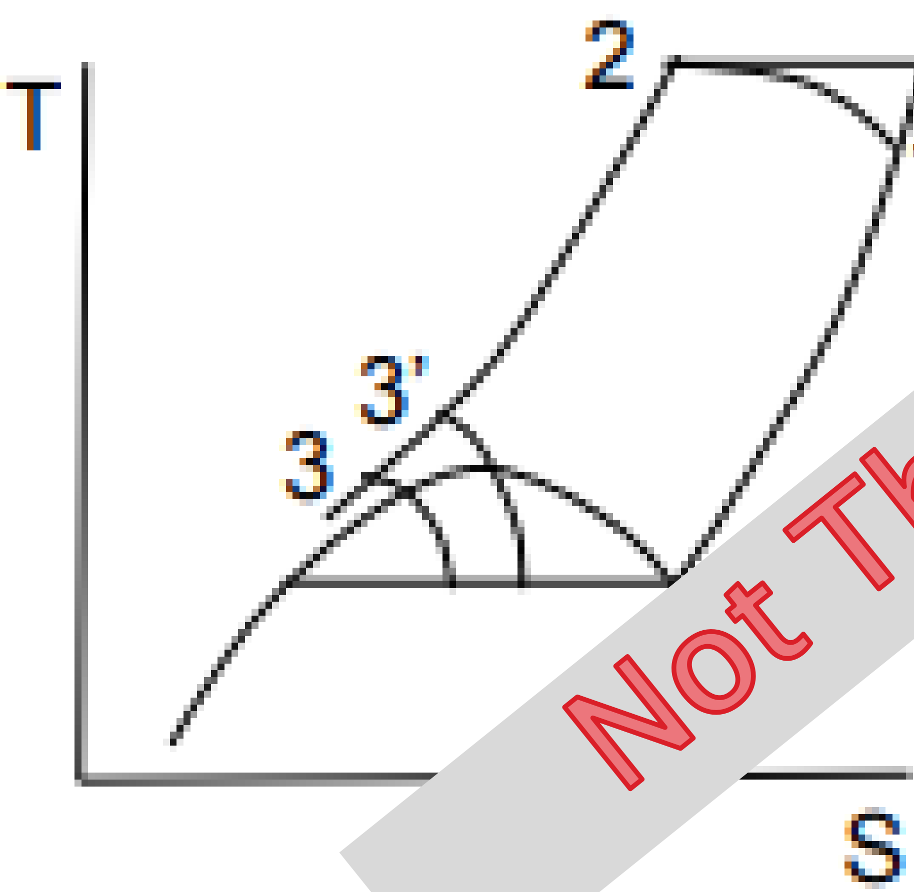
Theoretical Power : 7200 kJ/kg x 8/ 3600 = 16 kW ?

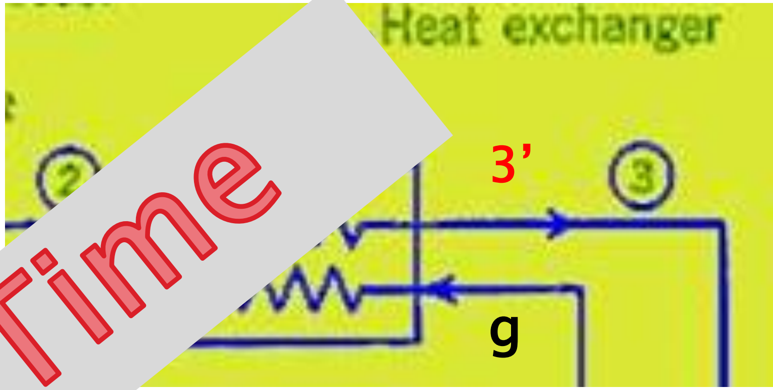
Considering the efficiency of Compressor and Heat Exchanger, the Actual power Requirement will be more than Double 40 kW
Power Cost of Liquid nitrogen will be Rs 20/ Litre

Actual Power cost is only Rs 5/ litre
This Cycle is Simple but not Cost Effective

Can we use the same Cycle for Helium Liquefaction ??

EFFECT : HEAT Exchanger EFFECTIVENESS





Not This Time

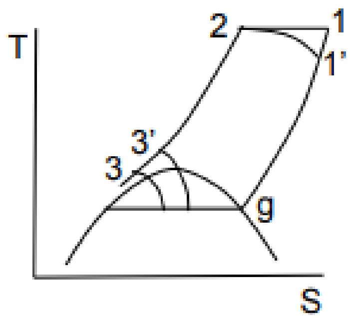
$$y = \frac{h_1' - h_2}{h_1' - h_f}$$

$$\varepsilon = \frac{h_{1'} - h_g}{h_1 - h_g}$$

We will replace h_1' by h_1 with effectiveness

Influence of Non-Ideal Components

- A non-ideal heat exchanger will have an effectiveness less than 1.
- A non-isotherm… …mpressor will require more work … …thermal compres…



$$\varepsilon = \frac{h_{1'} - h_g}{h_1 - h \ldots}$$

$$\eta_c = \frac{\left(\dot{W}/\dot{m}\right)_{isothermal}}{\left(\dot{W}/\dot{m}\right)_{actual}}$$

- The influence of these … …meters on the cooling capacity (refrigerator), liquid … …, and compression work for a simple Linde-Hampson system…

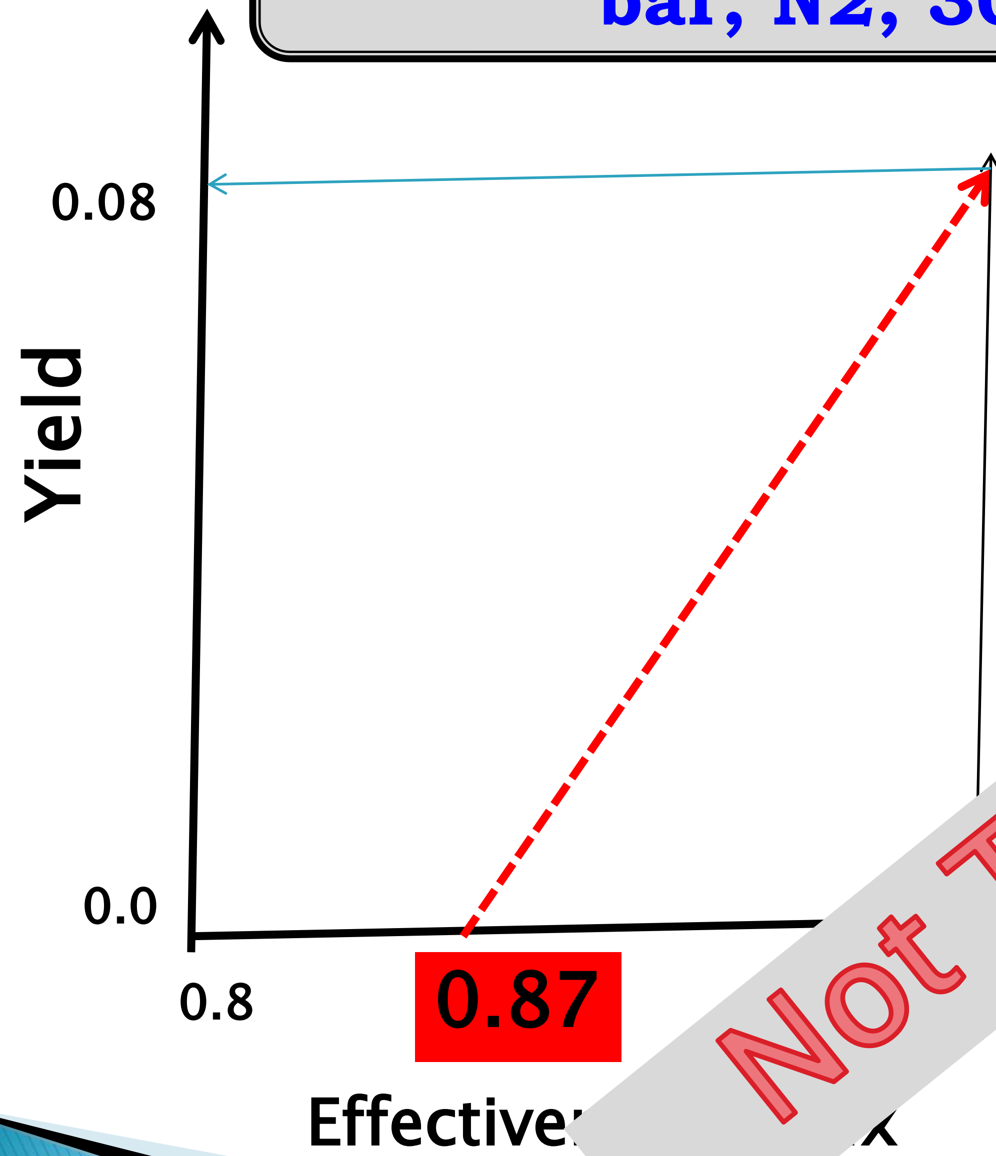
$$\ldots\left(h_1 - h_2\right) - \left(1 - \varepsilon\right)\left(h_1 - h_g\right)$$

$$y = \frac{h_{1'} - h_2}{h_{1'} - h_f} = \frac{\left(h_1 - h_2\right) - \left(1 - \varepsilon\right)\left(h_1 - h_g\right)}{\left(h_1 - h_f\right) - \left(1 - \varepsilon\right)\left(h_1 - h_g\right)}$$

$$\frac{\dot{W}}{\dot{m}} = \frac{1}{\eta_c}\left[T_1\left(s_{1'} - s_2\right) - \left(h_1 - h_2\right) + \left(1 - \varepsilon\right)\left(h_1 - h_g\right)\right]$$

Not This Time

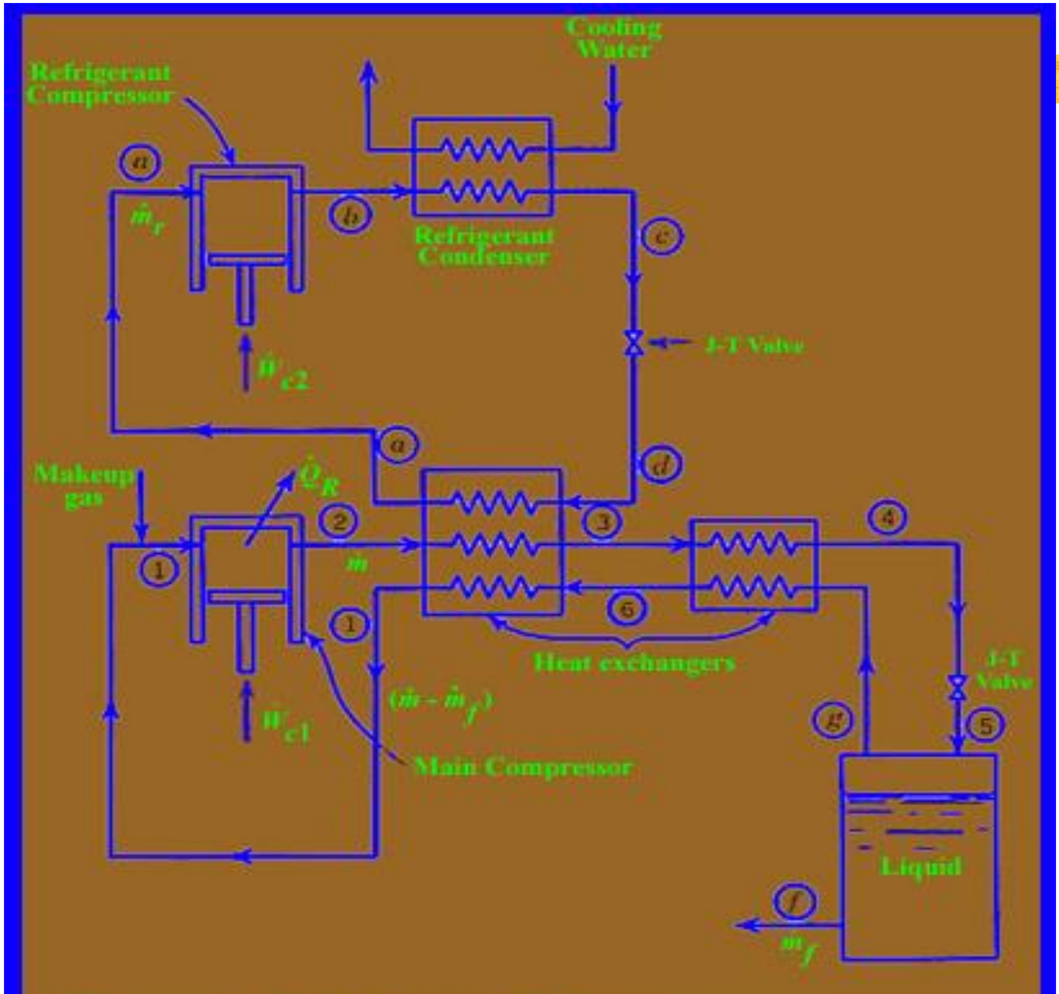
Example : p1= 1 bar ,p2= 200 bar, N_2, 300 K



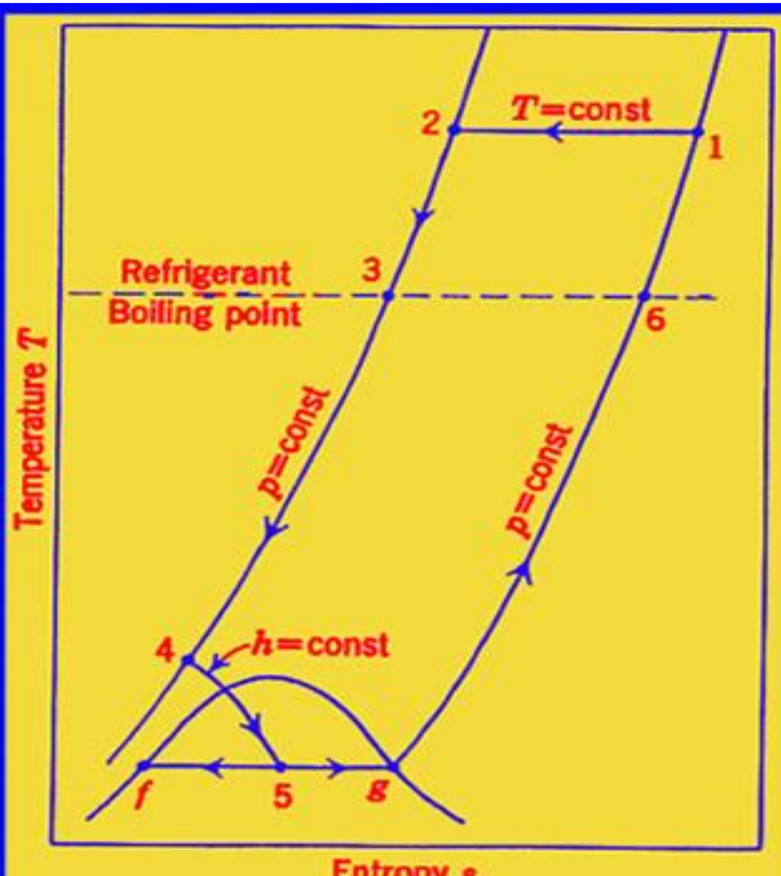
Next Cla
talkin
He action
um
er

Not This Time

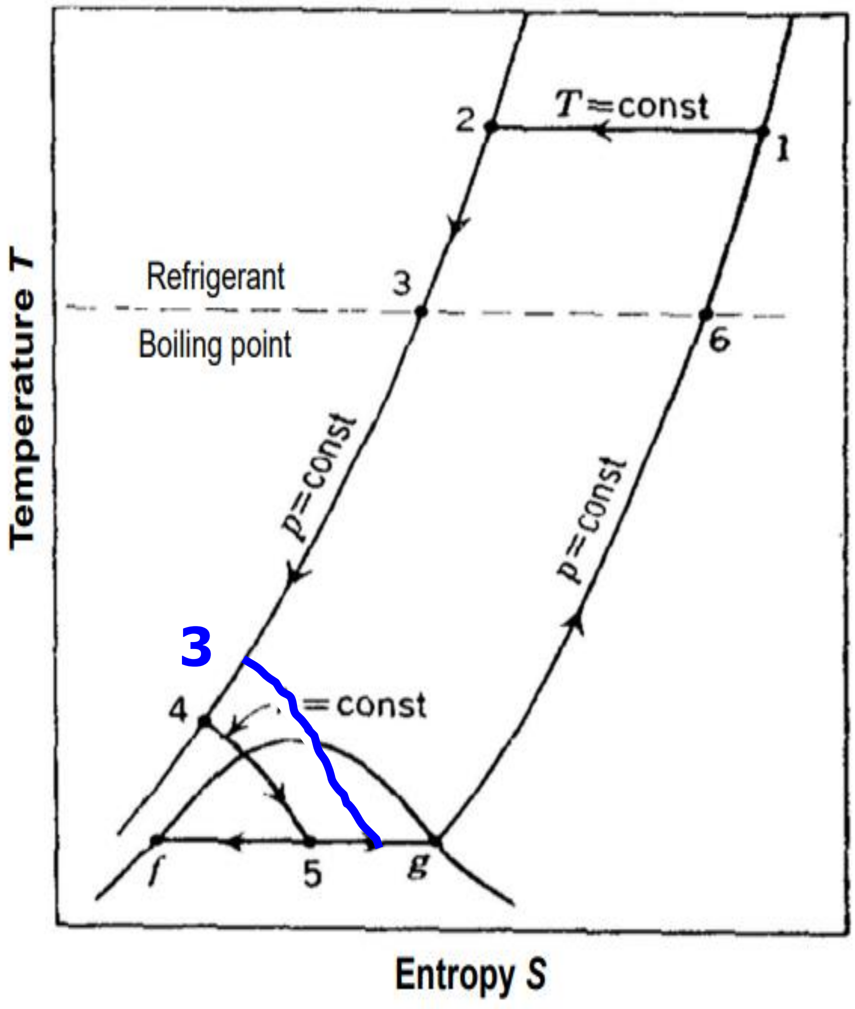
Precooled Linde-Hampson Cycle



Precooled Linde-Hampson system.



Precooled Linde-Hampson cycle. The state-points refer to the numbered points in the precooled Linde-Hampson system.



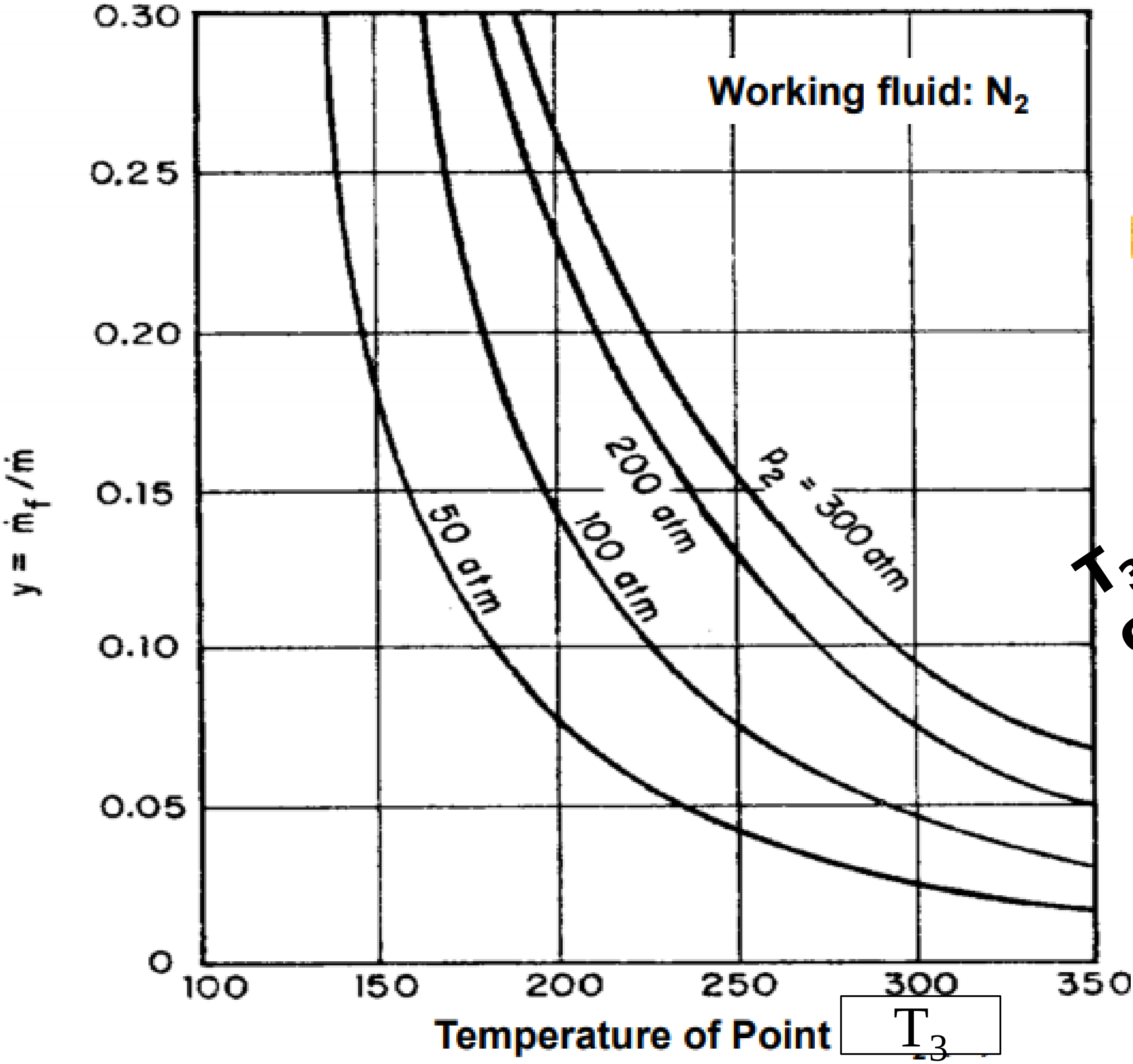
T-s diagram of Single throttling Linde cycle with precooling

$$\frac{\dot{m}_f}{\dot{m}} = y = \frac{h_1 - h_2}{h_1 - h_f}$$

$$y = (h_6 - h_3)/(h_6 - h_f)$$

$$\frac{W}{mf} = [T(S1 - S2) - (h1 - h2)]/y$$

Yield is higher, Hence W/ mf will be less



T_3 depends on cooling medium like Ammonia /LNG

Relationship between liquefaction rate and inlet T_3

LIQUID YOELD CAN BE INCREASED BY PRECOOLING

(by lowering the value h1)

Liquid yield for Linde precooled system with P_2= 100 bar

Precool temp.	300	250	200	150
$Y = m_f/m$	0.06	0.08	0.14	0.57

Power remains same , Add Refrigation power for precoolant

Simple L-H System for H2 and He ???

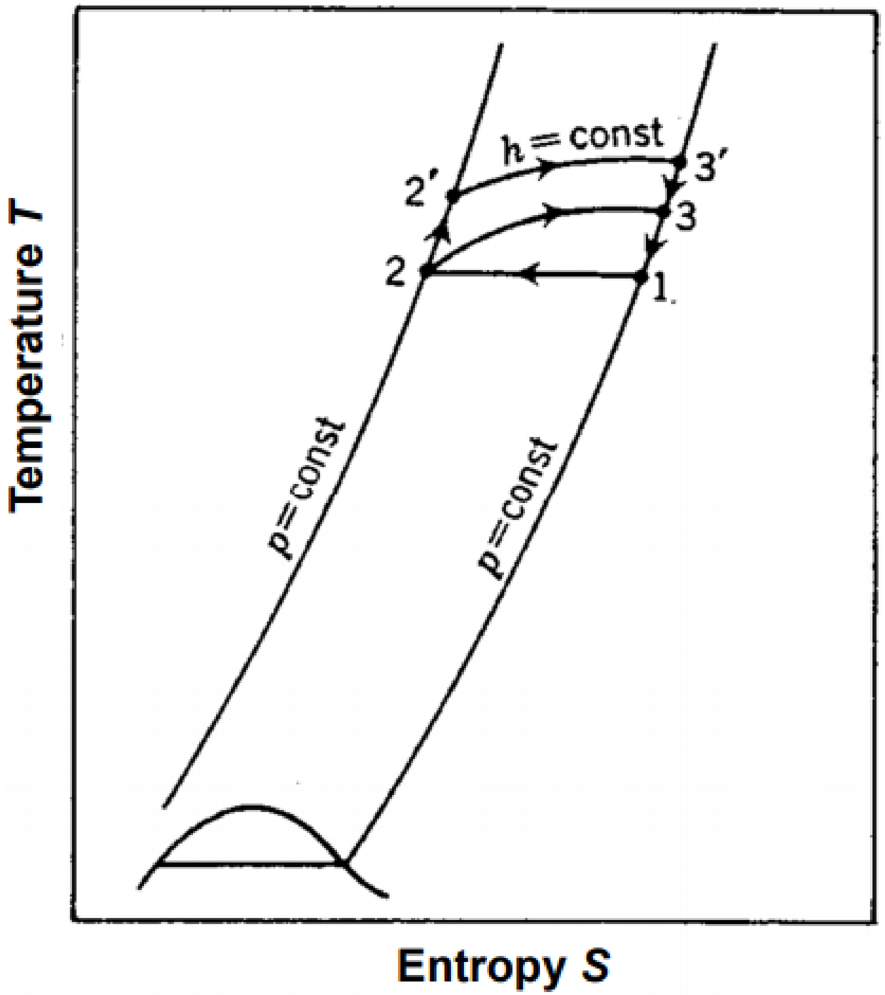
Do you Remember Max Inversion Temperature For He/ H2

-

A Linde cycle without pre-cooling can not be used for the liquefaction of neon, hydrogen and helium.

1. **The inversion temperature of these gases is lower than the ambient temperature and can not be cooled down to start the process**

2. **The inversion temperature of helium is 46 K, so if the Linde cycle with single throttling is used to realize the liquefaction of helium, it is necessary to use LH_2 to precool the temperature of the helium to below 46 K.**



T-s diagram of Linde cycle with single throttling for helium or hydrogen

LIQUEFACTION OF HELIUM

Max Inversion Temperature for Helium : 45 K (Below RT)

BASIC LINDE- HAMPSON SYSTEM WILL HAVE HEATING EFFECT.

We have to Precool with Liquid Nitrogen (78 k) and Liquid Hydrogen (20 K) prior to JT .

(First Liquefaction of Helium in 1908 : By Precooling L- H)

ALTERNATIVELY : ADDING ONE ADIABATIC EXPANSION PROCESS BY USING A TURBINE :

First Helium Liquefier By Kamerlingh Onnes

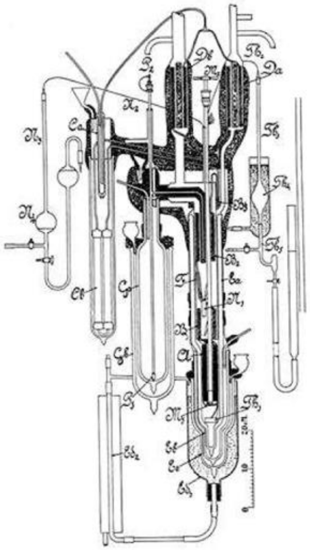
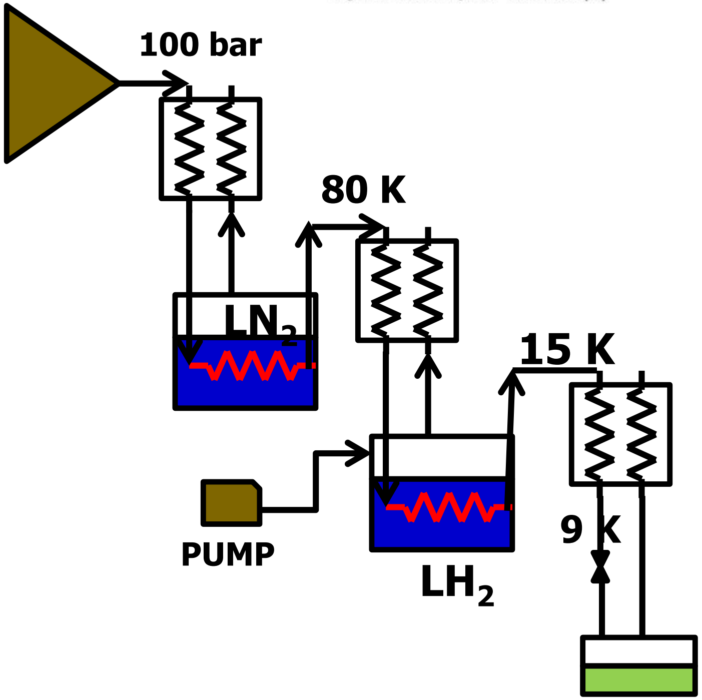


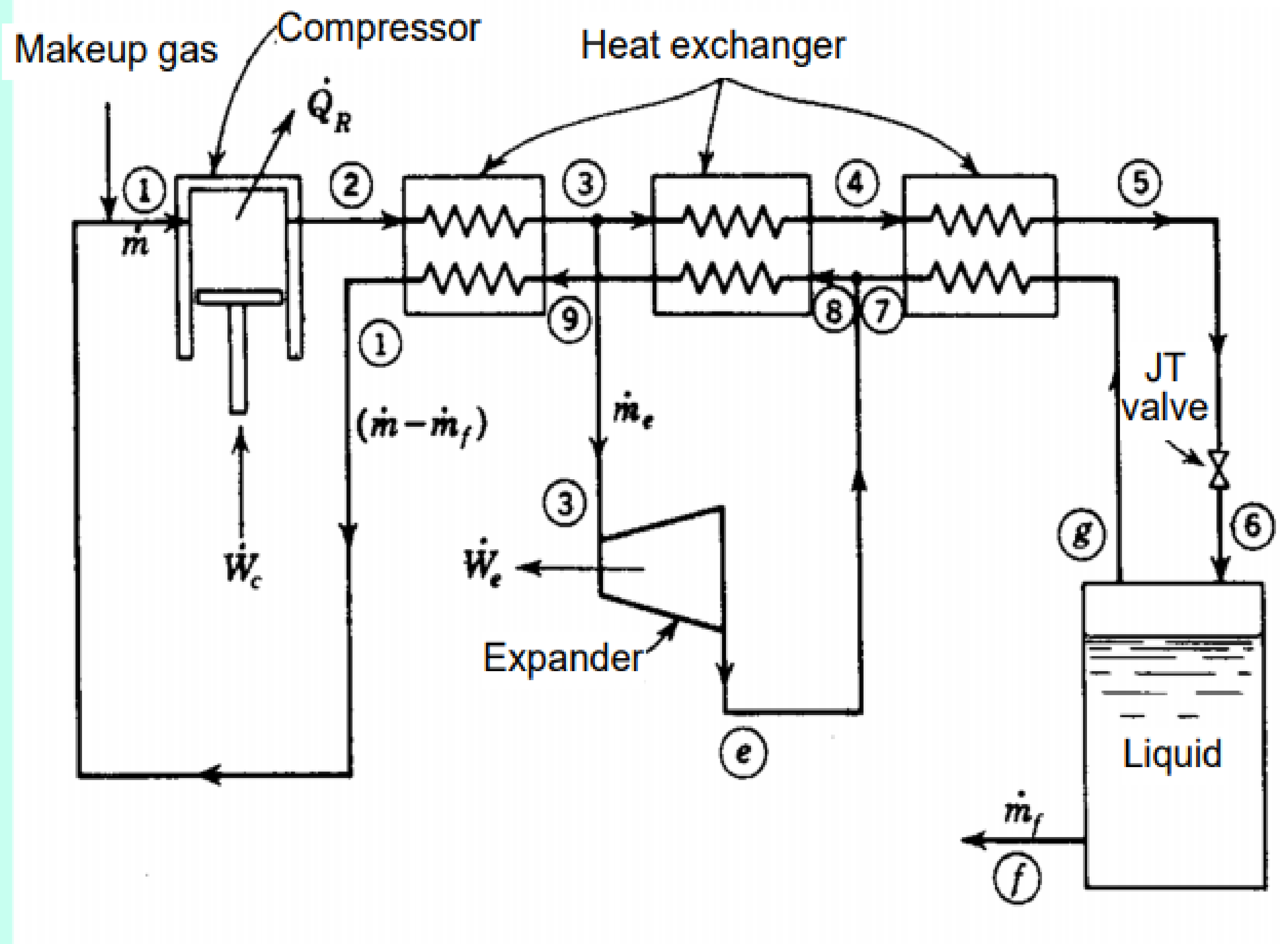
Figura 6 - Helium liquefier. Credit: Ref. [35].



CLAUDE CYCLE

1. In 1902, Claude, Frenchmen, first proposed the liquefaction cycle with expander, so the liquefaction cycle with expander was called the Claude cycle

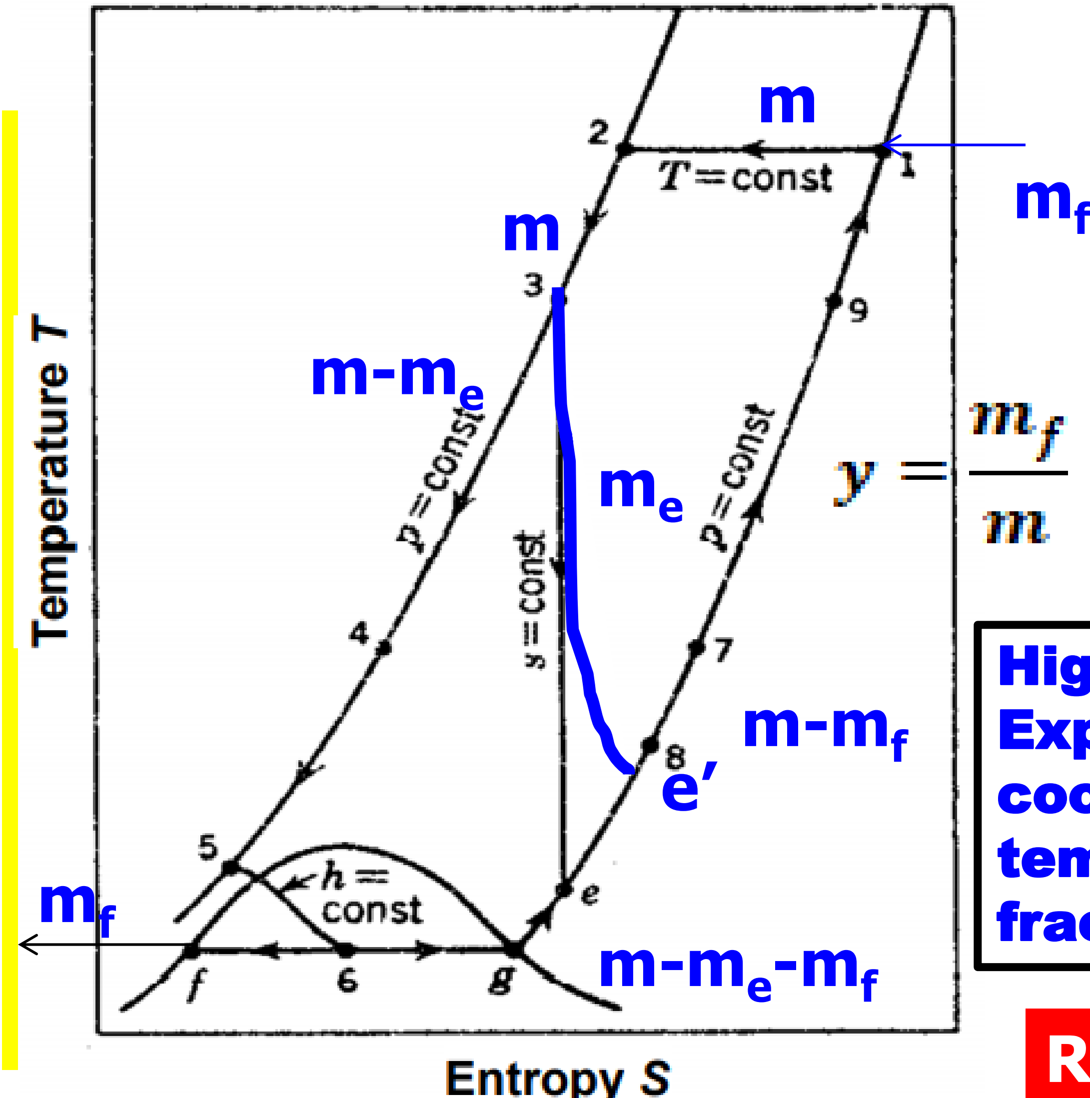
2. The Claude cycle is generally used in small and medium sized air separation units. Claude cycle with precooling has sufficient cooling capacity and is used in large and medium scale LO_2 and LN_2 equipment.



Claude cycle

Optimized value with Single Expander

X~ 60 to 80 %



m of the theoretical Claude cycle

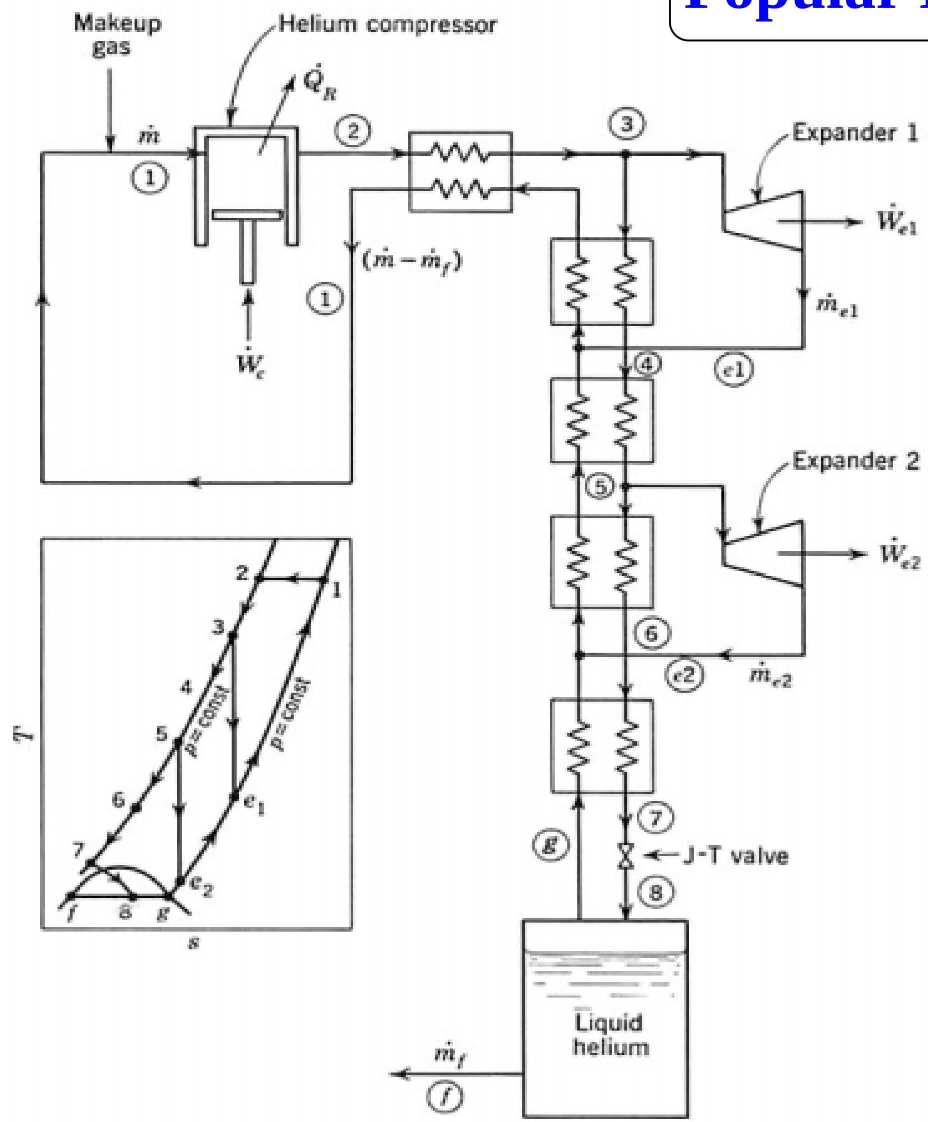
$$y = \frac{m_f}{m} = \frac{h_1 - h_2}{h_1 - h_f} + \frac{m_e}{m} \cdot \frac{h_3 - h_e}{h_1 - h_f}$$

Higher flow rate through the Expander will have higher cooling, that reduces the temperature (5). More fraction of liquid

Remember, Mass flow rate through JT is also reducing

Collins Liquefier

Popular During 1950-80

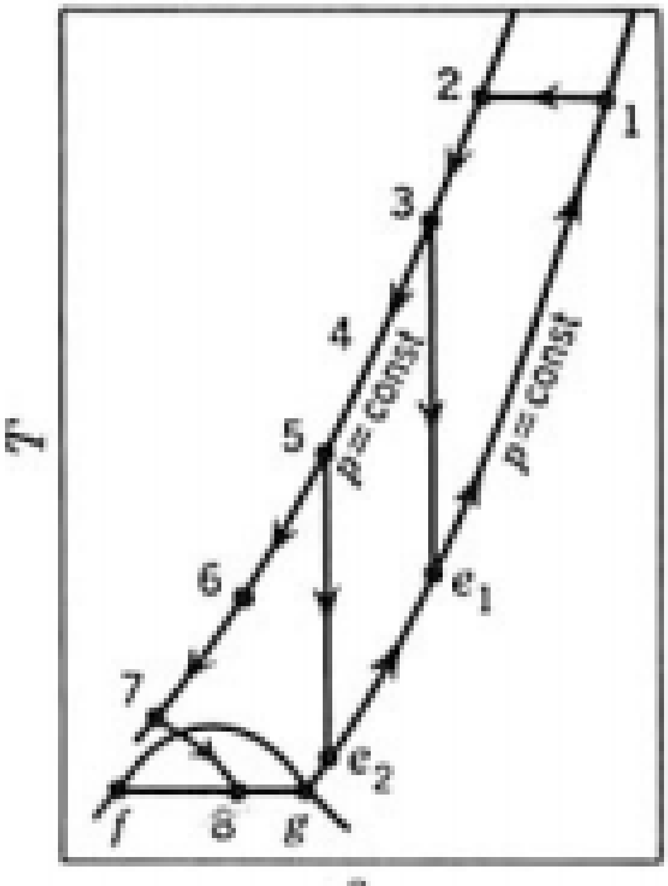


- Introduced by Sam Collins (MIT) in 1952
- Optimized performance via expander flow rates and temperatures
- LN_2 pre-cooling increases yield by factor of 3.

The yield and work requirement are given by

$$y=\left(\frac{h_1-h_2}{h_1-h_f}\right)+x_1\left(\frac{h_3-h_{e1}}{h_1-h_f}\right)+x_2\left(\frac{h_5-h_{e2}}{h_1-h_f}\right)$$

$$\frac{-W_{net}}{\dot{m}}=\left(T_1\left(s_1-s_2\right)-\left(h_1-h_2\right)\right)-x_1\left(h_3-h_{e1}\right)-x_2\left(h_5-h_{e2}\right)$$



Here Yield can be optimized with T_3, T_5, x_1 and x_2 at different pressure (p_2)

For standard Helium Liquefier
T3= 60 K, T5 = 20 K
X1= 15 %, x2 = 40 %

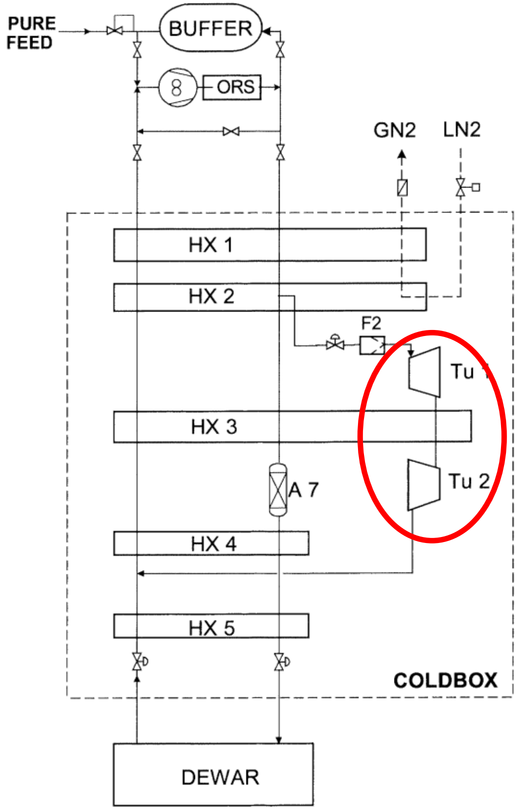
HELIUM LIQUEFIER WITH TURBINE

Capacity can be further enhanced by using two Expander and precooled with liquid Nitrogen. This is called Modified Claude Cucle.

Initial year, isentropic expansion was achieved by Reciprocating Piston type and later Turbine

Standard 1 kW class Refrigerator

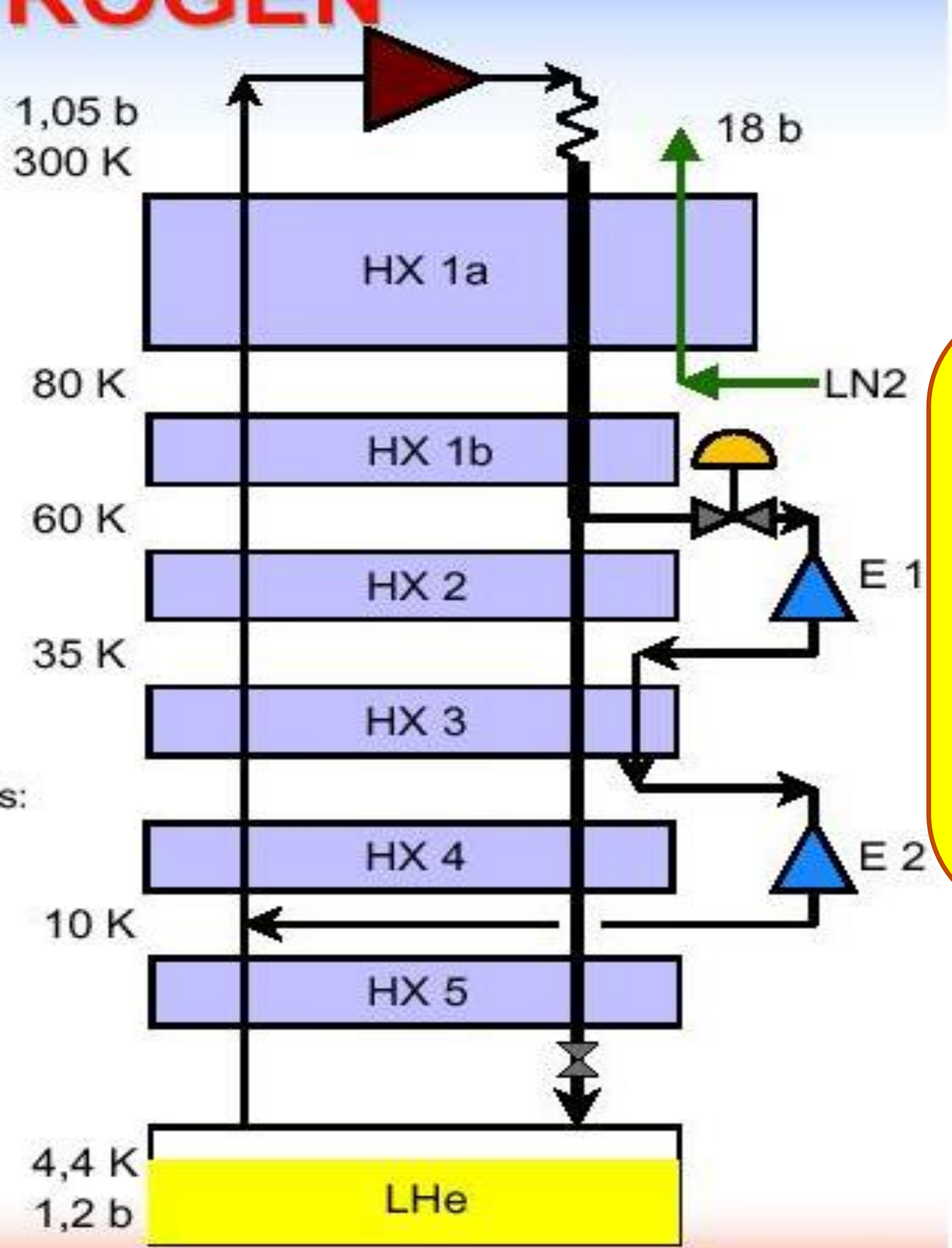
300 litres/hr



Advantage : **Turbines are more reliable than the expansion engines because the latter are susceptible to performance deterioration due to contamination.**

Disadvantage : Turbines do having a limited expansion ratio, that is a **limited ratio of inlet to outlet pressures.**

That was the reason Turbine are used in series rather than parallel for Reciprocating Expander



Major Components :

1. **Compressor**
2. **Heat Exchanger**
3. **Expander**
4. **JT Valve**

Most Popular Helium Liquefier in Low Temperature Laboratories (1965 – 1980)

ADL to CTI 1400

Capacity : 10 litre/hr (single Compressor) : Reciprocating 2 stage; 100 Nm3/hr , Reciprocating Expansion Yield = .08

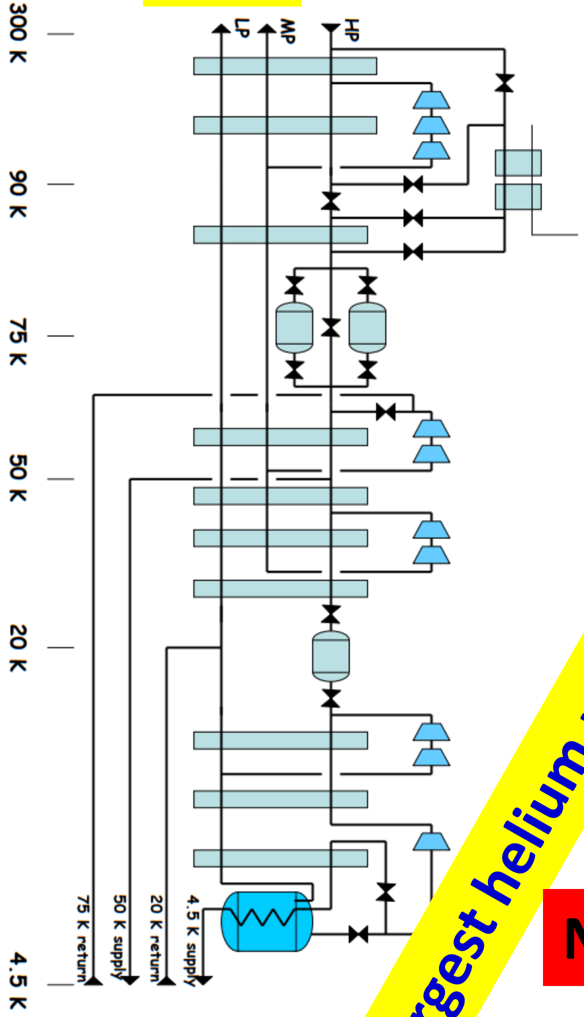
CTI 1410 → KOCH → PSI → LINDE (L 1410)

Automatic Engine speed, Screw Compressor, Modular

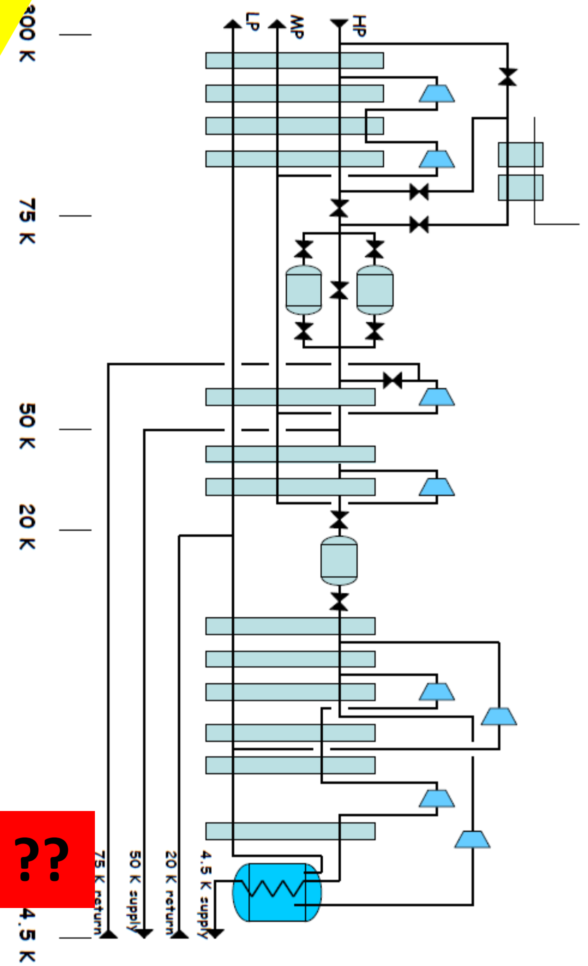
Production rate : 10 litres/ hr to 50 litres/ hr

18 kW at 4.5 K Helium Refrigerator for CERN LHC Project

LINDE



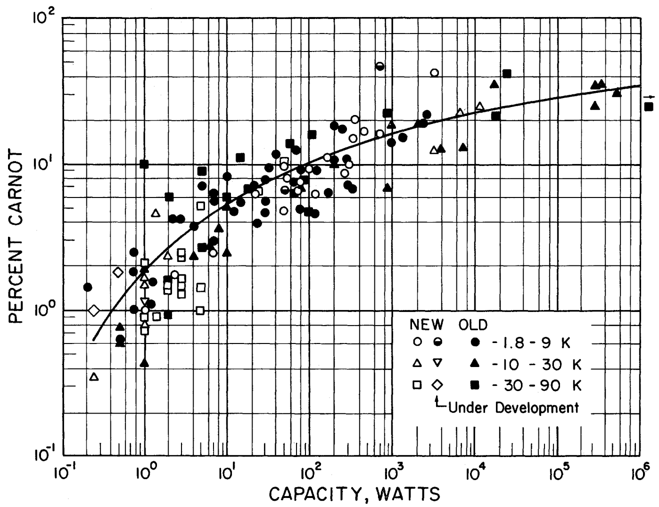
AIR Liquide



Largest helium refrigerator with Single Cold Box

Next 20 / 25kW ??

Strobridge Survey (Efficiency) 1974



GM Cryocooler ; **4 kW for 1W** refrigeration at 4.2 K

Laboratory Scale Helium Refrigerator (~ 100 W) :
700 W for 1 W

Medium Range 1kW Class (**300 W for 1W Range**)

Large Helium Refrigerator (18 kW for CERN :
225 W for 1 W

Whether we have reached peak value of 225 W ??

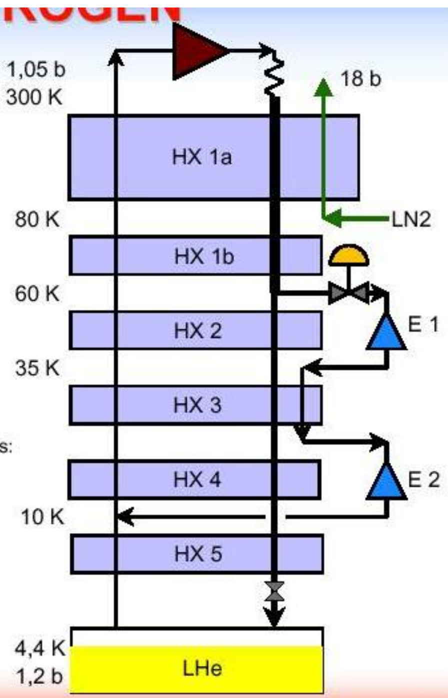
Efforts are on to replace the screw compressor by dry centrifugal compressors: deletion of the Oil Removal System and reduction of the electrical consumption by 12% to 20% depending on the number of compressor stages.

Isothermal efficiency of centrifugal compressors is higher than screw compressors, and this efficiency increases with the number of compressor stages.

Standard 1 kW at 4.3 K Helium Refrigerator needs a Compressor with capacity 100g/s and discharge pressure at 13 bar (g)

Isothermal Operation : Work required

$$W = \frac{m}{M} RT \ln\left(p_2 / p_1\right) = 150 kW$$

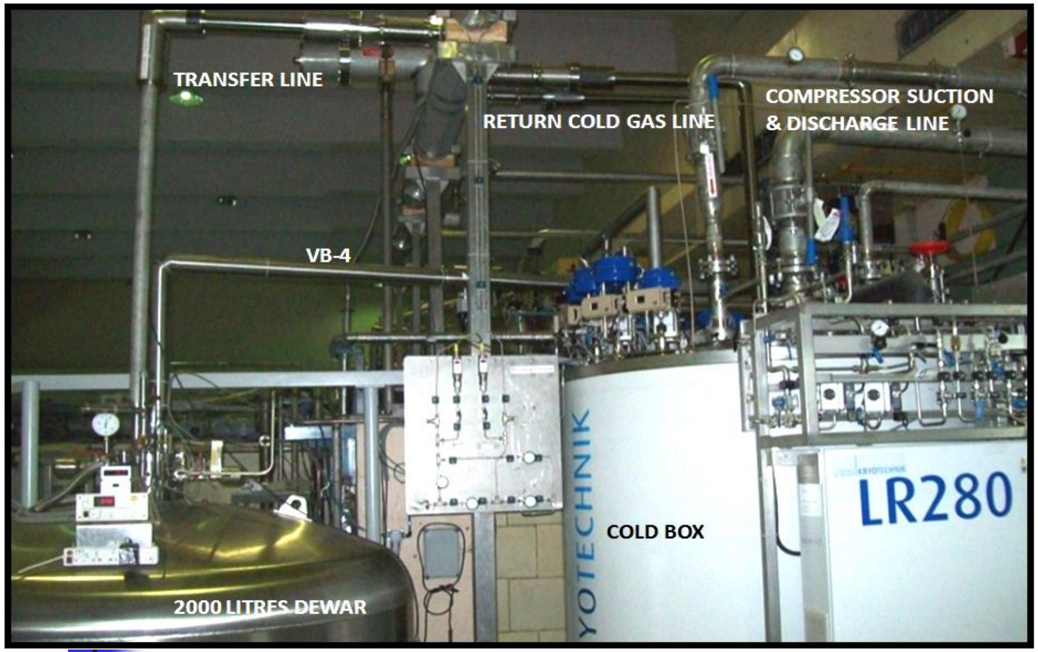


Actual Plug Power ; 305 kW

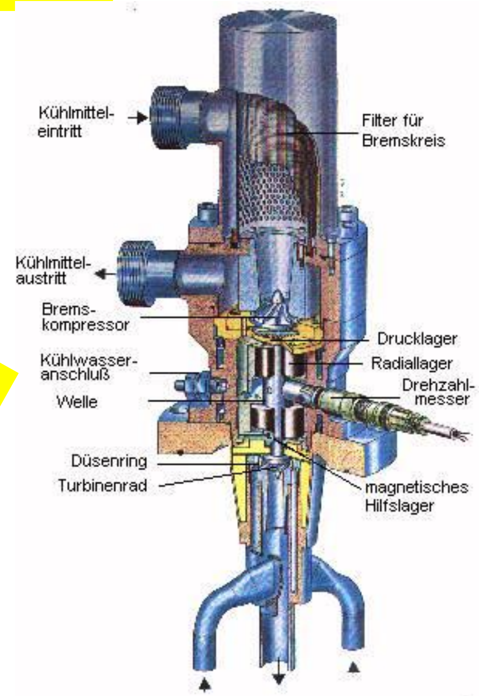
Compressor Efficiency : 49%

Inverse COP = 300 W/ W

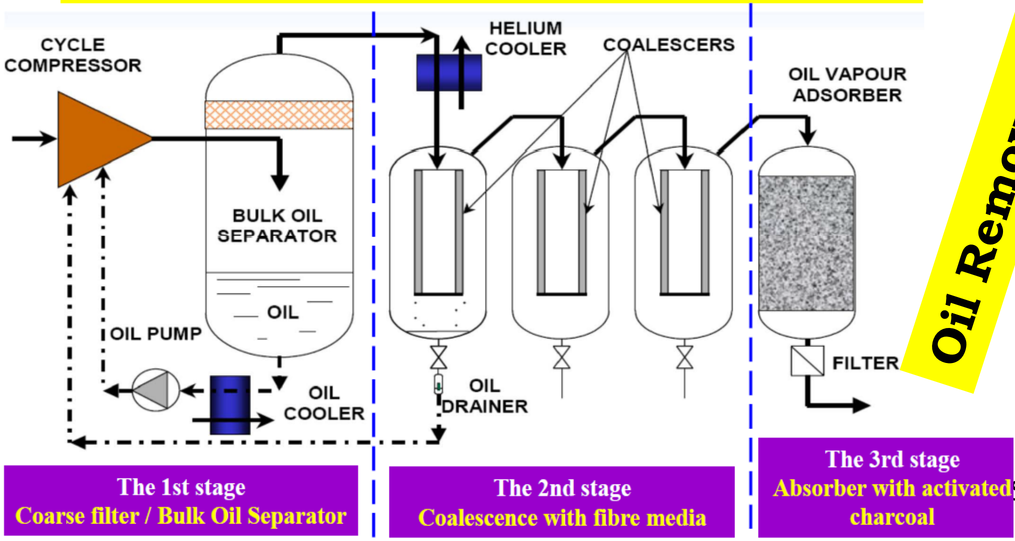
Major Components of Helium Refrigerator



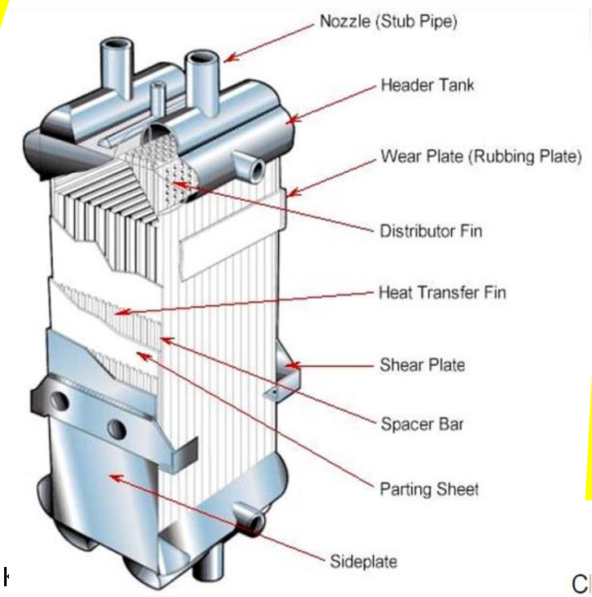
Turbine



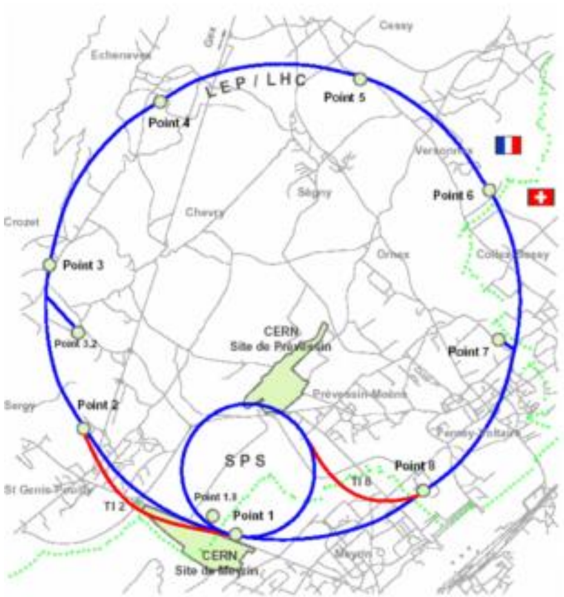
1. At the outlet of the 1st stage, there are a lot of aerosols and a little vapor
2. Fibre media is used to remove the Aerosol, but has no effect on vapor
3. Activated charcoal is used to remove the oil vapor, but has no effect on aerosol

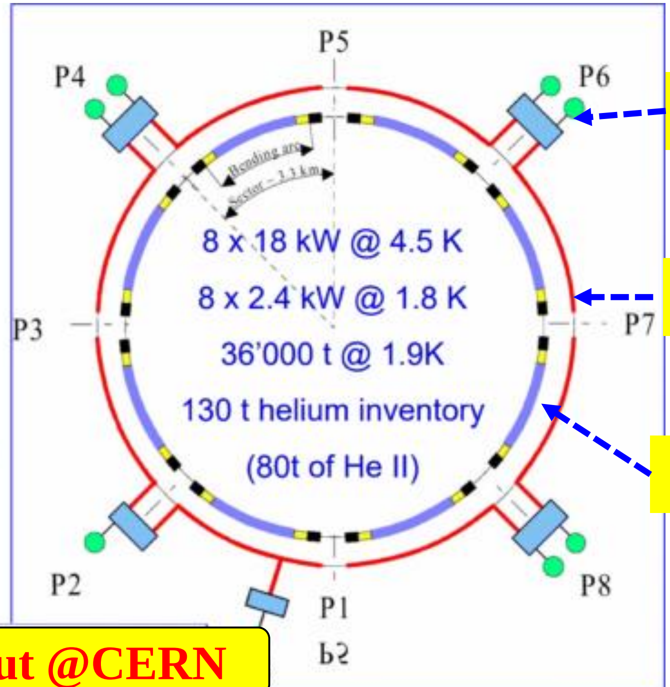


Oil Removal System



Heat Exchanger



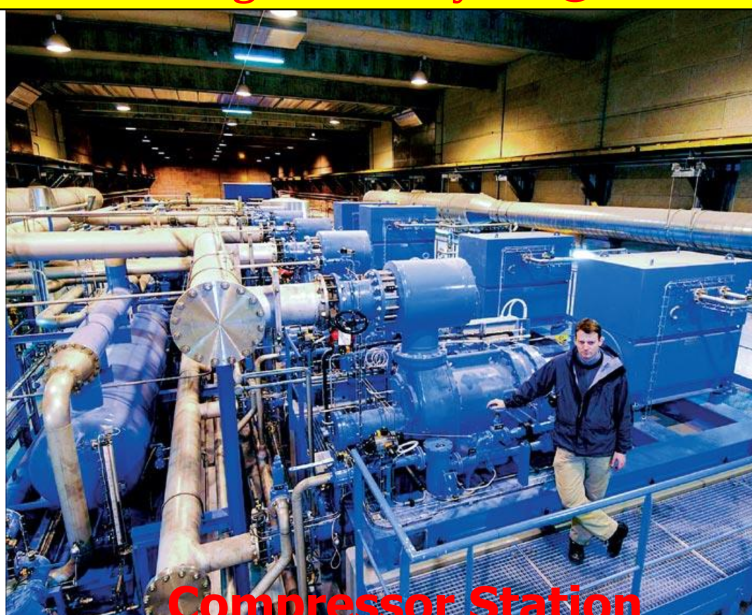


18 kW Refrigerator

LHe Distribution Line

Beam Line

Helium Refrigerator Layout @CERN



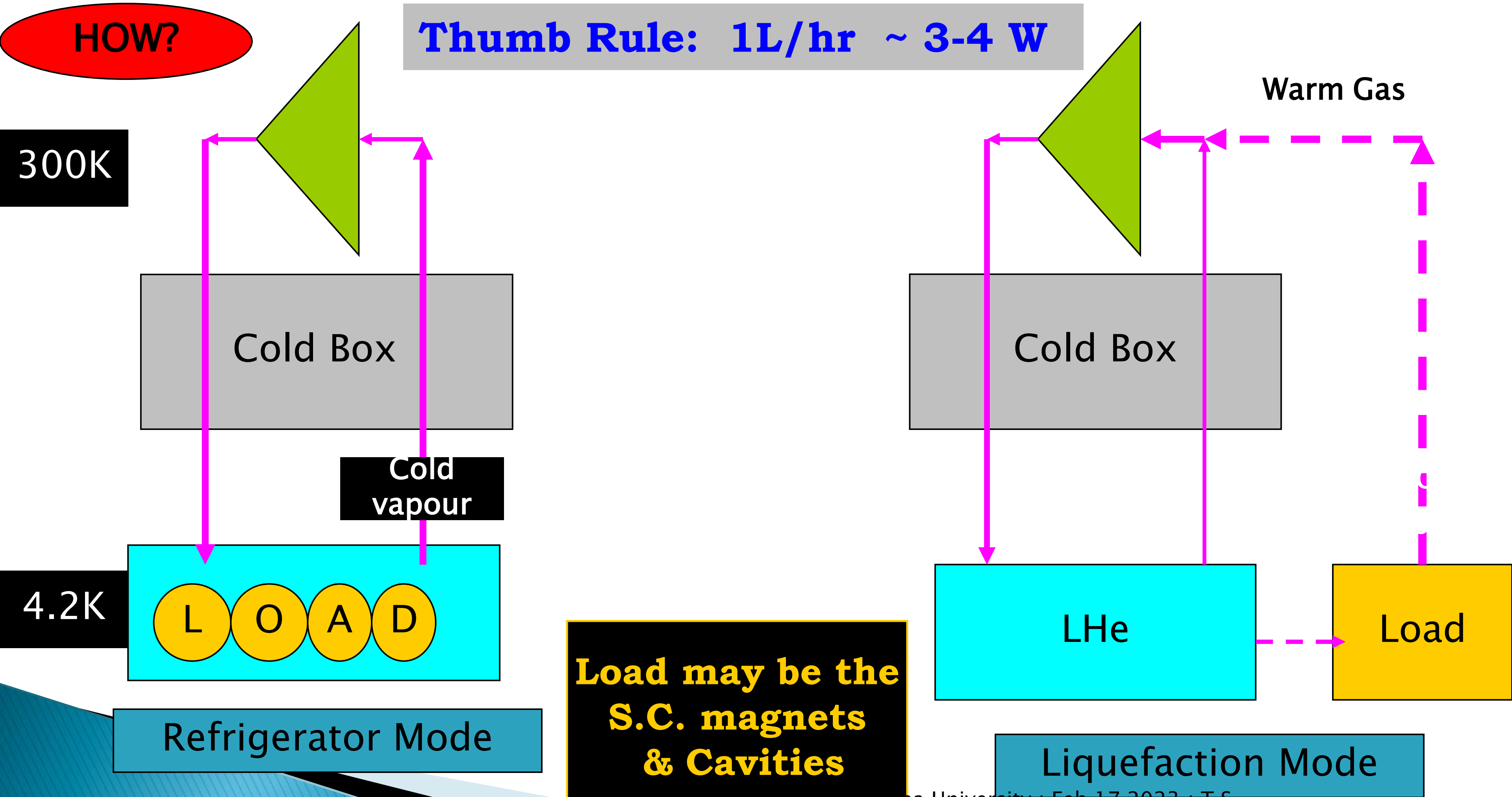
Compressor Station

Cold Box

Liquefaction Vs. Refrigeration

Same Thermo dynamical Cycle as Liquefaction Cycle. Difference in way of operation

Thumb Rule: 1L/hr ~ 3-4 W



Load may be the S.C. magnets & Cavities

Liquefaction Vs. Refrigeration

100 L/hr = 3.33 g/sec = 3.33 x 20 j/g = 66.6 W<< 300W

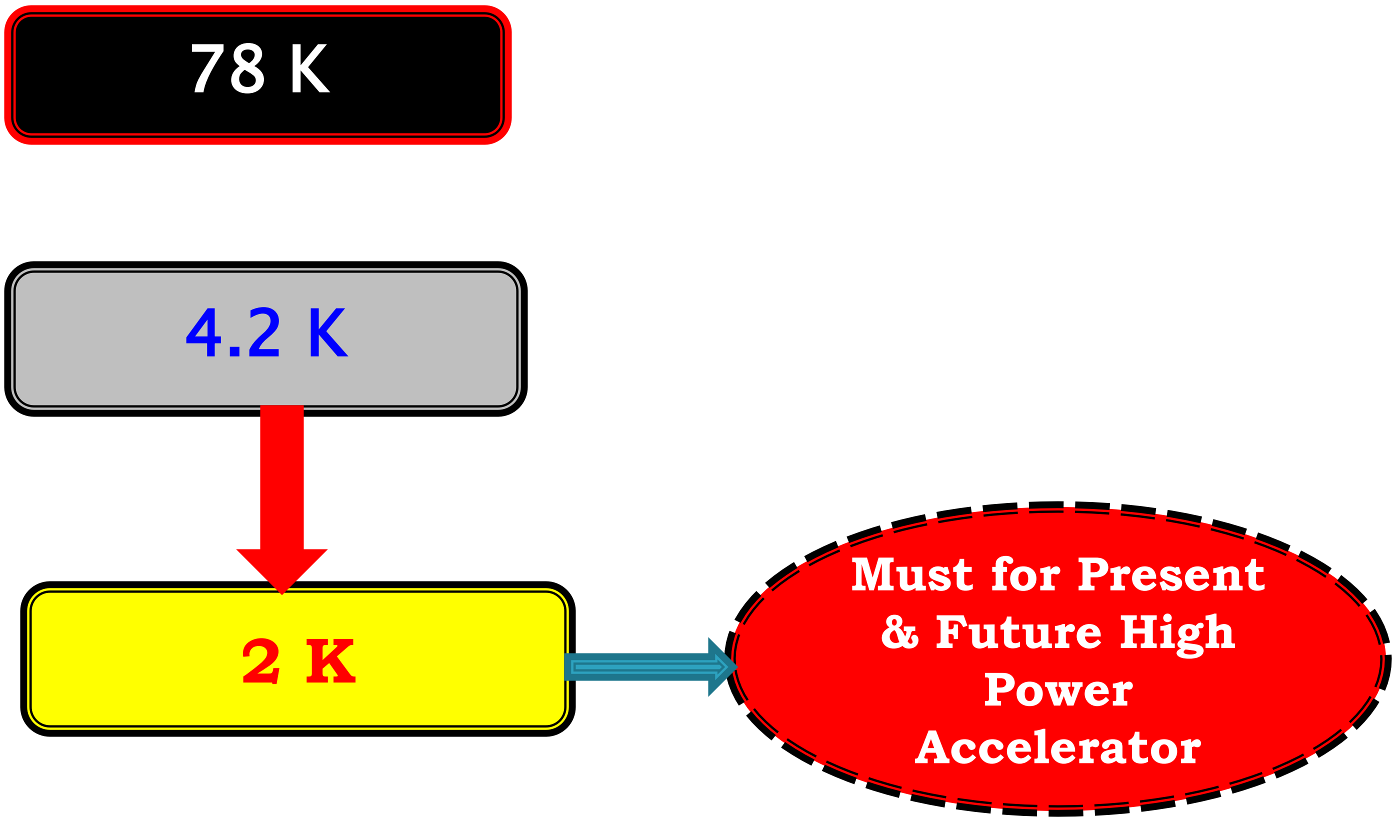
Thumb Rule: 1L/hr ~ 3-4 W

Why ???

1.Cold Enthalpy 4.2- 300 K is used

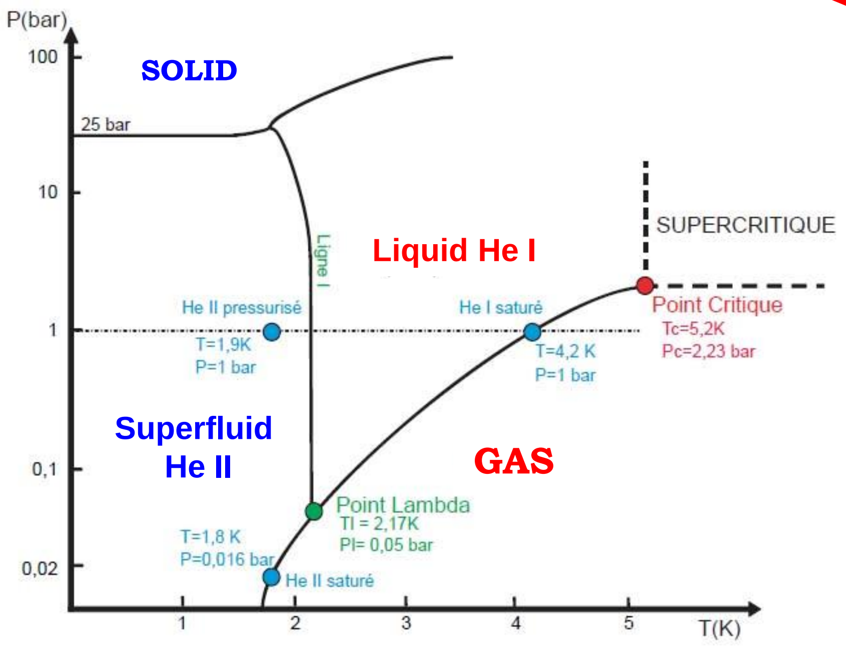
2.JT Temp will be lower and hence yield

Transition from He I to He II (Super fluid)

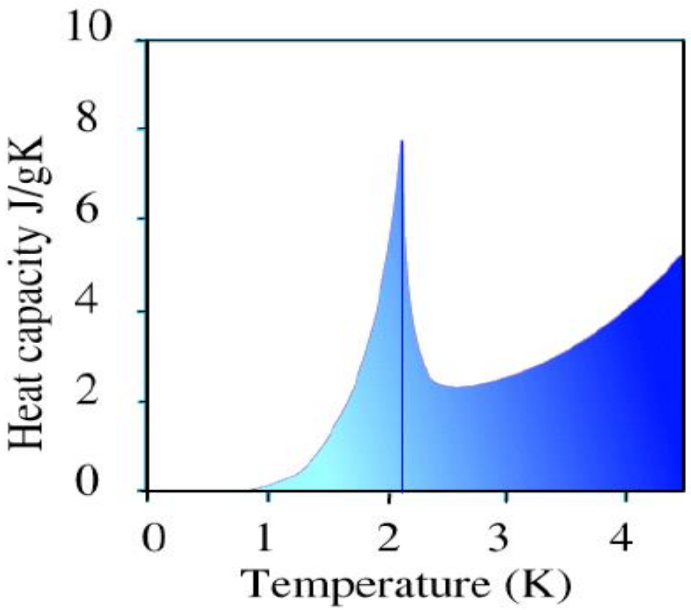


Super-fluidity is the characteristic property of a fluid with zero viscosity which therefore flows without loss of kinetic energy (no Pressure drop)

TRANSITION TO A SUPER-FLUID PHASE BELOW THE λ-point (2.17K)



1. **Low Viscosity**
2. **High Conductivity**
3. **High Specific Heat**



Advantages

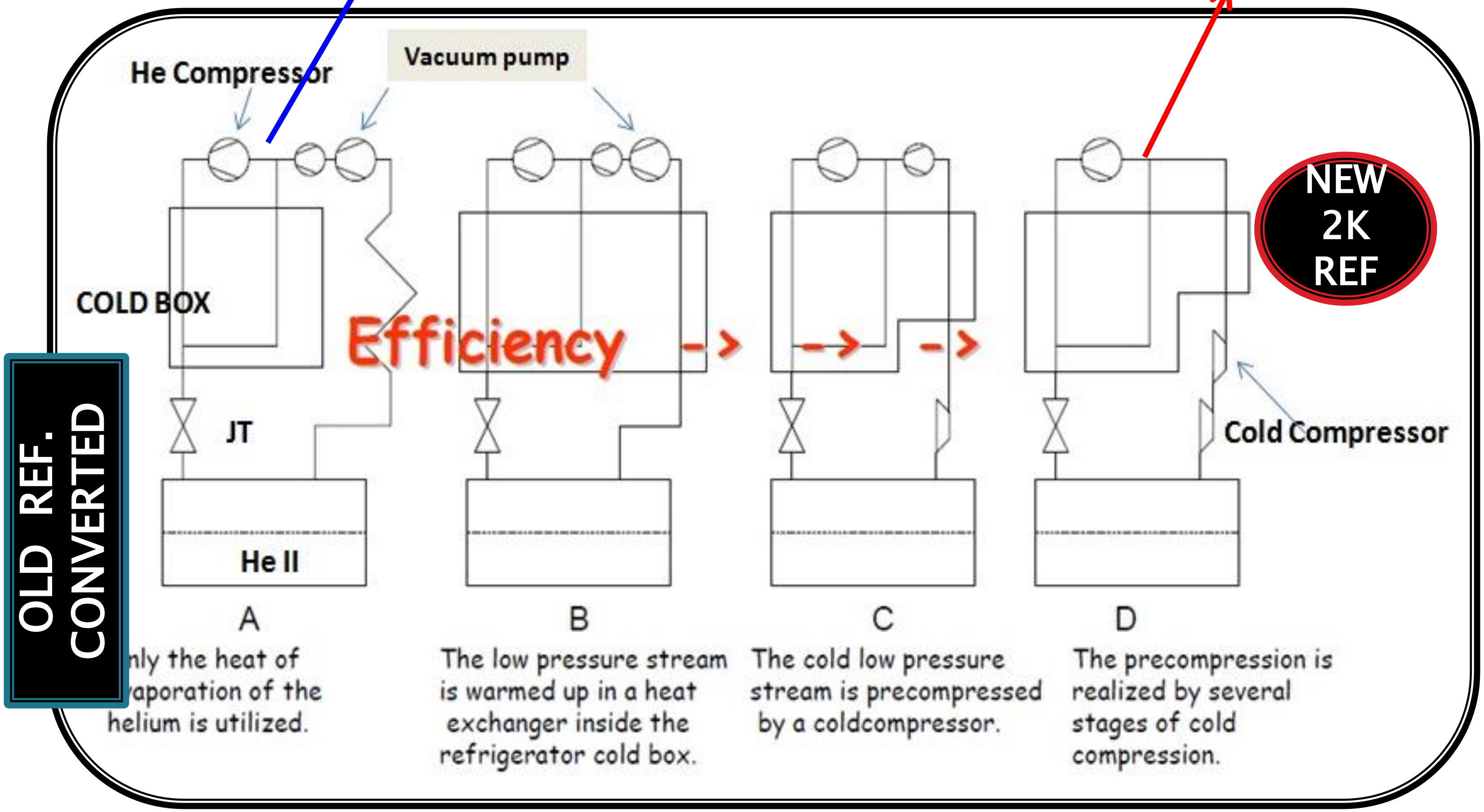
1. Super-fluid Helium can easily flow through SC strand /Cable

2. Small temperature rise with a heat input (specific heat)
3. Large Conductivity maintain equal temperature. SC Magnet is stable

2 K Helium Refrigerator

Small capacity 2 K system

High Capacity 2 K system

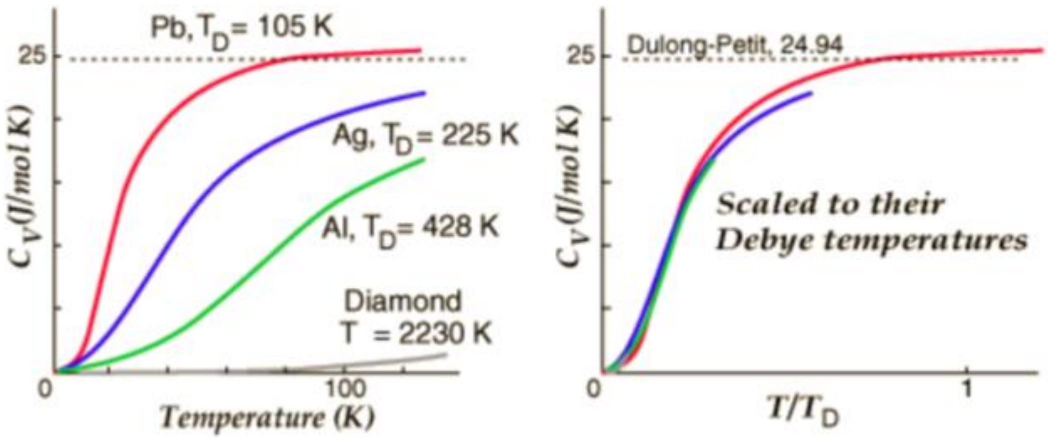


$$Q_{4.5} = 3Q_{2K+} + Q_{4.5K} + 0.1Q_{60K}$$

There are some time left

Material Properties at Cryogenic Temperature

At the left of Figure below, the experimental results of specific heats of four substances are plotted as a function of temperature and they look very different. But if they are scaled to T/T_D, they look very similar and are very close to the Debye theory.



The Specific heat of copper is 0.386 J/gm K and that of lead is only 0.128 J/gm K). Why are they so different? The difference is mainly because it is expressed as energy per unit mass; if you express it as energy per mole, they are very similar. It is in fact that similarity of the molar specific heats of metals which is the subject of the Law of Dulong and Petit.

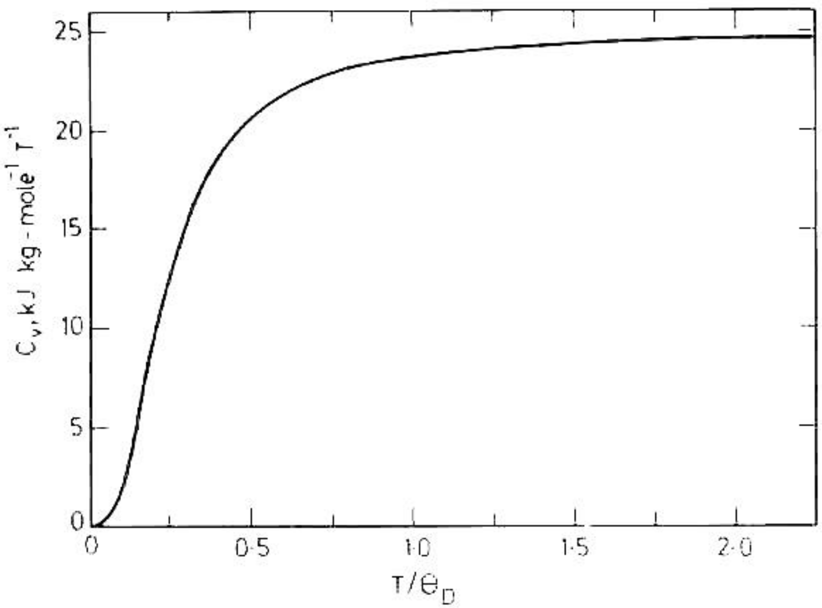
Copper	0.386 J/gm K x 63.6 gm/mole = 24.6 J/mol K
Lead	0.128 J/gm K x 207 gm/mole = 26.5 J/mol K

Specific Heat of Materials at Low Temperature

Energy (Joule) Required to change the temperature of 1g /1 g.Mole substance by one degree (J/ g.K) or / J/ Mole.K

$$C_v = 9R\left(\frac{T}{\theta_D}\right)^3 \int_0^{\theta/T} \frac{x^4 e^x}{(e^x - 1)^2} dx$$

At Room Temperature and Above
C_v (kg/ mole.K) = 3 R constant



At low Temperature

$$C_v = \frac{12\pi^2 R}{5}\left(\frac{T}{\theta_D}\right)^3$$

While cooled down from Room Temperature to Liquid Nitrogen, Specific heat reduced drastically

Electronic Specific Heat

The temperature dependence of Einstein model is just T. It becomes significant at low temperatures and is combined with the above lattice specific heat in the Einstein-Debye specific heat.

$$C_{metal} = C_{electron} + C_{phonon} = \frac{\pi^2 N k^2}{2E_f} T + \frac{12\pi^4 N k_B}{5T_D^3} T^3$$

$$C_{metal} = C_{electron} + C_{phonon} = \gamma T + \alpha T^3$$

At normal temperature , the electronic contribution to the total specific heat is quite small because of small value of ɣ.

At very low temperature (T< 1K) does becomes important because it varies as T while the Phonon contribution varies as T^3

Role of Specific Heat on Cool Down

To cool 1 gm mass from Room temperature to 4.2 K

$$Q = m\,C_p\,(300-4.2)\ \text{J},\quad C_p = f(T)$$

At low temperature, Cp is less, less heat to be extracted at low Temperature. Cryogen (Mc) is required to cool 1 Kg mass

$$M_c \cdot L = m \cdot C_p\,(300-4.2)$$

Requirement of Cryogen To cool Down

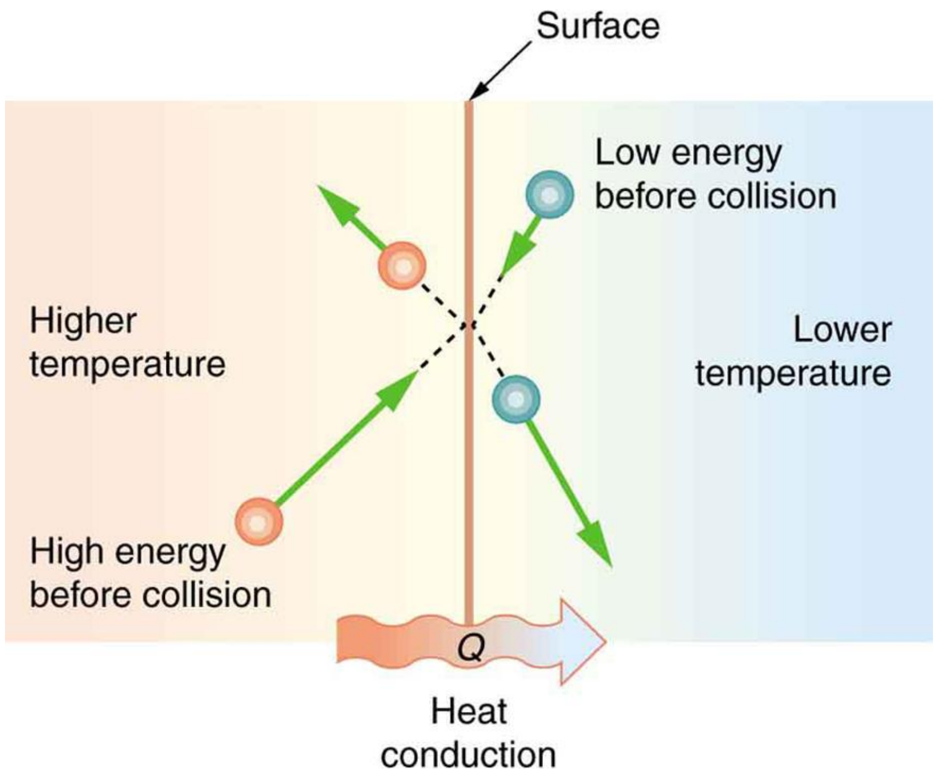
	300- 4.2K (Lhe) L/kg	78- 4.2 K (LHe) L/kg	(300- 4.2) With Cold Gas	300-78 K (LN2)
SS	33	1.44	0.80	0.53
Al	66	3.2	1.60	1.0

1. **Cp of Aluminium is double of SS**
2. **Precooling with LN2 saves Lhe**
3. **Slow Cooling uses cold enthalpy of gases**

Remember Latent Heat of LHe is only 20 against 200 J/gm for LN2

Thermal Conduction Mechanism

The (average) kinetic energy of a molecule/ Free electron in the hot body is higher than in the colder body. If two molecules/ electron collide, an energy transfer from the hot to the cold molecule occurs. The cumulative effect from all collisions results in a net flux of heat from the hot body to the colder body. We call this transfer of heat between two objects in contact thermal conduction.



Two parallel mechanisms are primarily responsible for the transport of heat in a metal at low temperatures.

1. **The most important is the electronic thermal conduction, the transport of thermal energy by the motion of conduction electrons.**

2. **The second is the lattice thermal conduction, heat trans- port by vibrations (called phonons) of the thermally excited interacting lattice ions.**

3. **For pure metals the lattice thermal conductivity is very much smaller than the electronic thermal conductivity. For Alloys / Non Metal , Lattice Contribution is comparable with Electronic Contribution**

4. **Impurities and lattice defects scatter electrons and decrease thermal conductivity.**

K, is the sum of two terms, the electronic conductivity Ke and the lattice conductivity, Kg ; that is, K = Ke+ Kg.

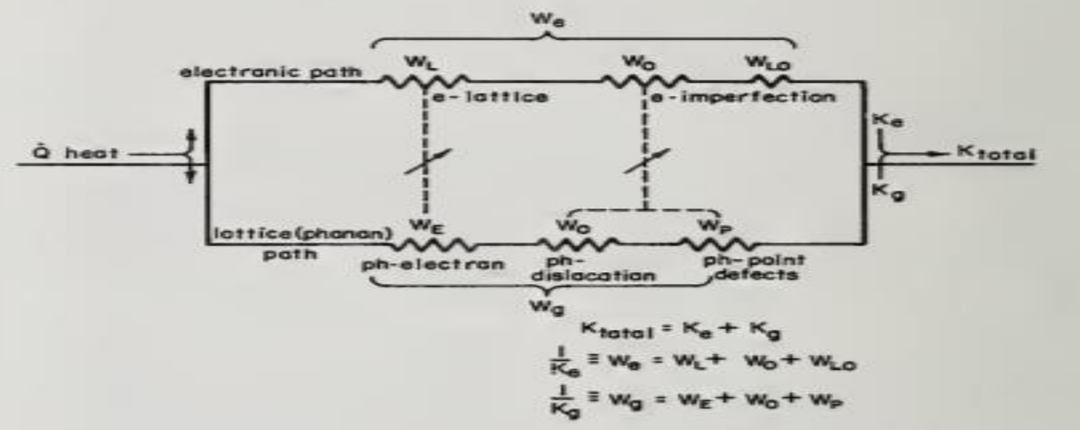
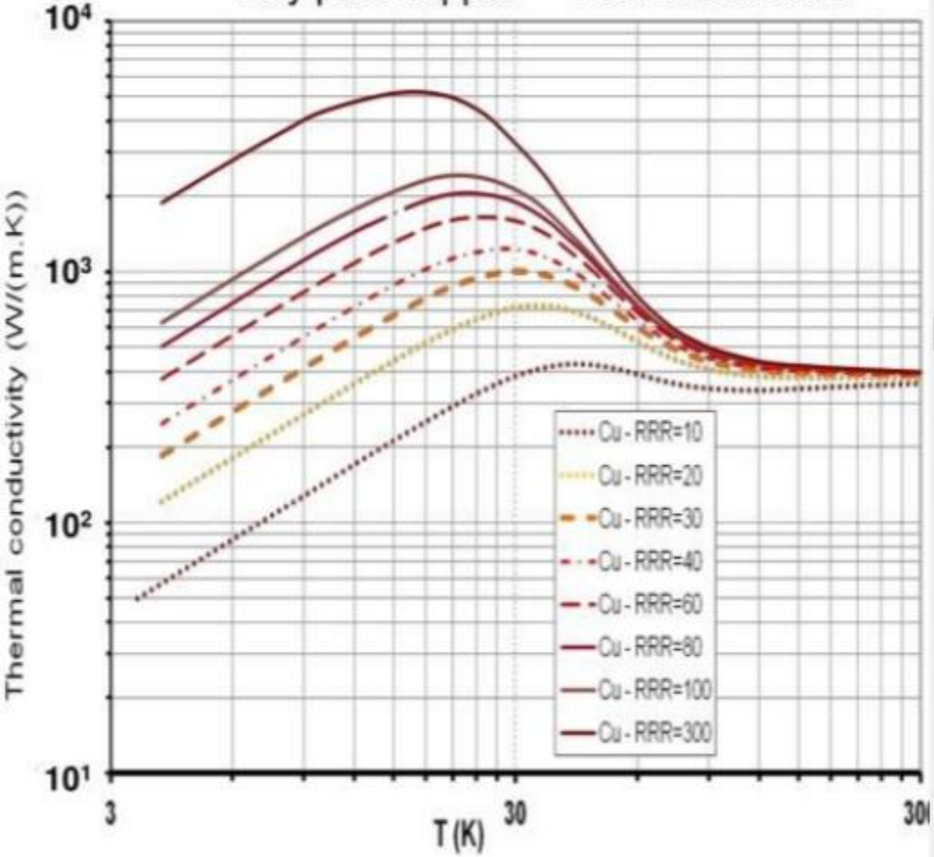


Figure 2.3.1. *Electrical analog for thermal conduction.* (The dashed lines with arrows indicate resistance that depend on the same basic scattering phenomena.)

THERMAL PROPERTIES

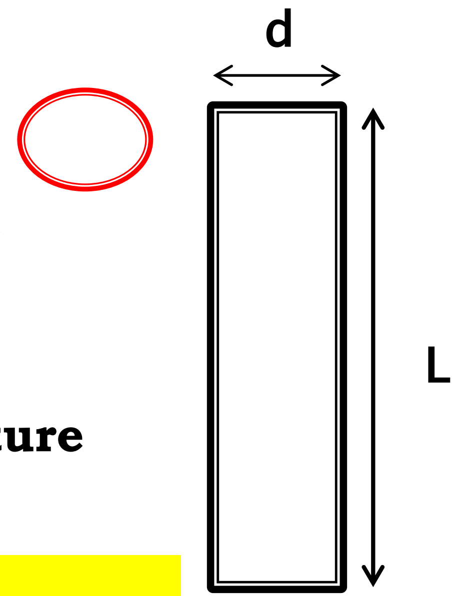
- Thermal conductivity
  - **For pure metals:**
    - k_{ph} is negligible
    - k has a maximum at low temperature
    - At low T°, k is affected by impurities
    - The more is the purity of the material,
      - the higher is this maximum
      - the lower is the T° of this maximum
    - $k \propto T$ at low temperature
  - **For metallic alloys:**
    - k decreases as T decreases
    - $k \propto T$ at low temperature
    - Wiedemann-Franz law:
      relates k_e and the electric resistivity ρ: $\rho \cdot k_e / T = 2.445 \cdot 10^{-8}$ (W·Ω/K²)
  - **For superconductors:**
    - $T > T_c$ (normal state) ⇒ cf. behaviour of metals
    - $T < T_c$ (Meissner state): $k_s \propto T^3$ and $k_s(T) << k_n(T)$ ⇒ thermal interrupter



HEAT TRANSFER MECHANISM

A. Solid conduction heat transfer : *Necktube, Support structure .*

$$Q_c = K_m \frac{A_C}{L}(T_h - T_C)$$



Ac = Cross sectional area (example for a rod of dia (d), Ac = $\pi d^2/4$, Similarly for a pipe of outer diameter d and thickness 't', Ac =πdt, L = Length of rod/ pipe,

Conductivity varies a lot between Room Temperature and Low Temperature (78 K or 4.2 K), K = f(T)

$$Q_C = \frac{A_C}{L}\int_{T_C}^{T_h} k\,dT$$

Table for Integral Value of Different materials are available with reference to Tc= 4.2 K

$$\int_{78}^{300} k\,dT = \int_{4.2}^{300} k\,dT - \int_{4.2}^{78} k\,dT$$

Conduction is reduced

- **Thin Pipe**
- **Long Length**
- **Insulating Material**

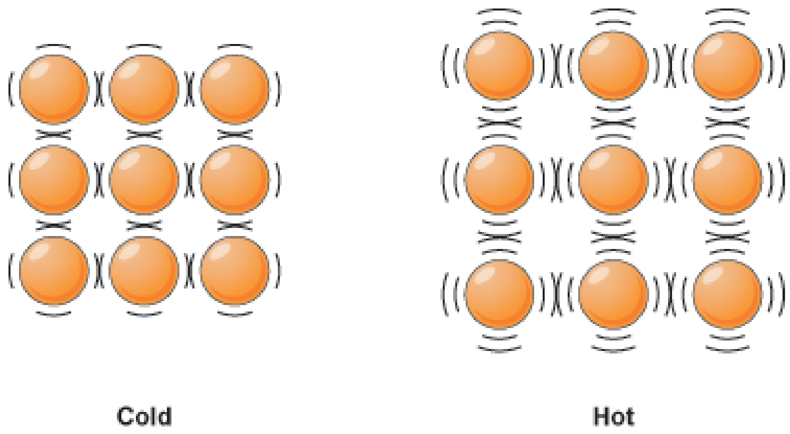
Thermal conductivity integrals

Tc=4 K

T_2	ETP copper	Aluminium 1100	Austenitic stainless steel	Glass	PTFE
[K]	[W cm^{-1}]	[W cm^{-1}]	[W cm^{-1}]	[mW cm^{-1}]	[mW cm^{-1}]
10	33.2	6.07	0.0293	6.81	4.4
20	140	27.6	0.163	20.0	16.4
30	278	59.2	0.424	36.8	32.3
40	406	96.2	0.824	58.6	50.8
50	508	134	1.35	84.6	71.6
60	587	170	1.98	115	93.6
70	651	202	2.70	151	116
80	707	232	3.49	194	139
90	756	258	4.36	240	163
100	802	284	5.28	292	187
120	891	330	7.26	408	237
140	976	376	9.39	542	287
160	1060	420	11.7	694	338
180	1140	464	14.1	858	390
200	1220	508	16.6	1030	442
250	1420	618	23.4	1500	572
300	1620	728	30.6	1990	702

- **Reduction of heat flow to the cold boundary temperature by thermal interception at intermediate temperature**

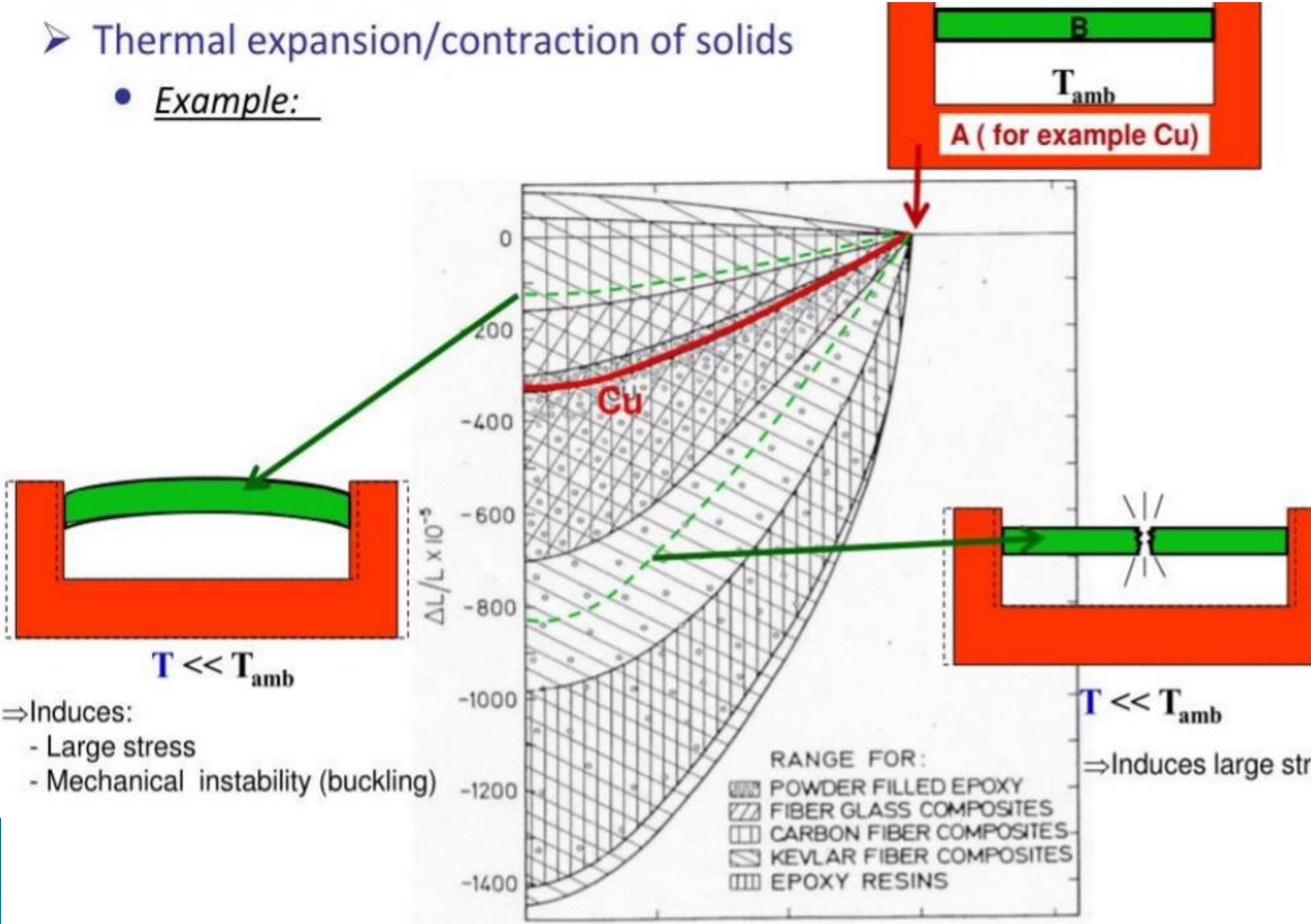
Thermal Contraction/ Expansion



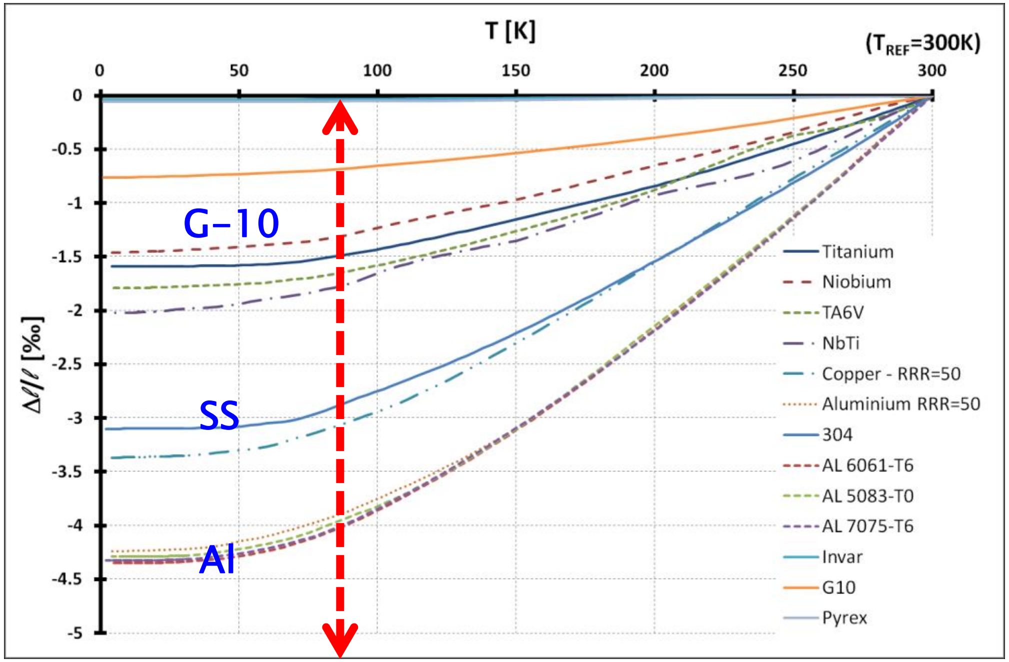
When heated, solids (and liquids and gases) gain thermal energy. The particles start to move about more – their vibrations take up more space, so there is expansion in all directions. The opposite is true when the temperature falls – the material will get smaller (contract).

➢ Thermal expansion/contraction of solids

- *Example:*



Thermal Contraction at Low Temperature

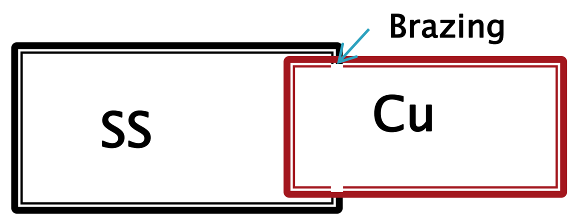


$$\Delta L = \alpha L (T_2 - T_1)$$

$$Stress = E.\alpha.(T_2 - T_1)$$

E= Young Modulus

= Thermal expansion Coefficient



- **90 % of Contraction happens between 300 K to 78 K. Contraction Between LN2 Temperature and LHe Temperature is bare minimum**

- **Non Metal (G- 10) have less thermal Expansion Co- efficient than Metal (CU, SS)**
- **Approx 3- 4 mm contraction on cooling a rod of SS, Cu, Al of Length 1 Meter**

- **Different Thermal Expansion co-efficient between Material can be used constructively or there can be design failure**

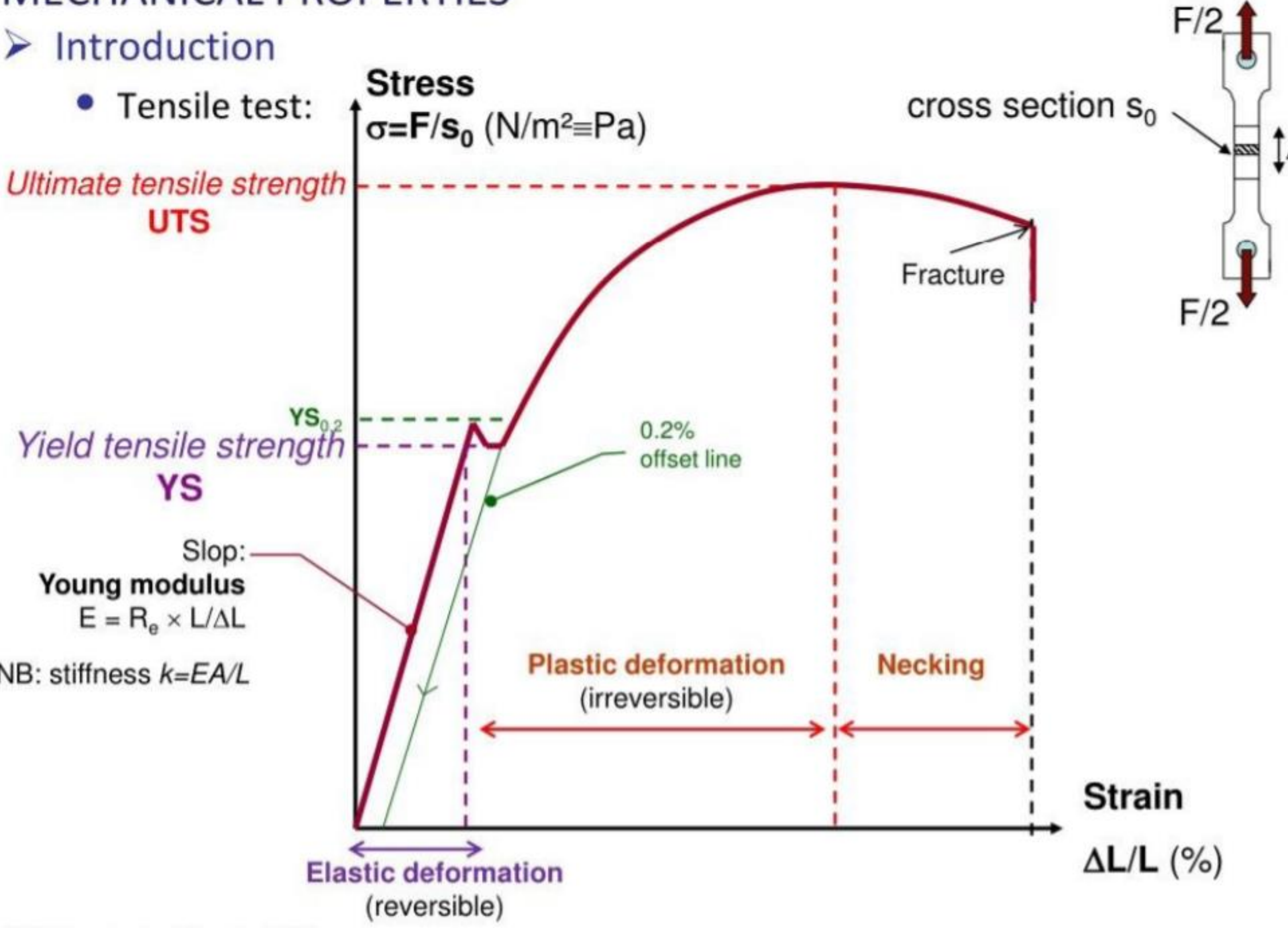
Mechanical Properties

Sr. No.	Property
1	Yield and Ultimate Strengths
2	Fatigue Strength
3	Impact Strength
4	Hardness and Ductility
5	Elastic Moduli

MECHANICAL PROPERTIES

➢ Introduction

- Tensile test:



Materials Used at Cryogenic Temperature

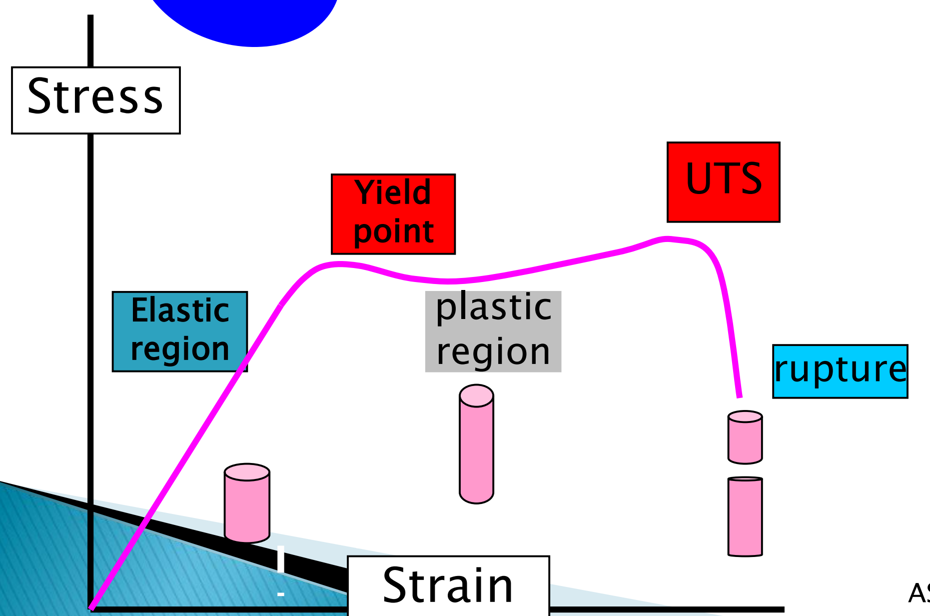
Significant Change on Property (Mechanical, Thermal) on cooling it down from RT to Cryogenic Temperature

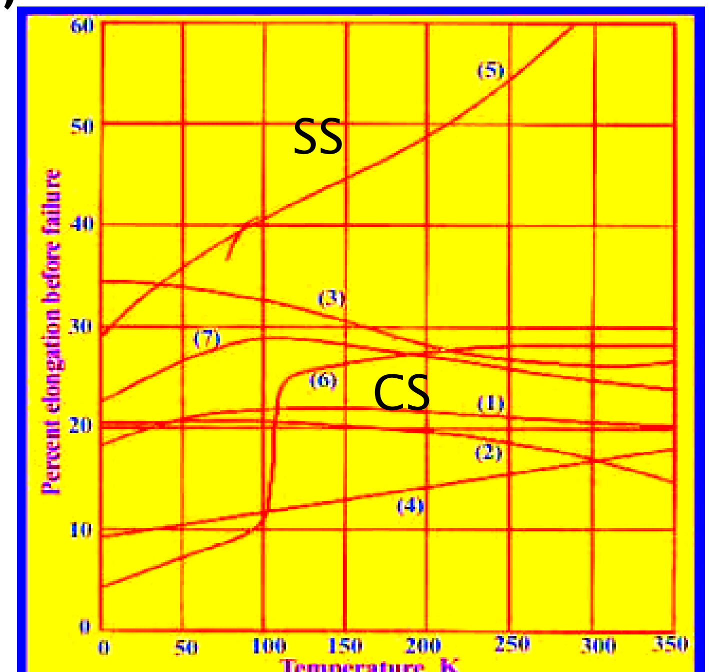
Ductile to Brittle : Percentage of Elongation Before failure reduced significantly

(Yield strength and UTS almost same)

NO — Carbon Steel, Nylon, Plastic Material

Yes — SS, Cu, Al, Teflon





Percent elongation for various materials: (1) 2024-T4 aluminium; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel; (7) 9 percent Ni steel.

Contact mail : tsdatta59@gmail.com

Thanks

Namaste