CRYOGENICS FOR ACCELERATOR- 2

T.S. DATTA

Inter- University Accelerator Centre

New Delhi

Cryogenic Course Material

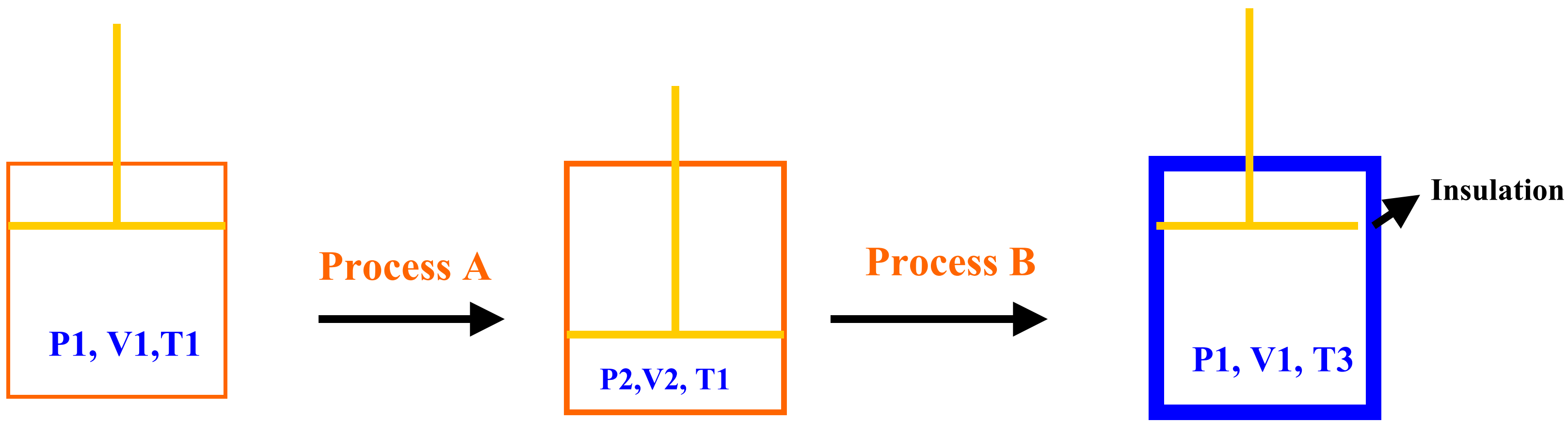
- Introduction : What is Cryogenics and Why Cryogenics for accelerator , Present Scenario
- How to Generate low Temperature / Production of Cryogen : Thermodynamics / Refrigeration Cycle, Practical Refrigerator
- How to Store Cryogen : Heat transfer, Cryomodule Design, Properties of Material :
- Measurement at Low temperature :

Liquefaction of gases/ Low temp Achievement

- Basic Thermodynamic Cycle
- T- S Chart
- Liquefaction cycle for N2 and He
- Components for Liquefaction
- Performance of Practical Refrigerator/ Liquefier

BASIC THERMODYNAMIC PROCESS FOR COOLING

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



Isothermal compression is achieved with water/ air cooling System. $W = m \cdot T \, (R/M) \ln (P_2/P_1)$.

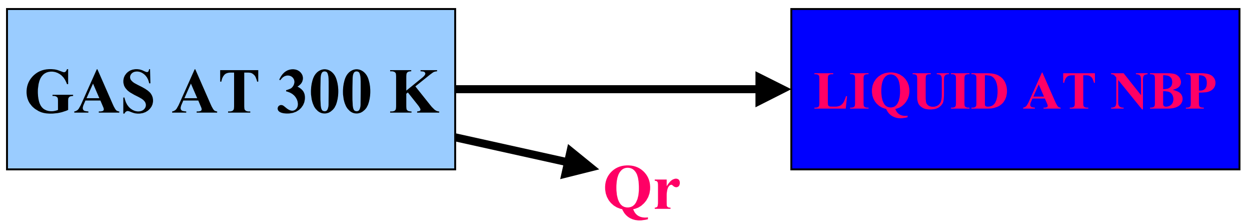
Example : 1 gm gas T= 300 K, P2/ P1 = 15

Helium : 1600 W (20 NM3), N2 = 200W (2. 8 NM3

T3 < T1 (Cooling)

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

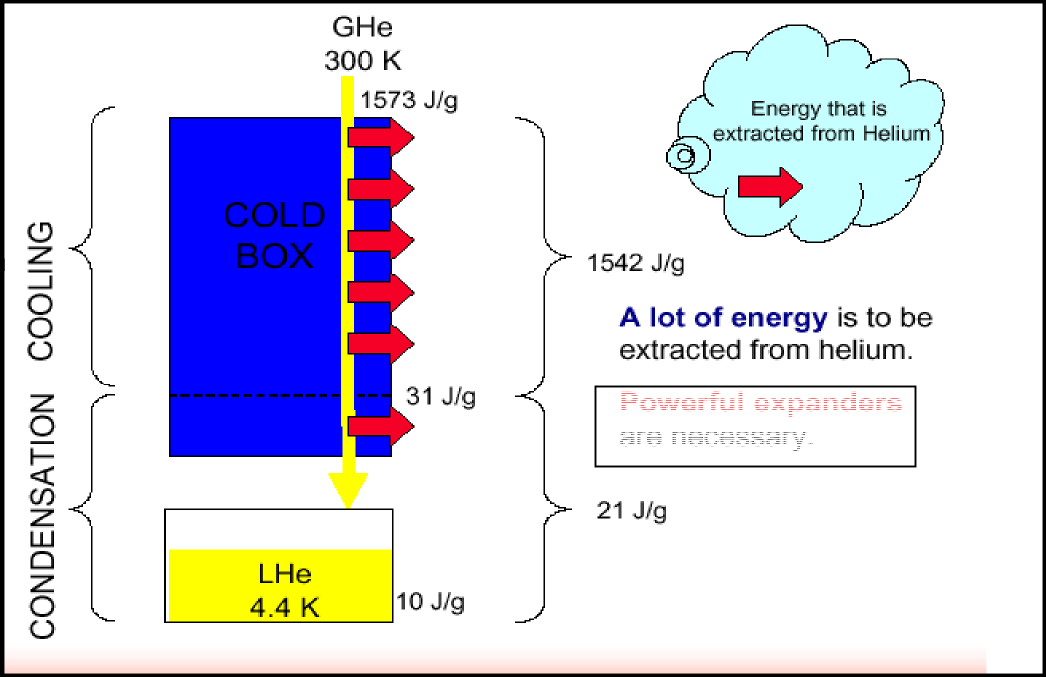
Latent Heat

To Liquefy "Permanent Gases"

Need

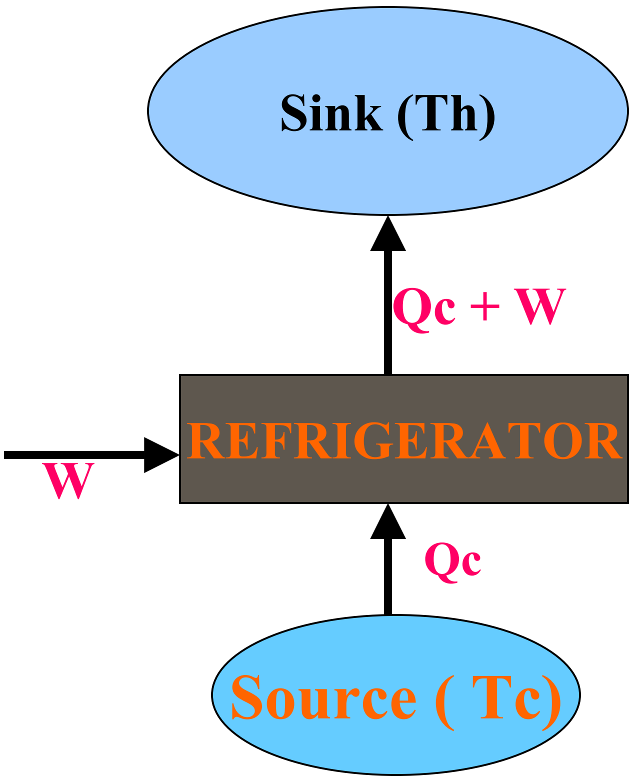
Cooling

Or in other way U need to extract the energy from the GAS for example HELIUM



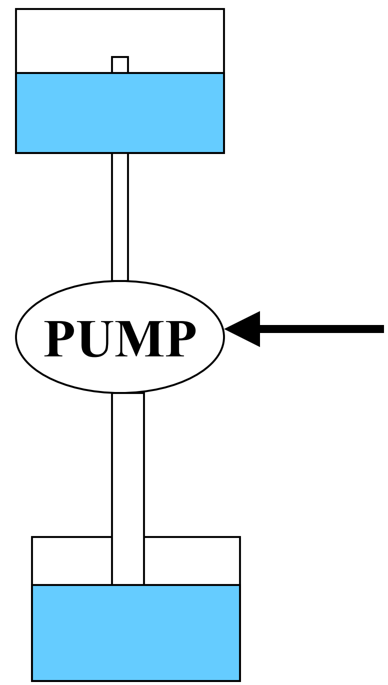
Refrigerator

To Transfer Heat from Source to Sink if source Temperature is less than Sink



Refrigerator is Analogus 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)



Power (W) required to extract 1 W refrigeration at Tc is : W = 1/ (COP)I = (Th- Tc) / Tc, Th = 300 K , Tc Vary from 200 K to .000001 K

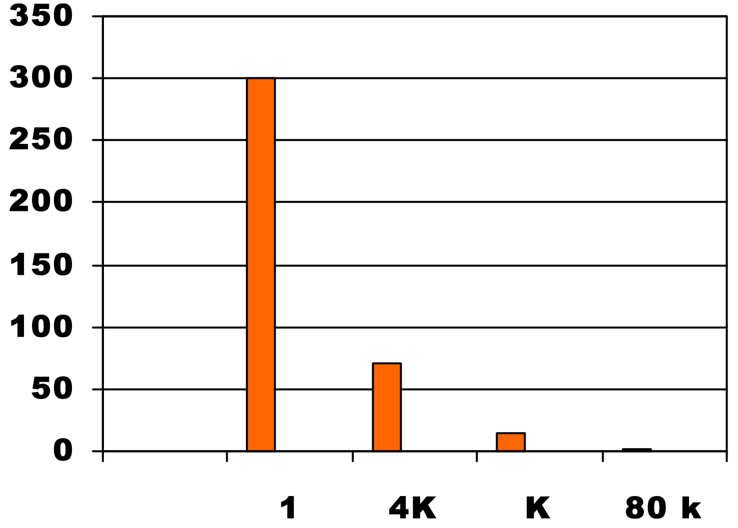
N2 , Tc = 78 K , W = 1.68 W

H2, Tc = 20 K W = 14 W

He , Tc = 4.2 K, W = 70 W

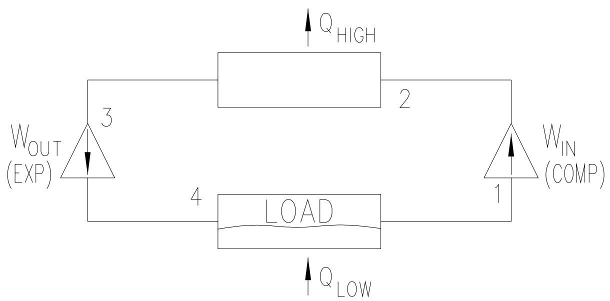
Tc = 0.1 K , W = 3000W

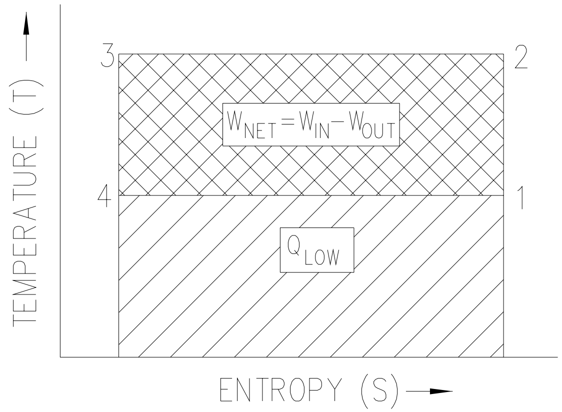
Tc = 0.01 W= 30000 W



These are Theoretical Power. We have to multiply first with efficiency Of the Cycle and then multiply with mechanical efficiency of all Components of refrigerator

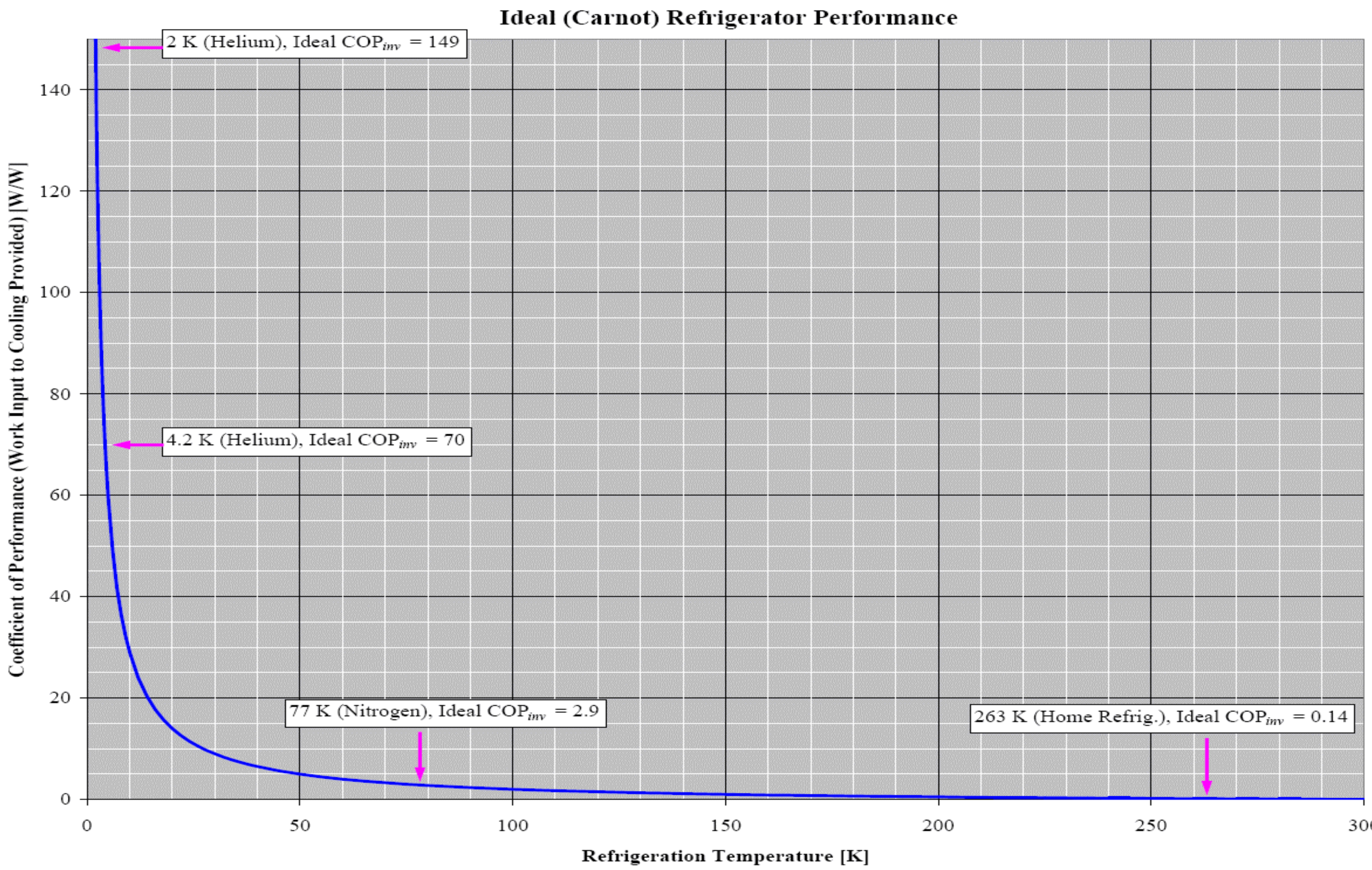
Carnot Refrigeration Cycle



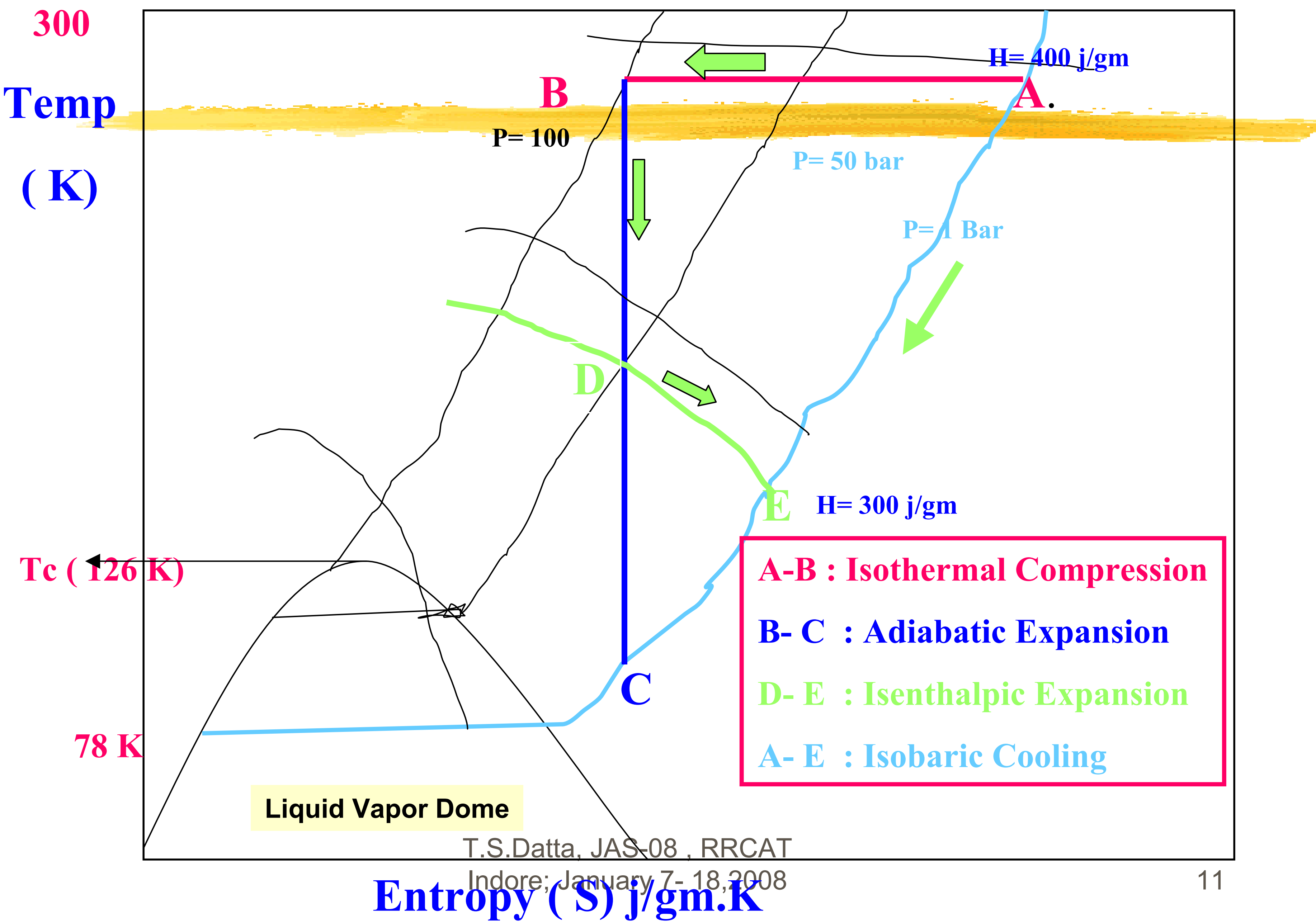


- 1-2, Compressor Fluid is compressed isentropically.
- 2-3, Condenser Heat is rejected isothermally (at *T2*)
- 3-4, Expander Fluid is expanded isentropically.
- 4-1, Evaporator Heat is absorbed isothermally (at *T1*)

Carnot Helium Refrigeration and Liquefaction Systems

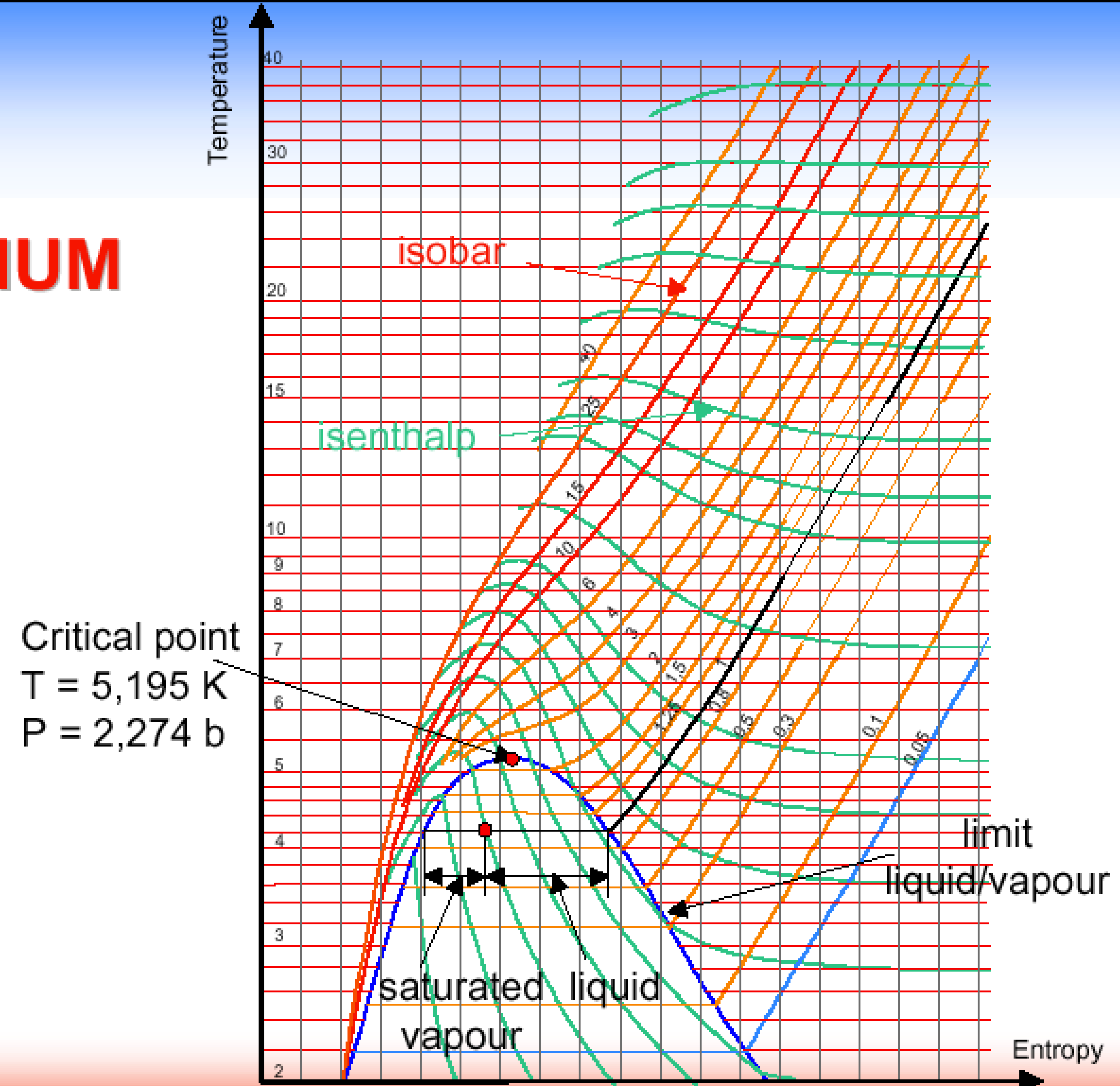


T(Temperature) - S (Entropy) CHART FOR GAS



T-S Diagram

HELIUM



To Liquefy "Permanent Gases"

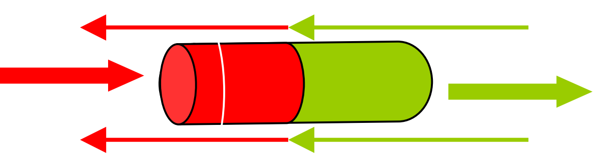
Cooling

Isobaric Cooling

dP = O

Done By

Heat Exchanger

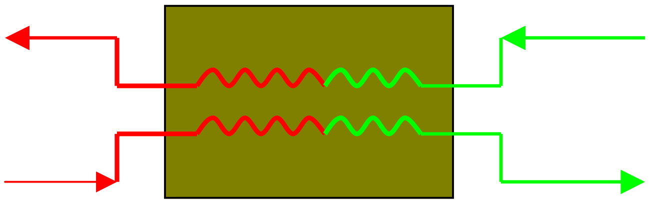


Cooling by Adiabatic Expansion [Isentropic]

Free Expansion
Does External work

Cooling by Joule -Thomson Expansion [Isenthalpic]

No External work



But Practically
<<100% efficient
T1>T1' & T2>T2'

> 0 for Cooling
< 0 for Heating

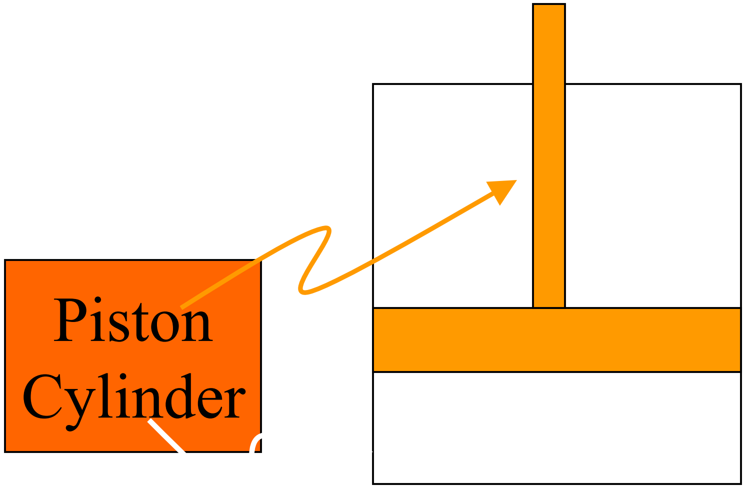
Property of any Gas

Cooling by Isentropic Expansion
Or Adiabatic Expansion
Or Free Expansion

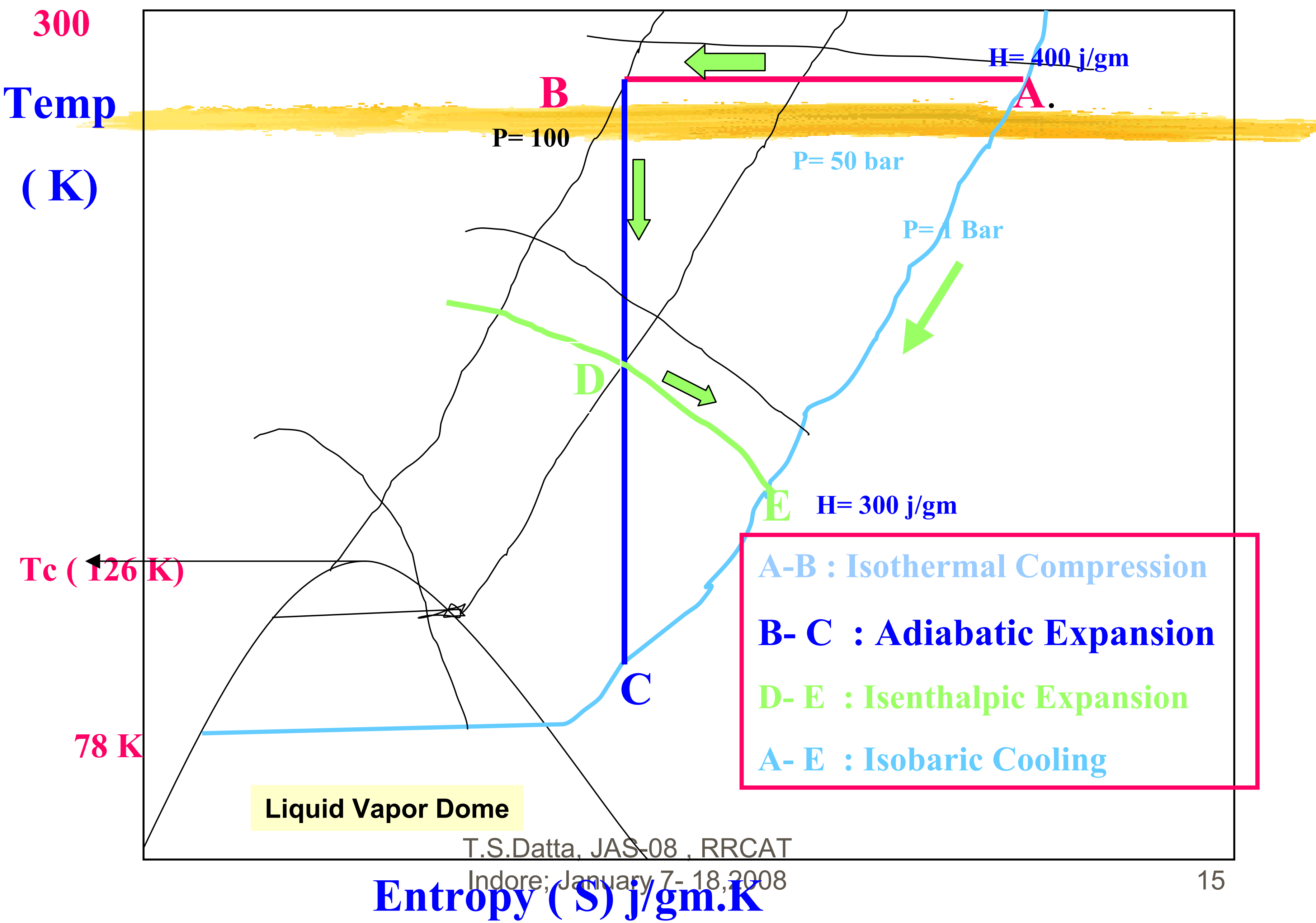
- **Thermally Isolated System**

  dq=0

  No Heat flow (IN/OUT) to the System



T(Temperature) - S (Entropy) CHART FOR GAS



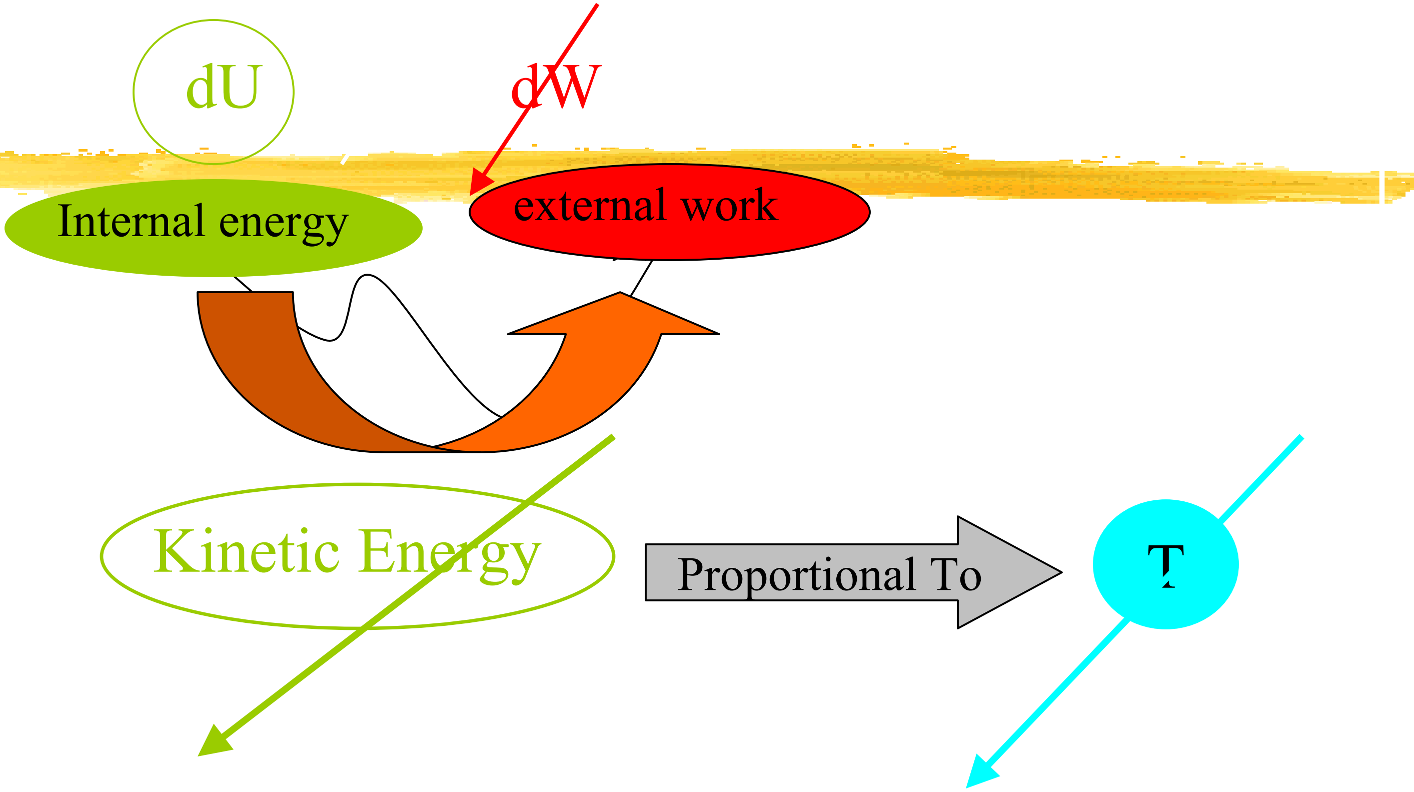
A-B : Isothermal Compression

B- C : Adiabatic Expansion

D- E : Isenthalpic Expansion

A- E : Isobaric Cooling

external work



Hence Cooling!!!!

Expansion Coefficient

$$\mu_s = (dT/dP)_s$$

$$\mu_s = [T(dV/dT)_p]/C_p$$

*** For Ideal Gases : PV= RT** μ_s **= V/Cp (+) ive > 0**

Cooling in Expansion

* For Real Gases (means Van-Der-Waals gases) :

$$(p + a/v^2)(v-b) = RT$$

$$\mu_s = (dT/dP)_s = (v/C_p)[\{1-(b/v2)\}/\{1-(2a/vRT)\}\{1-b/v2\}]$$

$$b \ll v \text{ i.e. } b/v \ll 1$$

That means $\mu_s > 0$

dP = dT hence Cooling

ADIABATIC/ ISENTROPIC EXPANSION : Gas does an external work by lifting piston in reciprocating engine or rotates the turbine blade.

It looses energy ---Thermally isolated (dq = 0, ds = 0) ------- Temperature drops

Isentropic expansion Coefficient $\mu_s = (dT/dp)_s = T/ Cp (dv/dT)_p = v/ cp$ for ideal gas

For van der Walls gas : $\mu_s = v (1- b/v)/ Cp [1- (2a/vRT)(1- b/v)^2]$

Unlike μ_{jt} . μ_s is always positive that is cooling at any temperature and pressure. Second one Temperature drop is more compared to JT expansion for same dP

To Liquefy "Permanent Gases"

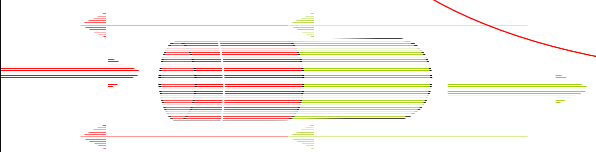
Cooling

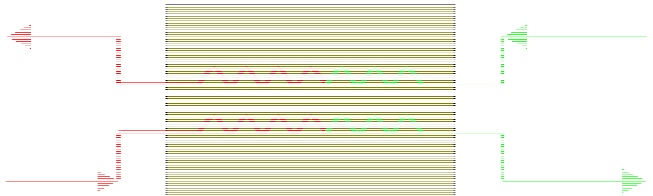
Isobaric Cooling

dP = O

Done By

Heat Exchanger





Cooling by Adiabatic Expansion Isentropic]

Free Expansion
Does External work

Cooling by Joule -Thomson Expansion [Isenthalpic]

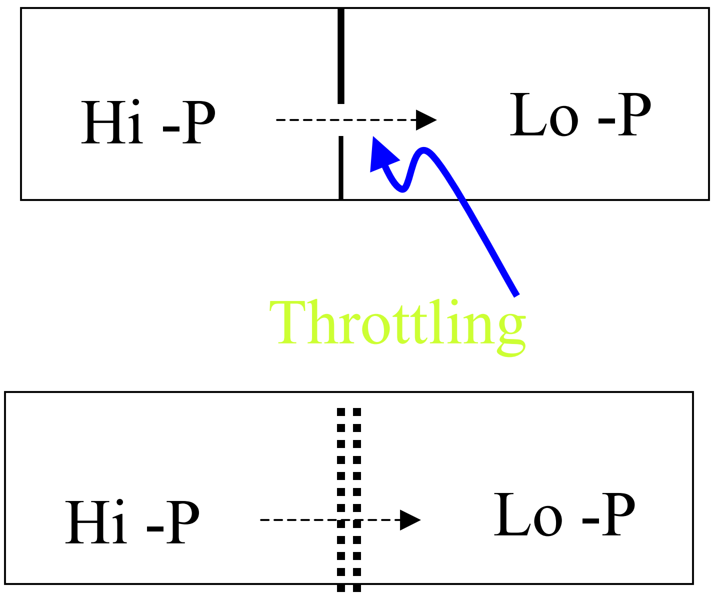
No External work

But Practically
<<100% efficient
T1>T1' & T2>T2'

> 0 for Cooling
< 0 for Heating

Property of any Gas

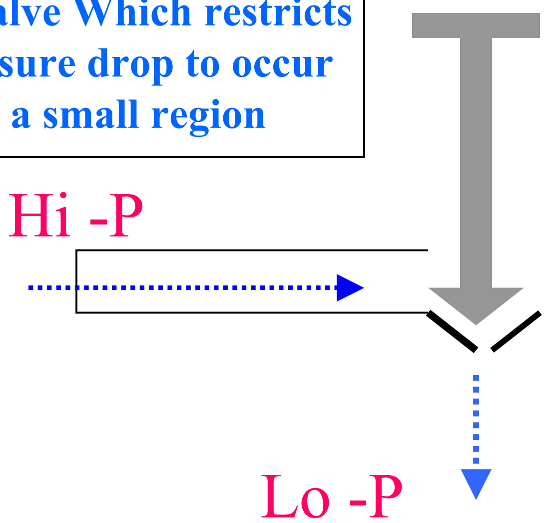
Joule -Thomson Expansion



Expansion Thru Porus Plug

More Ideal Condition but technically difficult

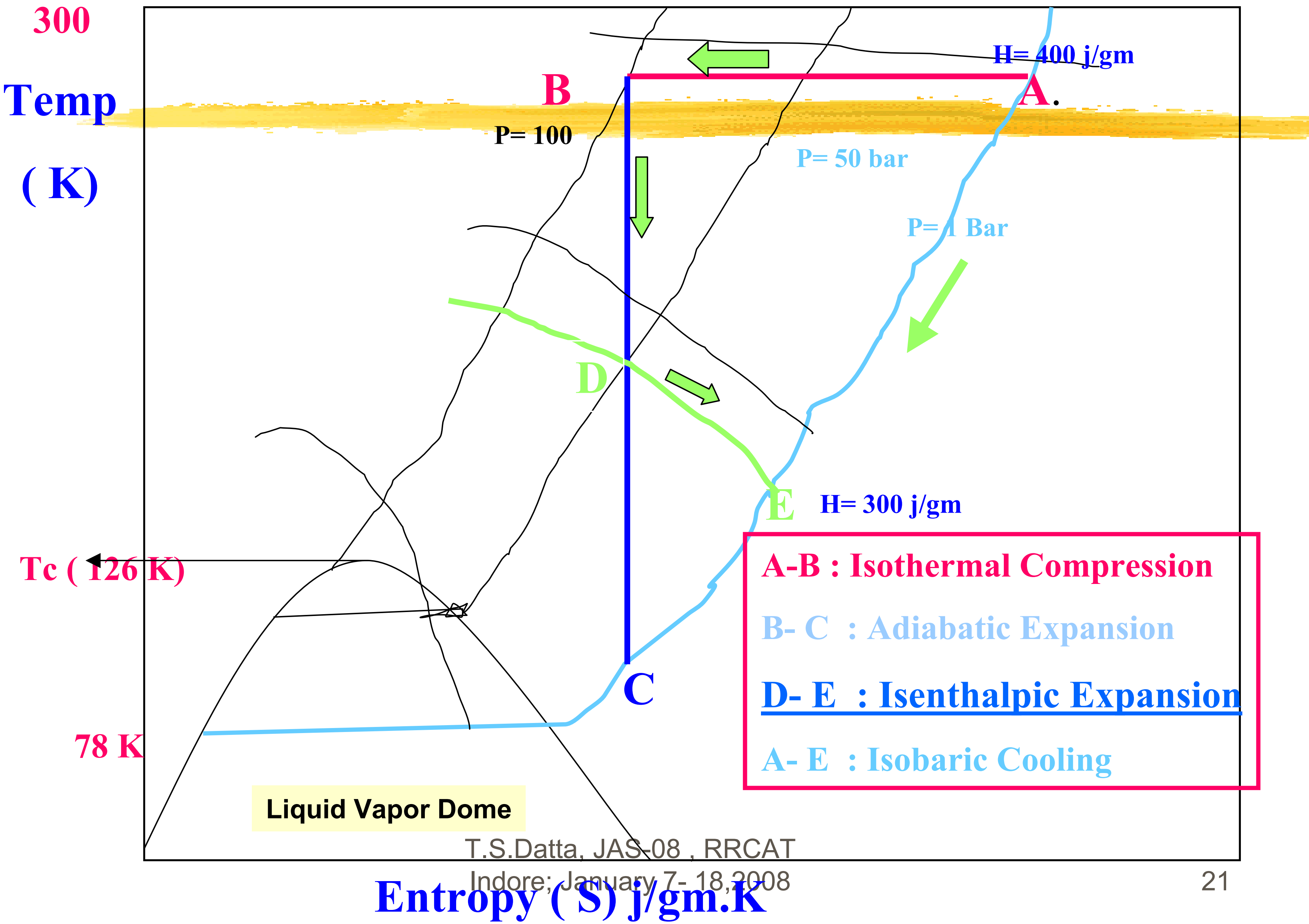
Needle valve Which restricts the pressure drop to occur over a small region



Joule -Thomson Valve

Less Ideal condition but technically easy

T(Temperature) - S (Entropy) CHART FOR GAS



ISENTHALPIC EXPANSION (Joule- Thomson Cooling)

Gas does an internal work againt intermoleculer interaction and loose its energy. Hence Temperature reduced.

$$\mu_{jt} = (dT/ DP)\, h = 1/ Cp\, [\, T(dv/dT)p - V]$$

For Ideal Gas $\mu_{jt} = 0$

No Cooling or Heating on Expansion

Cryogenic operating condition (low temp, High pressure) gas does not behave ideally

For real gas (Van dar walls)

$$\mu_{jt} = [(2a/RT)\,(1- b/v)^2 - b]/ Cp[\, 1- (2a / vRT)(1- b/v)^2]$$

at low pressure

$$\mu_{jt} = 1/Cp\, [(2a/RT) - v]$$

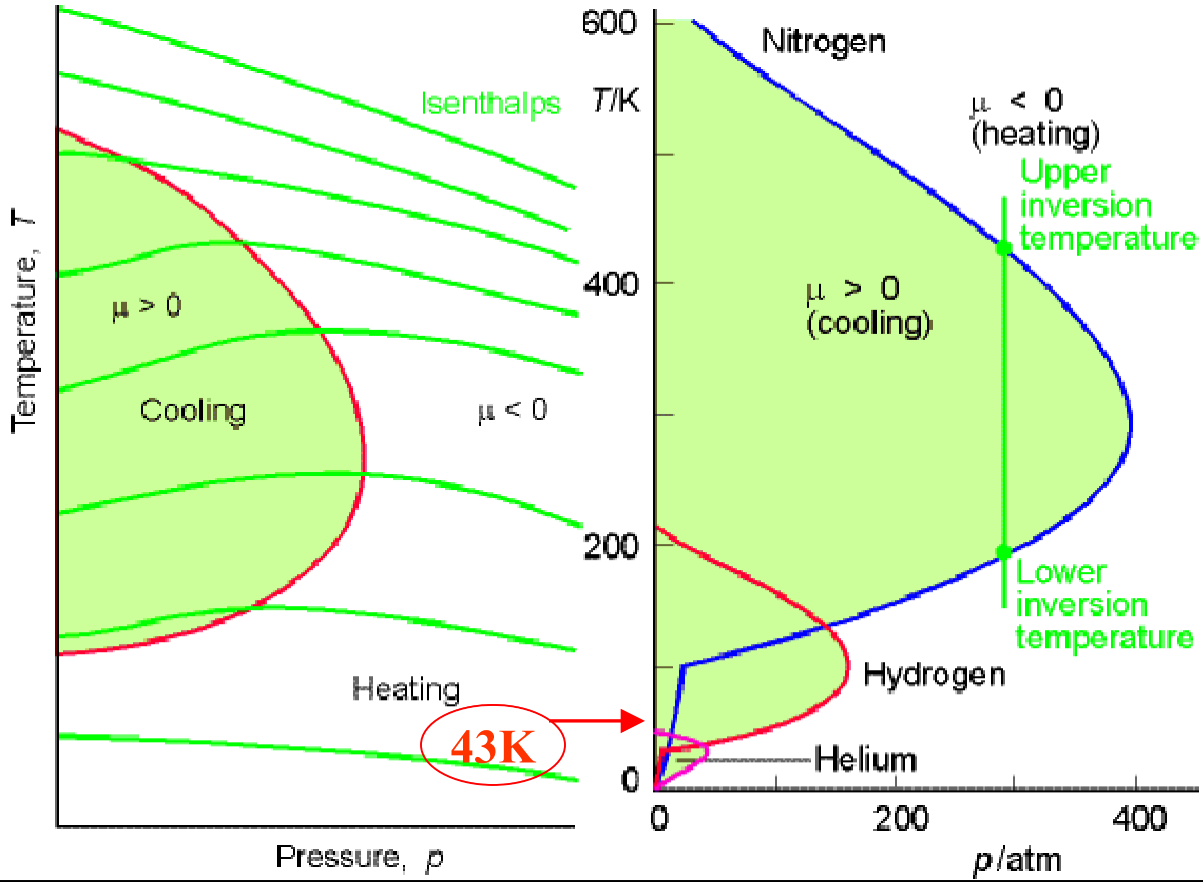
Joule -Thomson Expansion

Inversion Curve

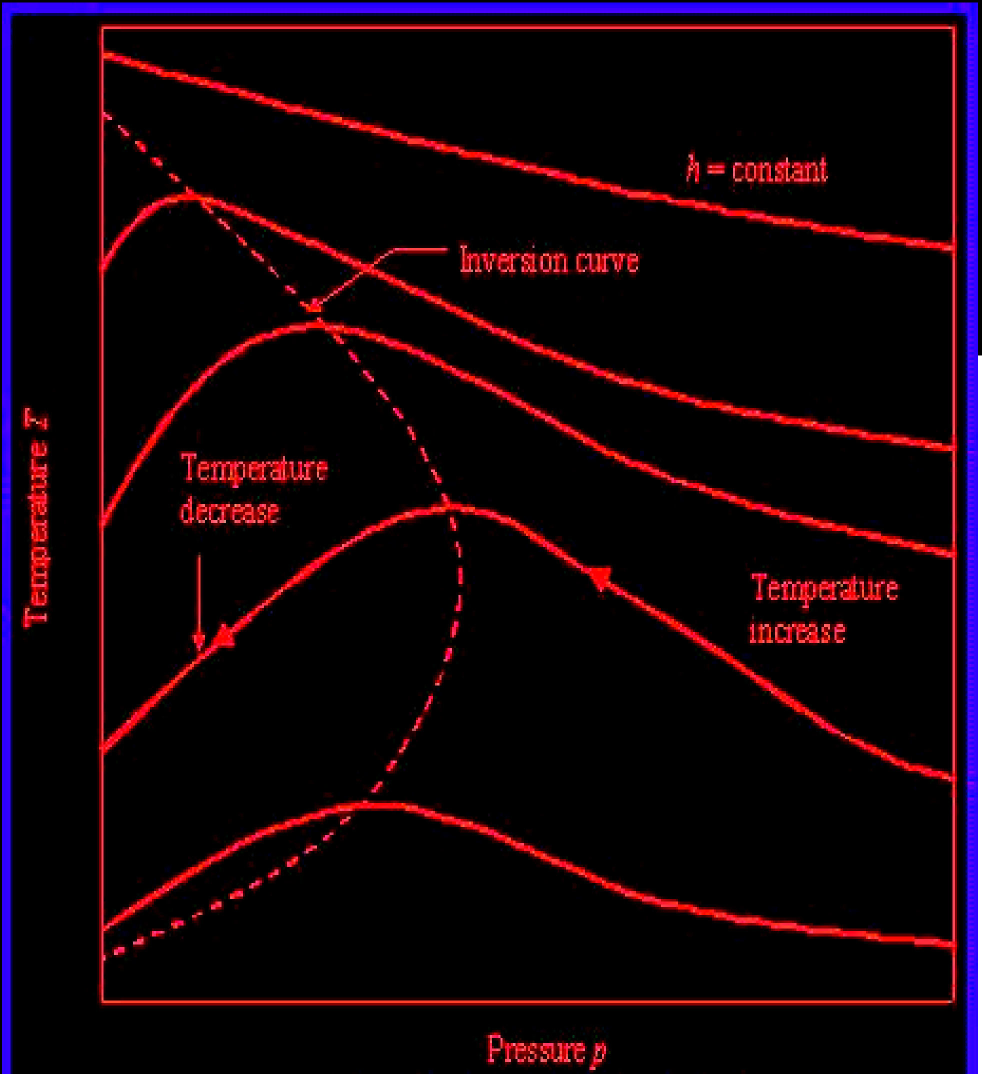
μ > 0: *dT* is -ve when *dP* is -ve, gas cools on expansion

μ < 0: *dT* and *dP* have opposite signs, gas heats up on expansion

μ = 0: perfect gas, *T* unchanged by J-T expansion



Joule -Thomson Expansion



Isenthalpic Expansion of a Real Gas

μ_{jt} = Positive (Cooling)

μ_{jt} = Negetive (Heating)

Max Inversion Temperature : Temperature on the inversion Curve at p = 0, Timax = 2a/ bR

Above max inversion temperature we will not be able to cool the gas for any set of pressure combination.

Gas	*He*	*H2*	*Ne*	*N2*	*Ar*	*O2*
Timax	45	205	250	621	794	761

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

Linde- Hampson Cycle [Joule-Thomson Cycle]

Mainly based on Joule -Thomson Expansion

He	4.2 K	43 K
H2	20.3 K	202 K
N2	77.4 K	623 K
O2	90.2 K	761 K

< Room Temperature

Need Cooling below Tinv(max) before J-T Expansion

> Room Temperature

Joule - Thomson Ex alone can Liquefy N2 & O2

Linde- Hampson Cycle is for N2 or O2 Liquefaction not for He or H2

Isentropic Expansion Vs. Isenthalpic Expansion

expansion co-efficient

$\mu_s = [T(dV/dT)p]/Cp$ $\mu_{jt} = [T(dV/dT)p-v]/Cp$

$\mu_s - \mu_{jt} = v/Cp > 0$

$\mu_s > \mu_{jt} \longrightarrow (dT/dP)_s > (dT/dP)_{Jt} = v/Cp > 0$

That means

Cooling By Isentropic Expansion > Cooling By Isenthalpic Expansion

Example

He

@ 10 bar @ 19.5K

dH=O

Isenthalpic Expansion

18.5 K

Thru J-T valve

dS=0

Isentropic Expansion

8K

Thru Expansion engine

Isentropic Expansion Vs. Isenthalpic Expansion

expansion co-efficientnt

$\mu_s = [T(dV/dT)p]/Cp$ $\mu_{jt} = [T(dV/dT)p-v]/Cp$

$\mu_s - \mu_{jt} = v/Cp > 0$

$\mu_s > \mu_{jt} \longrightarrow (dT/dP)_s > (dT/dP)_{Jt} = v/Cp > 0$

That means

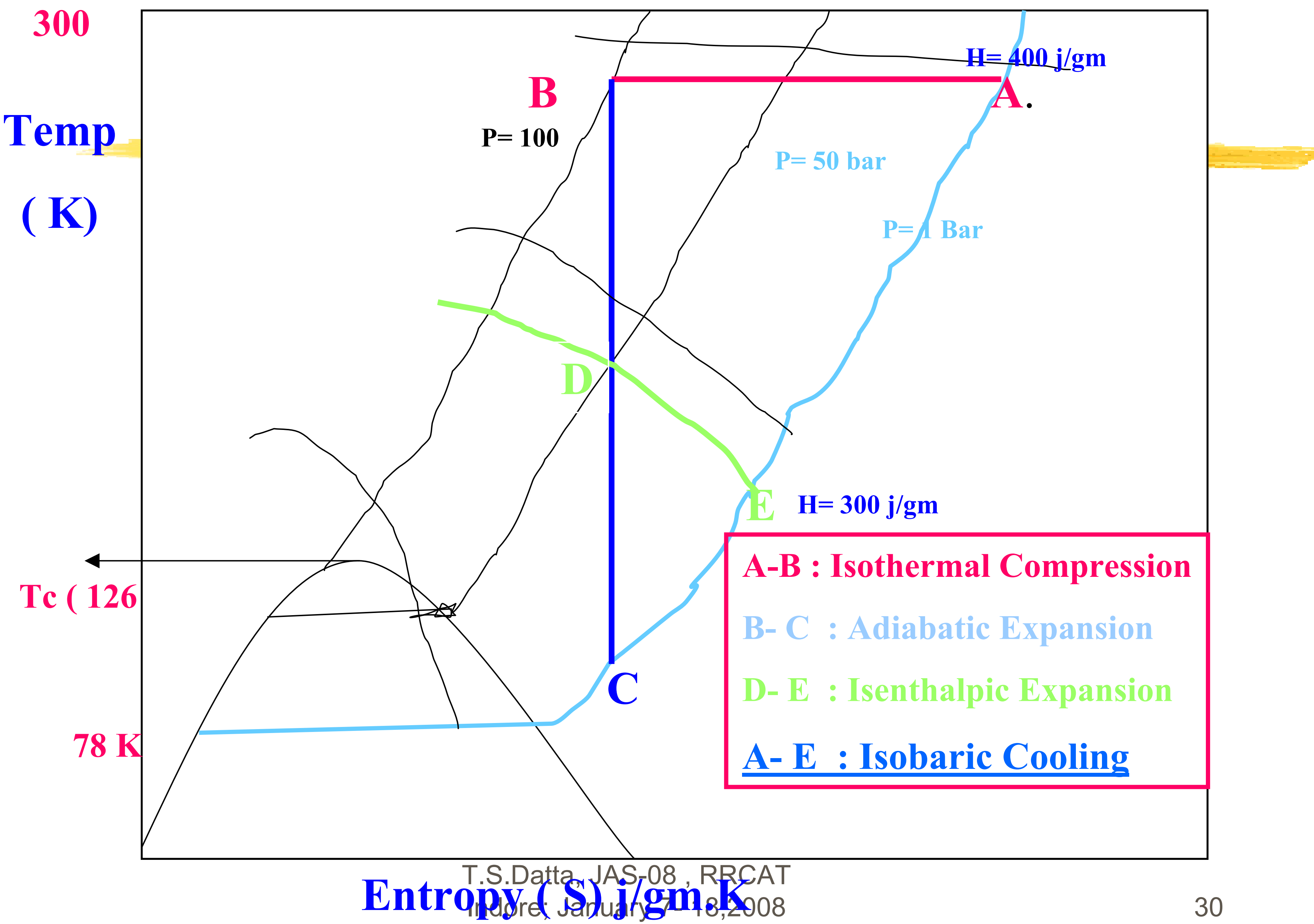
Cooling By Isentropic Expansion

Cooling By Isenthalpic Expansion

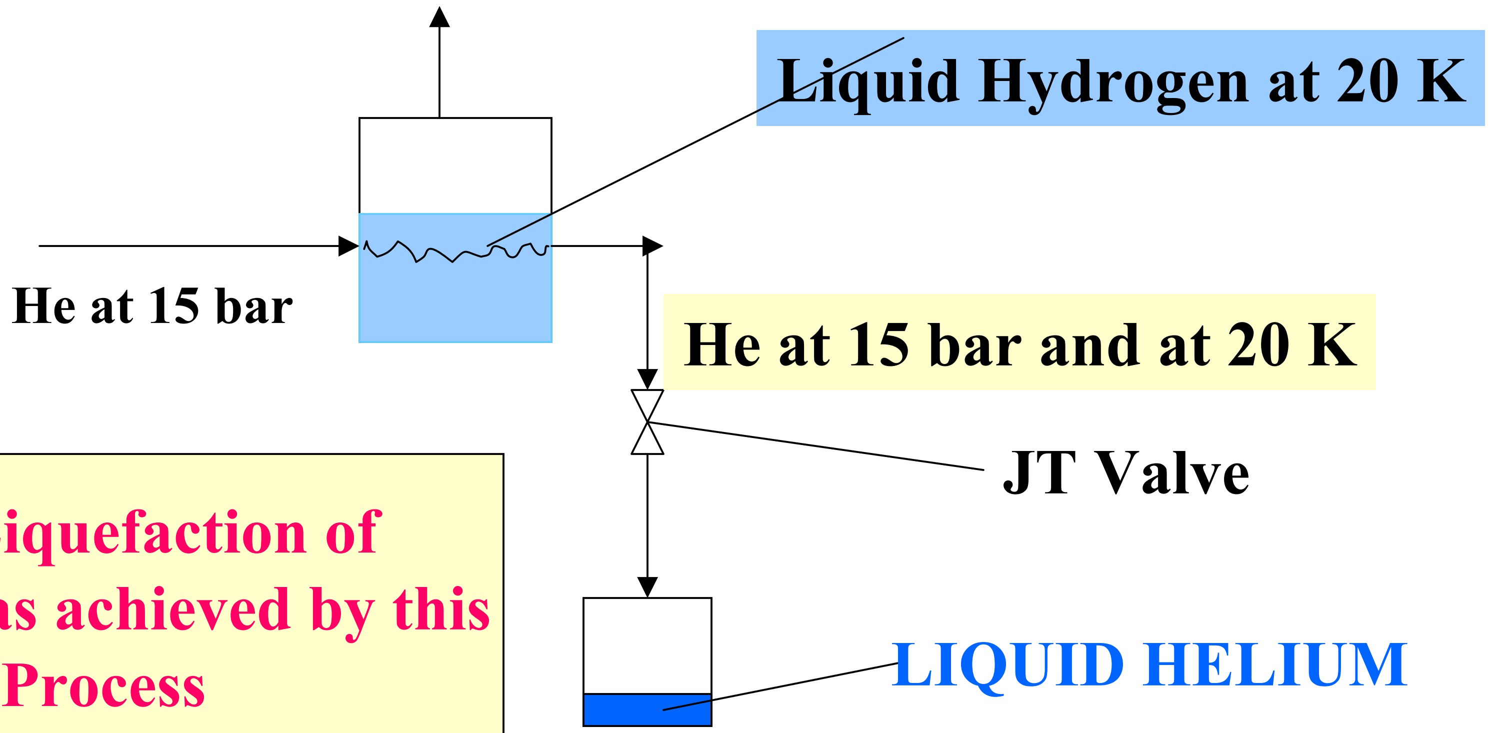
$\mu_{jt} \longrightarrow \mu_s$ When $v \longrightarrow 0$

that means @ Hi-P + @ Lo-T

T - S CHART FOR GAS



ISOBARIC COOLING



First Liquefaction of Helium was achieved by this Process

PERFORMANCE PARAMETERS OF A LIQUEFIER

LIQUID YIELD = mf/ m (Fraction of compressed gas liquefies)

Power Required to produce unit production of Liquid = Wa/ mf

FOM = (Wi/mf) / (Wa/ mf)

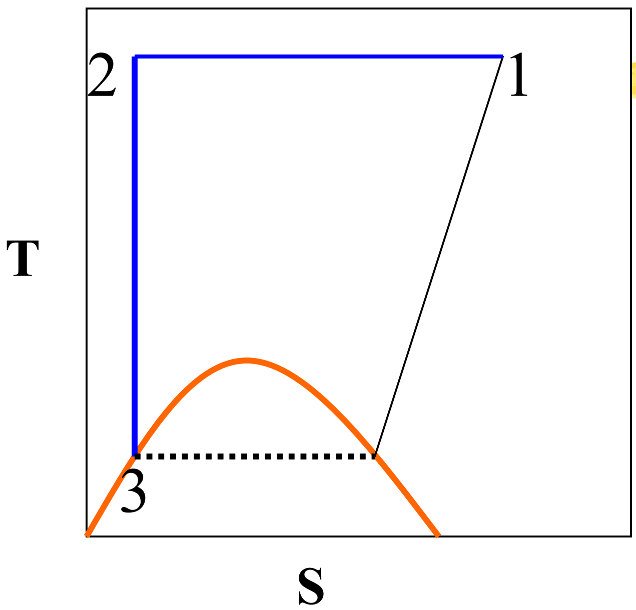
Wi/ mf = ideal power required

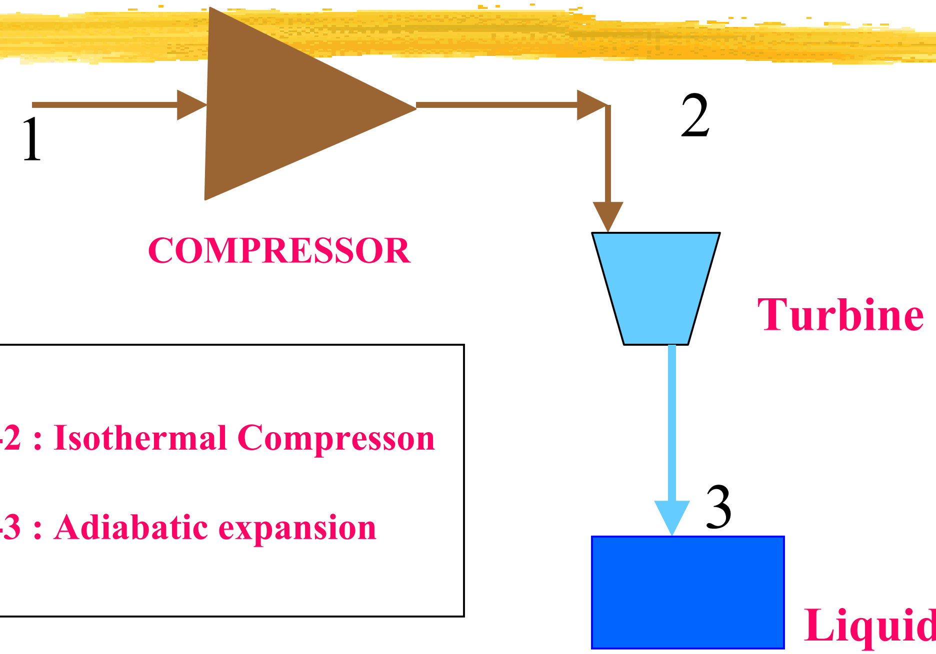
IUAC

Compressor Capacity : 56 gm/sec, liquid production rate : 150 l/hr = 5gm/sec : mf = .09

We Consume power of 200KW to produce 150 l/hr, Wa/mf = 40 KJ to produce 1 gm liquid, Wi/mf = 7KJ , FOM = 0.17

IDEAL THERMODYNAMIC CYCLE FOR COOLING





1-2 : Isothermal Compresson

2-3 : Adiabatic expansion

Liquid Yield = mf/m = 1

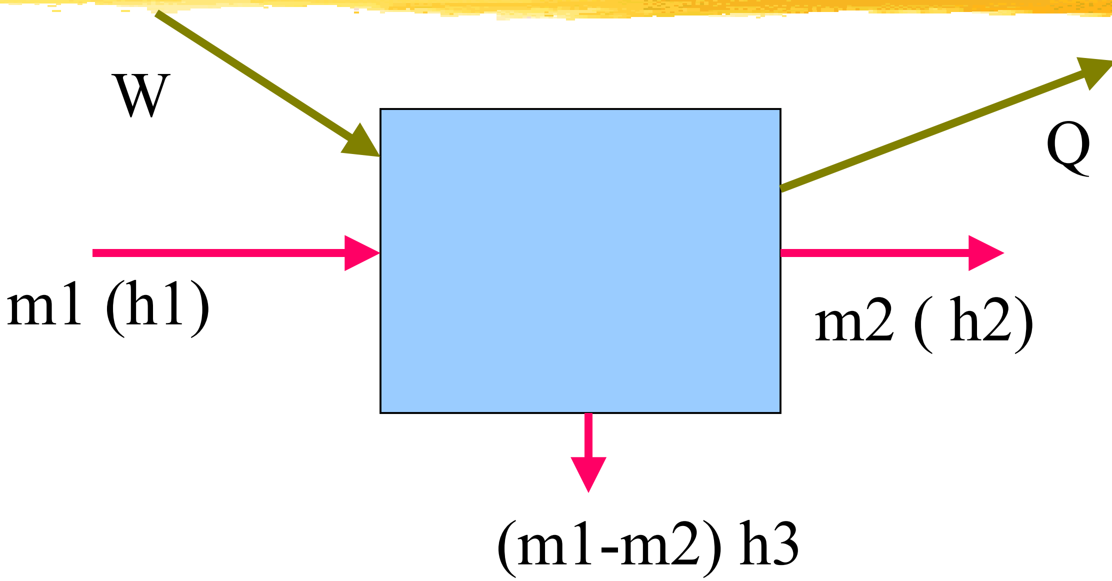
Power Required : W/m = T1 (S1- S2) - (h1- h2)

IMPRACTICAL : DISCHARGE PRESSURE REQUIRED : 700,000 bar

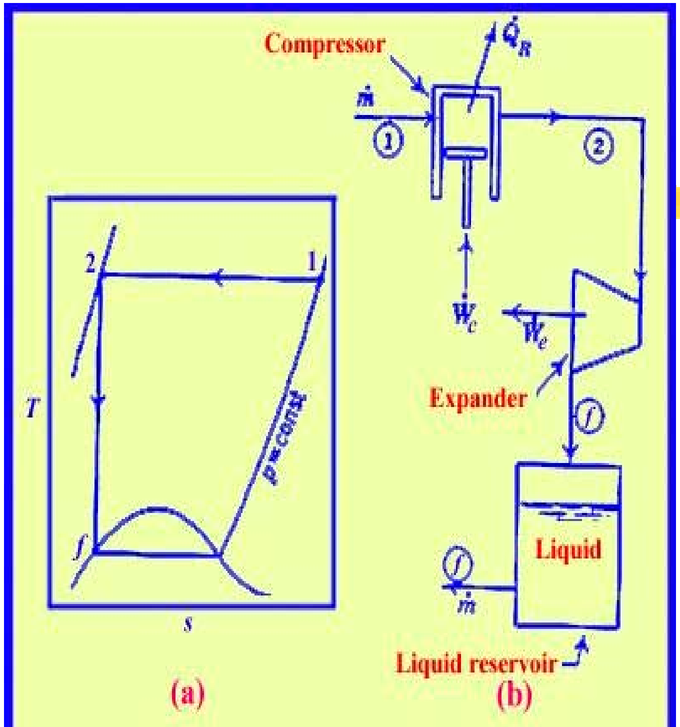
Ideal Work Requirement for 1 Kg Liquid Production

N2 = 768 KJ, He = 6800 KJ, H2 = 12000 KJ

ENERGY & MASS BALANCE OF CLOSED SYSTEM



m1h1 +W = m2h2 + (m1-m2)h3 +Q



The thermodynamically ideal liquefaction system.

*** Coefficient of Performances (COP)**

COP = Work required to liquefy unit mass compressed

Flow Equation:

$$Q_{net} - W_{net} = \sum_{outlet} \dot{m}h - \sum_{inlet} \dot{m}h$$

$$-W/m = T_1(S_1 - S_f) - (h_1 - h_f)$$

Work done to liquefy unit mass compressed

e.g He $T_1 = 300K$, $S_1 = 32$ J/g, $h_1 = 1573$ J/g

$T_f = 4.2K$, $S_f = 3.2$J/g, $h_f = 9$J/g

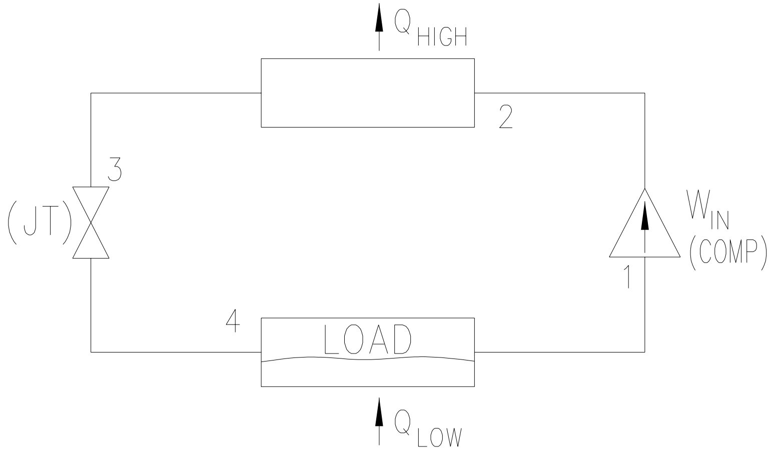
Work required per unit mass liquefied

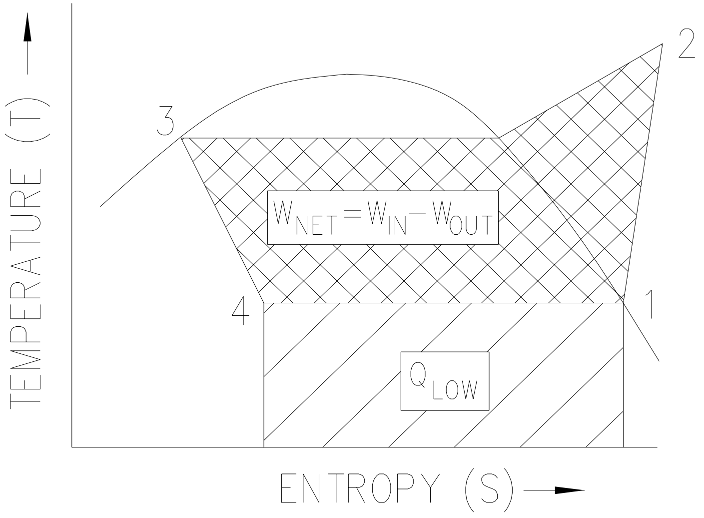
$\sim 300 (32-3.2) - (1573- 9)$ J/g

~ 7000J/g

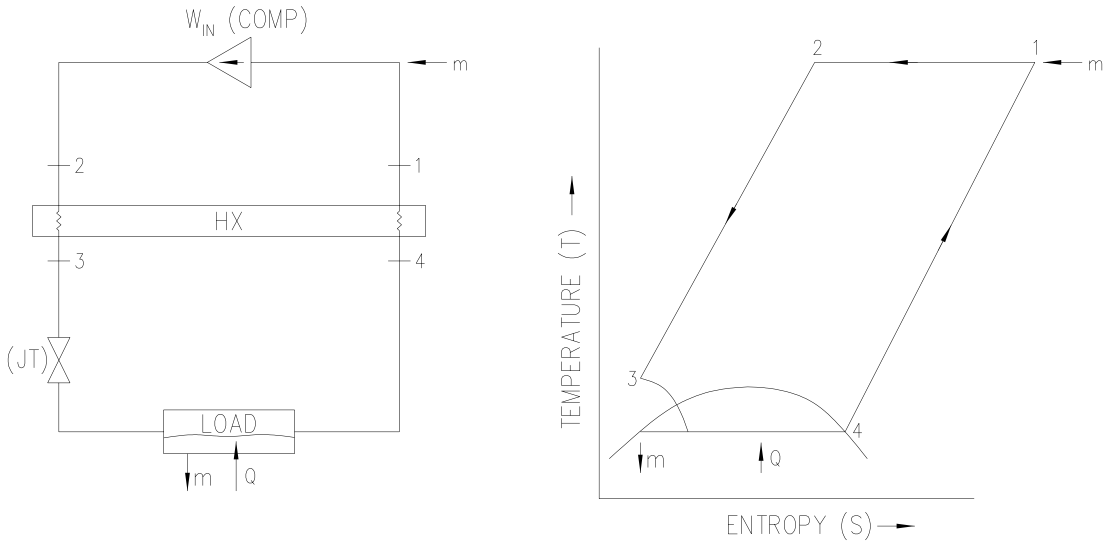
Vapor compression process

e.g.: Typical Freon refrigerator



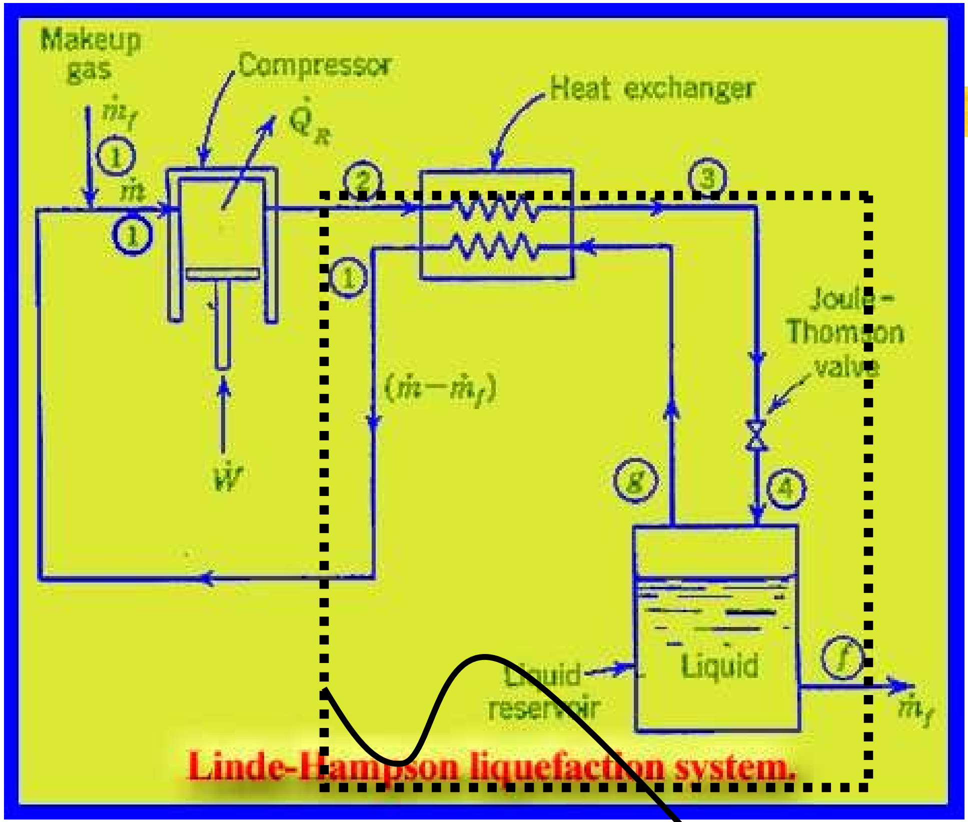


⌘Hampson process

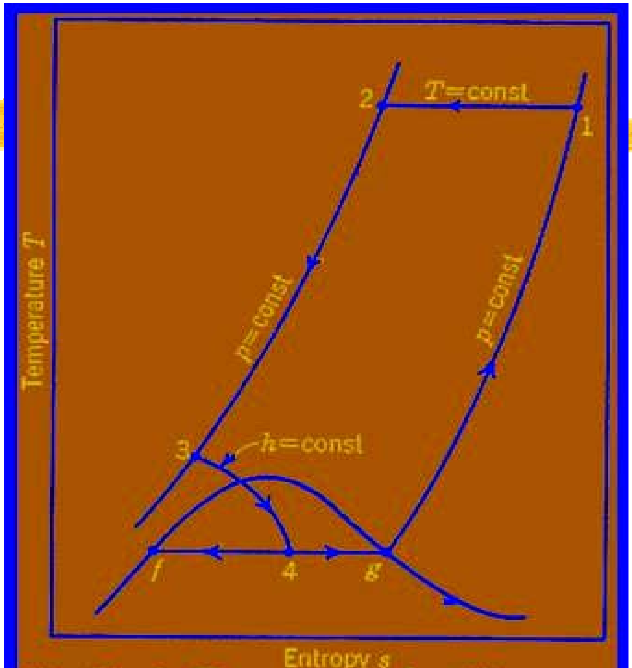


- This uses a heat exchanger (HX) between the compressor and the load for heat energy exchange between the supply and return streams.
- This process supports lower temperature load operations more efficiently than the vapor compression process.

Schematic of L-H (J-T) cycle



Linde-Hampson liquefaction system.



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

Balance the Enthalpy [H (IN) = H (OUT)]

Yield (Y) = (h1-h2)/(h1-hf)

L-H (J-T) cycle

Work Done Required

Balance the Enthalpy [H (IN) = H (OUT)]

Yield (Y) = (h1-h2)/(h1-hf) <1

Work Required per unit mass liquefied

$-W/m_f = [(h_1-h_f)/(h_1-h_2)][T_1(S_1-S_2)-(h_1-h_2)]$

For Ideal case : m= mc = mf

$- W/m = T_1(S_1 - S_f) - (h_1 - h_f)$

Work done to liquefy unit mass compressed

FOM = Work(ideal)/Work(real)

$= [(h_1-h_2)/h_1-h_f)][\{T_1(S_1-S_2)-(h_1-h_f)\}/\{T_1(S_1-S_2)-(h_1-h_2)\}]$

Energy balance on the closed system (HX, Exp Valve & liquid receiver)

$m.h_2 = (m - m_f)h_1 + m_f h_f$ or $m_f/m = y \text{ (yield)} = (h_1 - h_2)/(h_1 - h_f)$

Y increases : By lowering h2 (Discharge pressure, $\mu_{jt} = 0$.)

h1 & hf are constant

Although production rate can be enhanced by rising the discharge pressure
but what cost ?

$W + mh_1 = Q + mh_2$, and Q for isothermal process $= T_1 (S_1 - S_2)$

The work requirement per unit mass liquefied is

$$W/m_f = y [T_1 (S_1 - S_2) - (h_1 - h_2)]$$

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)

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

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

m= mf x y = 8 kg/hr / 0.06 = 133 kg/ hr = 106 M3/ hr

Power required : 7200 KJ/ kg x 8/ 3600 = 16 KW ?

LIQUID YOELD CAN BE INCREASED BY PRECOOLING

(by lowering the value h1)

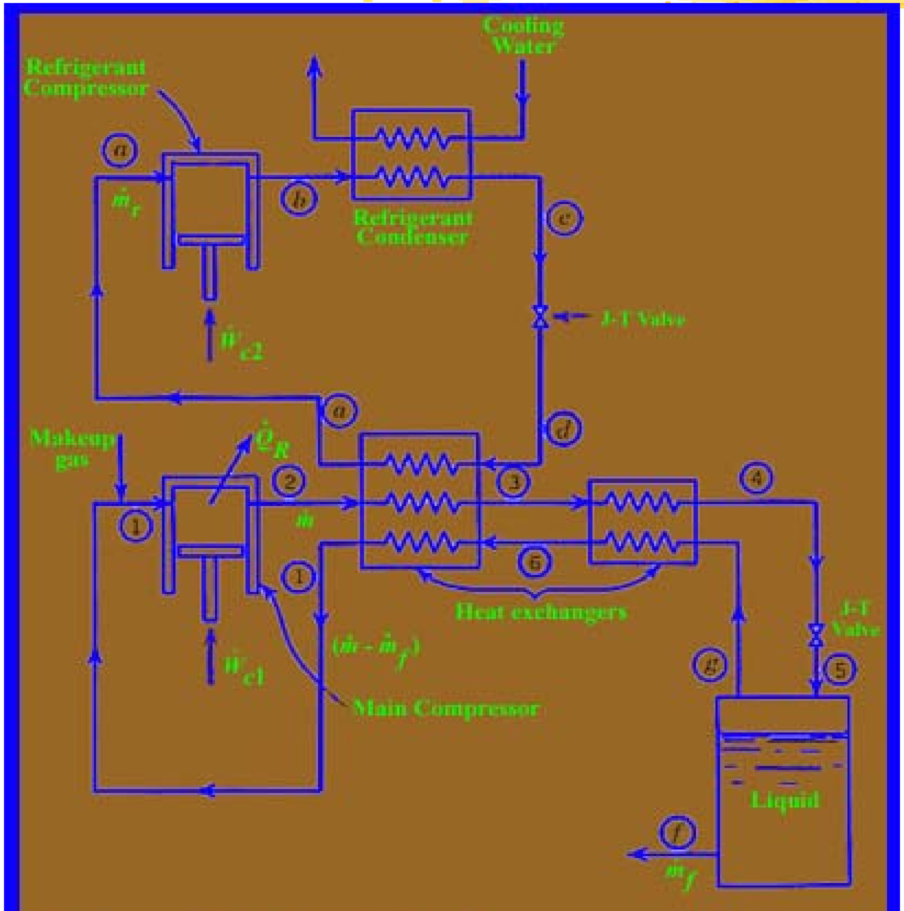
Yield (Y) = (h1-h2)/(h1-hf)

Liquid yield for Linde precooled system with P2= 100 bar

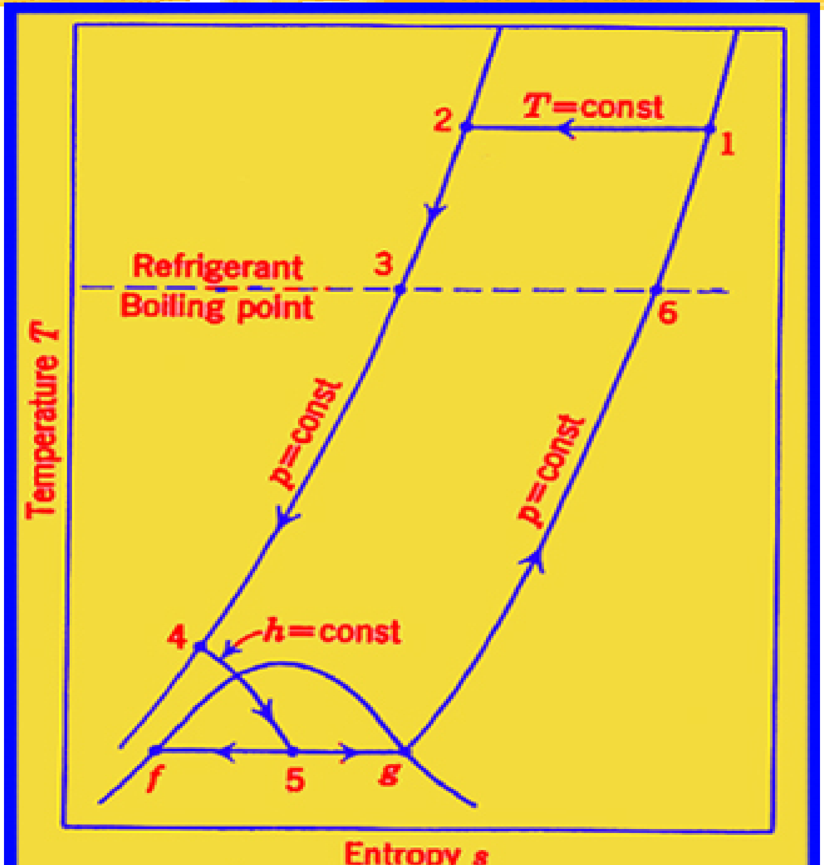
Precool temp.	300	250	200	150
$Y = m_f/m$	0.06	0.08	0.14	0.57

Power remains same , Add Refrigation power for precoolant

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.

L-H (J-T) cycle

Work Done Required

Performance of the Linde-Hampson system using different Fluids

(p_1 = 101.3 kPa; p_2 = 20.265 MPa (200 atm); $T_1 = T_2$ = 300 K; heat-exchanger effectiveness =100 percent; compressor overall efficiency = 100 percent.)

Fluid	Normal Boiling Point (K)	Liquid Yield $y = \dot{m}_f/\dot{m}$	Work per Unit Mass Compressed (kJ/kg)	Work per Unit Mass Liquefied (kJ/kg)	Figure of Merit $FOM = \dot{W}_i/\dot{W}$
N_2	77.36	0.0708	472.5	6673	0.1151
Air	78.8	0.0808	454.1	5621	0.1313
CO	81.6	0.0871	468.9	5381	0.1428
A	87.28	0.1183	325.3	2750	0.1741
O_2	90.18	0.1065	405.0	3804	0.1671
CH_4	111.7	0.1977	782.4	3957	0.2758
C_2H_6	184.5	0.5257	320.9	611.0	0.5882
C_3H_8	231.1	0.6769	159.0	235.0	0.5976
NH_3	239.8	0.8079	363.1	449.4	0.7991

LIQUEFACTION OF HELIUM/ HYDROGEN

MAX INVERSION TEMP (**45 K FOR HE. AND 205 FOR H2**) IS BELOW ROOM TEMPERATURE

SIMPLE LINDE SYSTEM WILL HAVE HEATING EFFECT.

EVEN PRECCOLED BY LN2 FOR HELIUM WILL NOT WORK.

BY USING LH2 AS A PRECOOLANT: WE NEED ANOTHER CYCLE FOR HYDROGEN : COST

ALTERNATIVELY : ADDING ONE ADIABATIC EXPANSION PROCESS BY USING A TURBINE

Linde- Hampson Cycle
[Joule-Thomson Cycle]

Mainly based on Joule -Thomson Expansion

	[redacted]	[redacted]
He	4.2 K	43 K
H2	20.3 K	202 K
N2	77.4 K	623 K
O2	90.2 K	761 K

< Room Temperature

Need Cooling below Tinv(max) before J-T Expansion

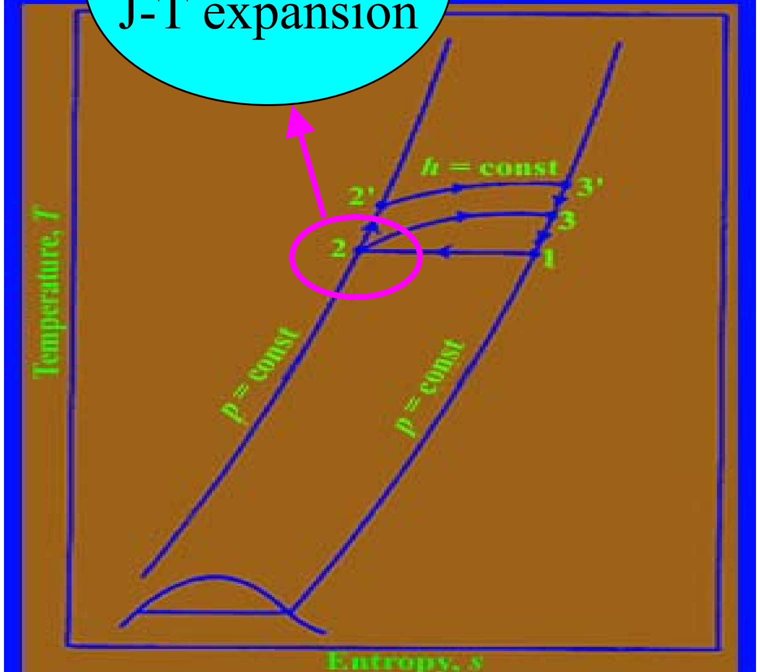
> Room Temperature

Joule - Thomson Ex alone can Liquefy N2 & O2

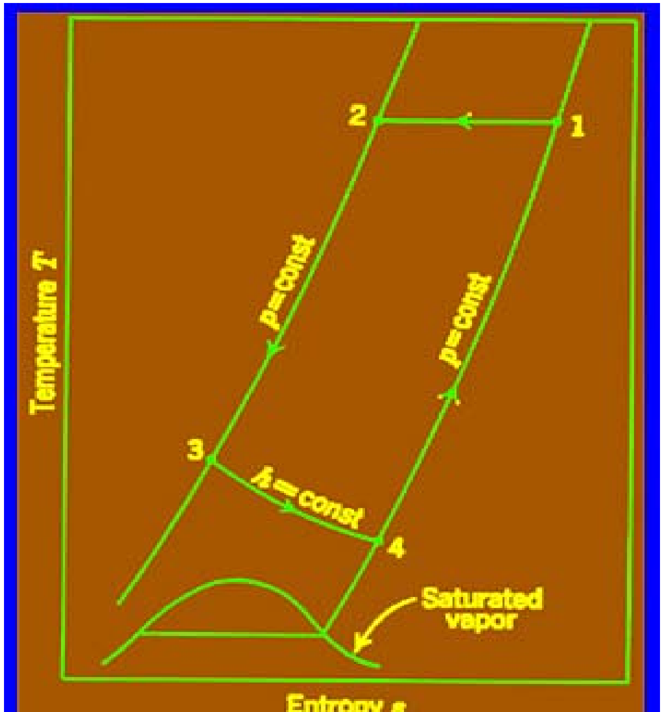
Linde- Hampson Cycle is for N2 or O2 Liquefaction not for He or H2

Why Not Helium or Hydrogen?

Heating on J-T expansion

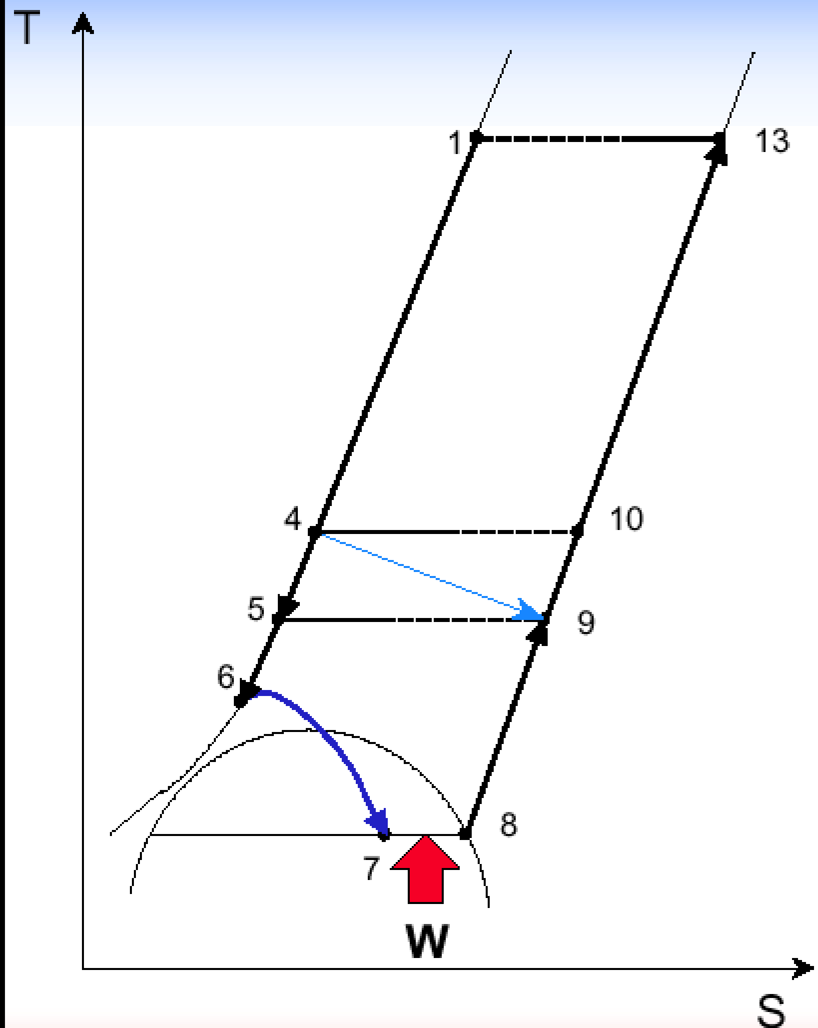


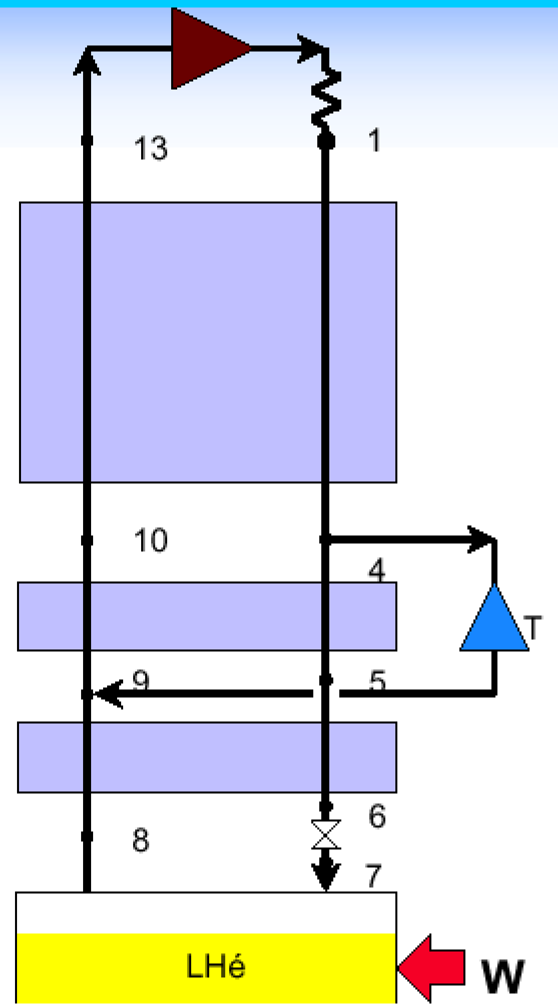
Start-up of a Linde-Hampson system (no precooling) using helium or hydrogen as the working fluid. The fluid expands through the expansion valve from point 2 to point 3 and its temperature increases, since this condition is to the right of the inversion curve.



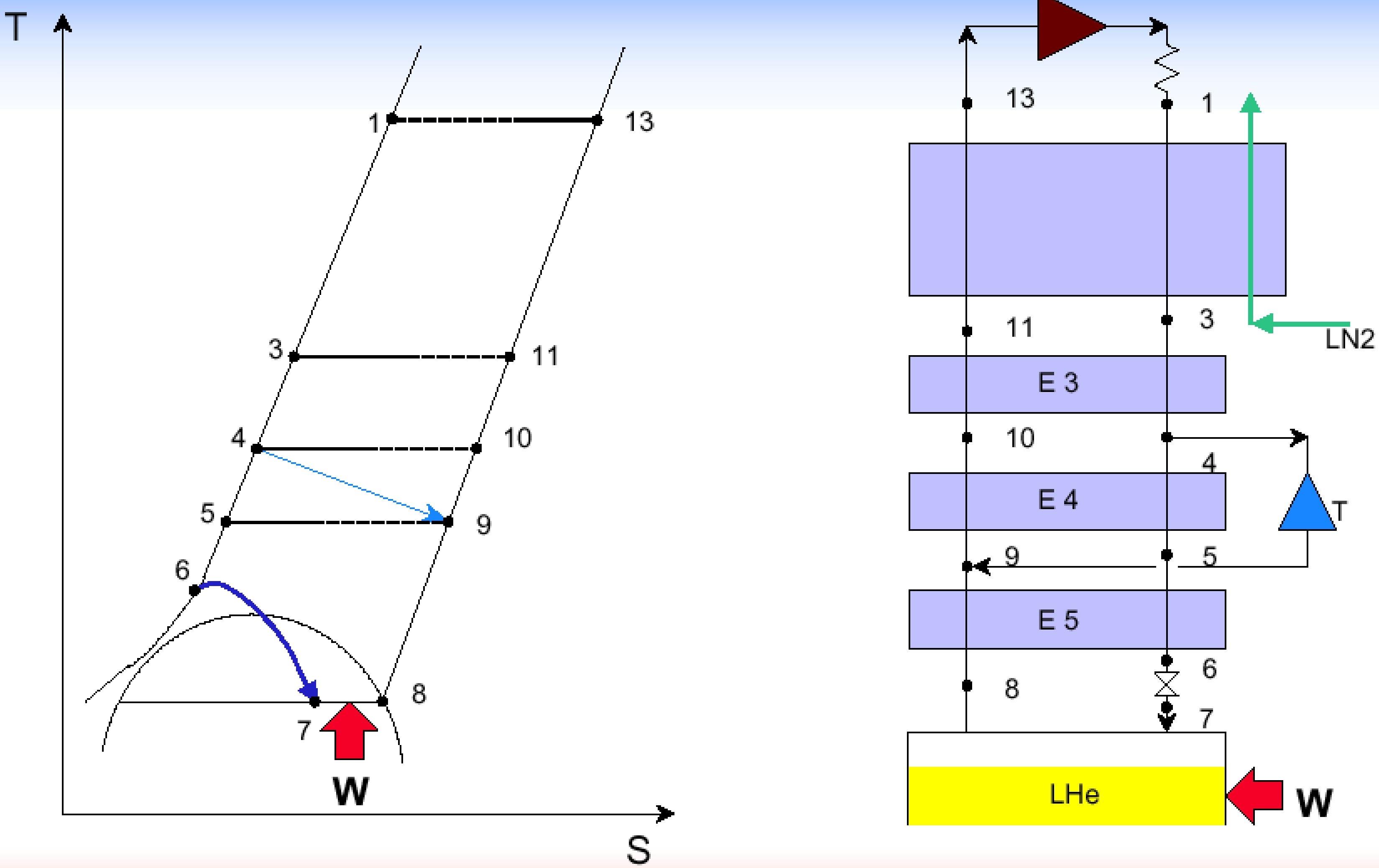
The performance of the Linde-Hampson system for helium or hydrogen. Even if the cycle started in the right direction and the temperature is lowered, it is still physically impossible to transfer enough energy in the heat exchanger to produce liquid.

THE CLAUDE CYCLE with One Expander

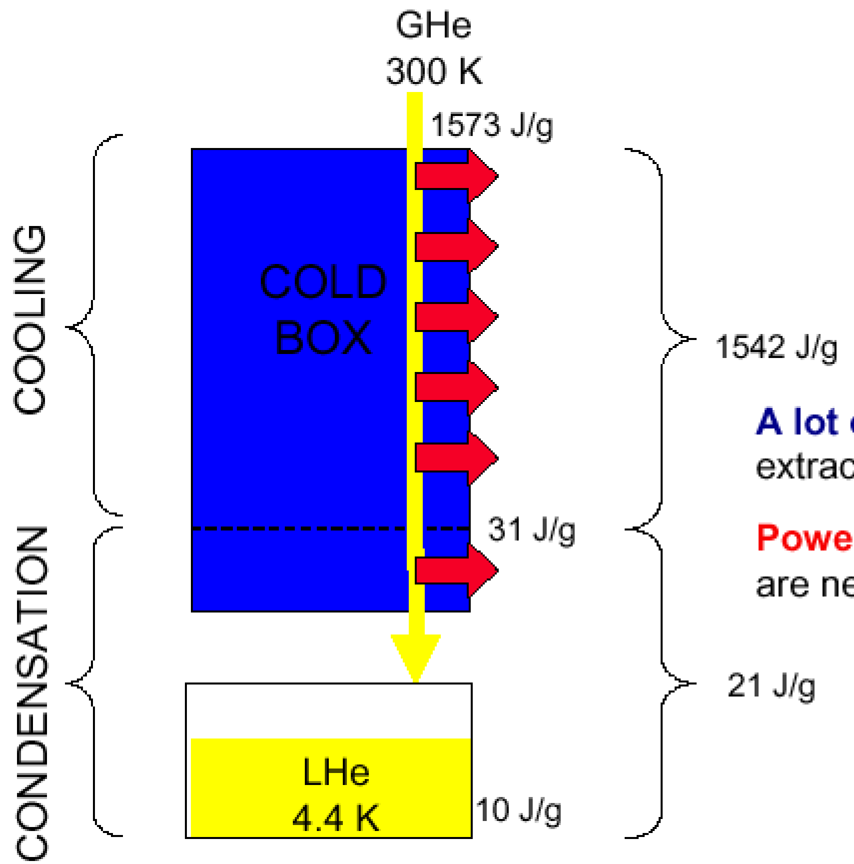




THE CLAUDE CYCLE 1 Expander + LN2



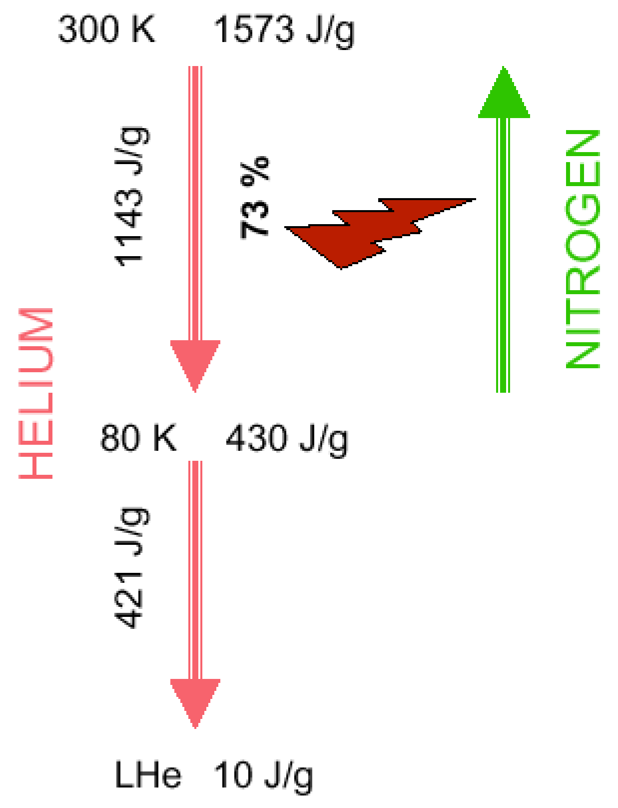
THE LIQUEFACTION MODE



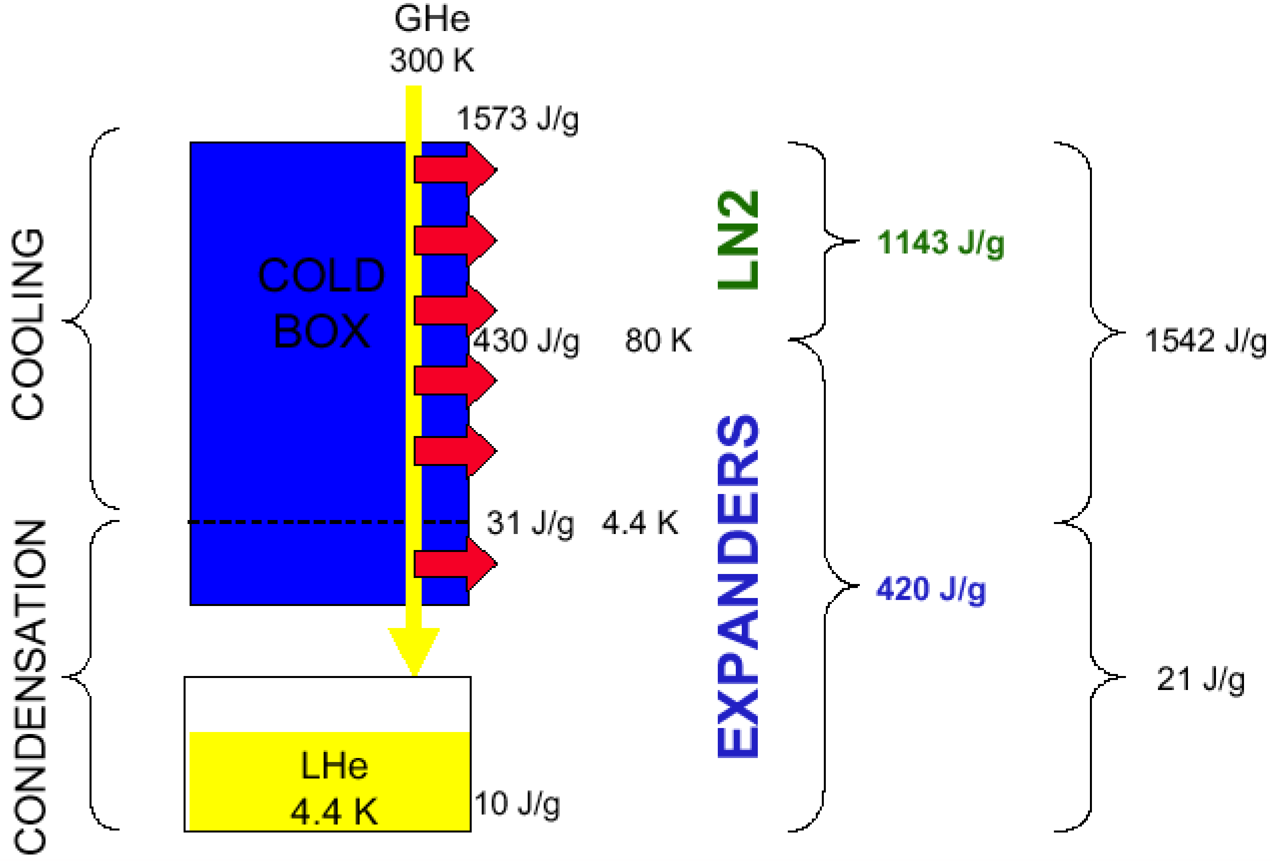
A lot of energy is to be extracted from helium.

Powerful expanders are necessary.

NITROGEN PRE-COOLING PRINCIPLE



NITROGEN PRE-COOLING OF A LIQUEFIER



HOW MUCH LN2 IS THEORETICALY NECESSARY ?

Energy to be extracted to cool the equivalent mass of 1 Litre of helium from 300 to 80 K:

$$125.0 \times 5.2 \times (300 - 80) = 14300 \text{ J}$$

Quantity of liquid nitrogen to vaporise:

$$14300 / (200 + 234) = 329.5 \text{ g}$$

or 329.5 / 808 = 0.4 Litre of liquid nitrogen

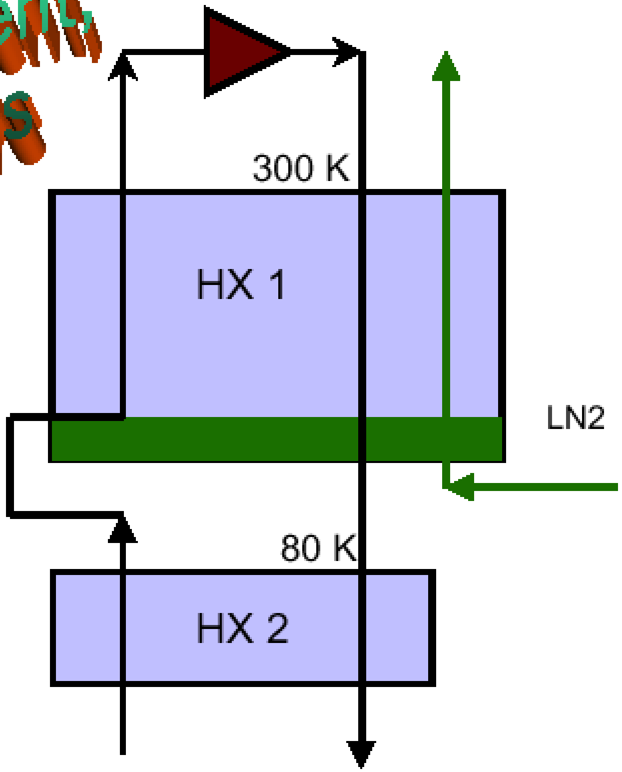
Be careful, this is theory ! Do not forget:

- The warm heat exchanger is not perfect
- There are LN2 storage and distribution losses

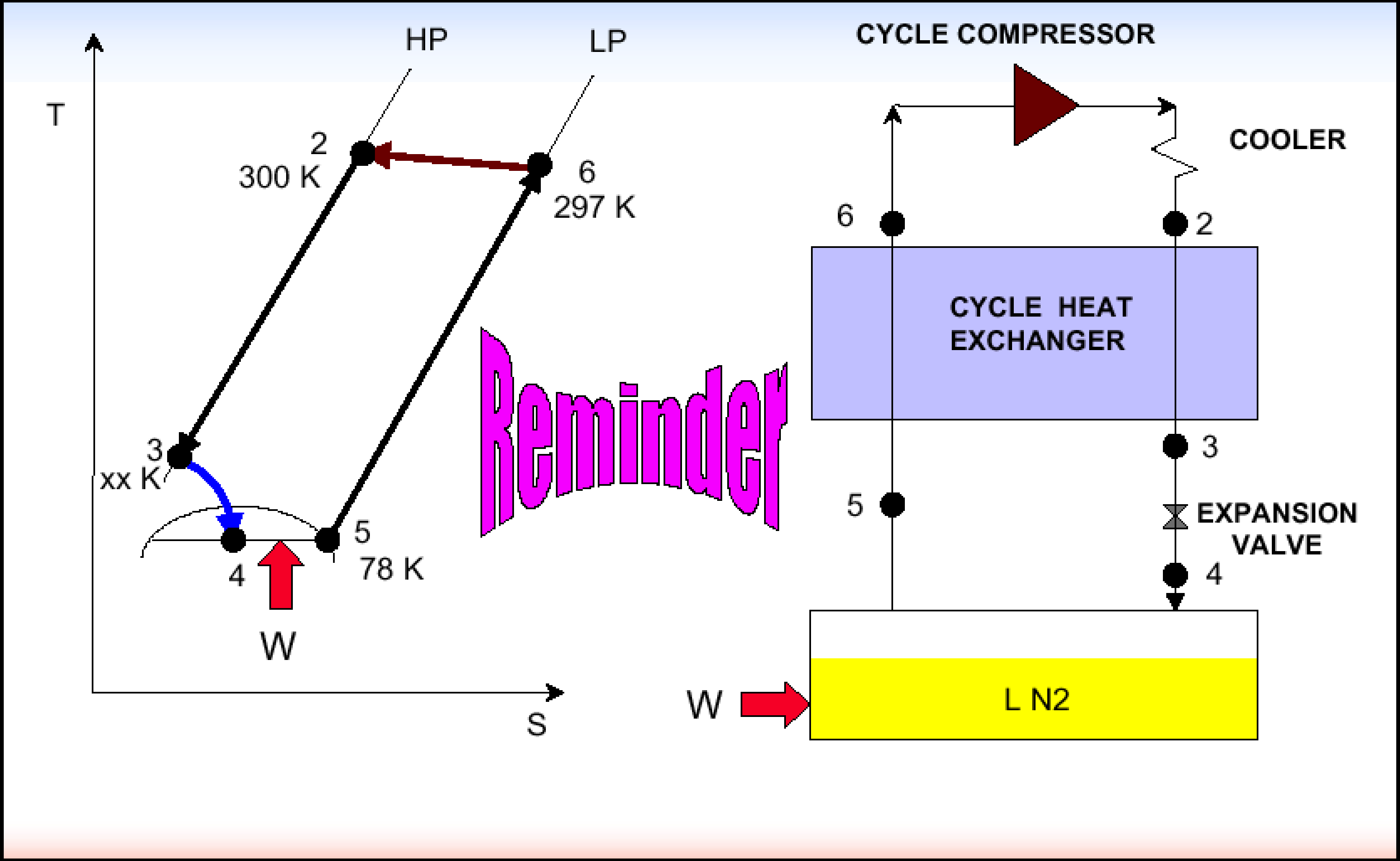
NITROGEN CHANNELS IN THE MAIN HEAT EXCHANGER (2)

A simpler arrangement, for small liquefiers

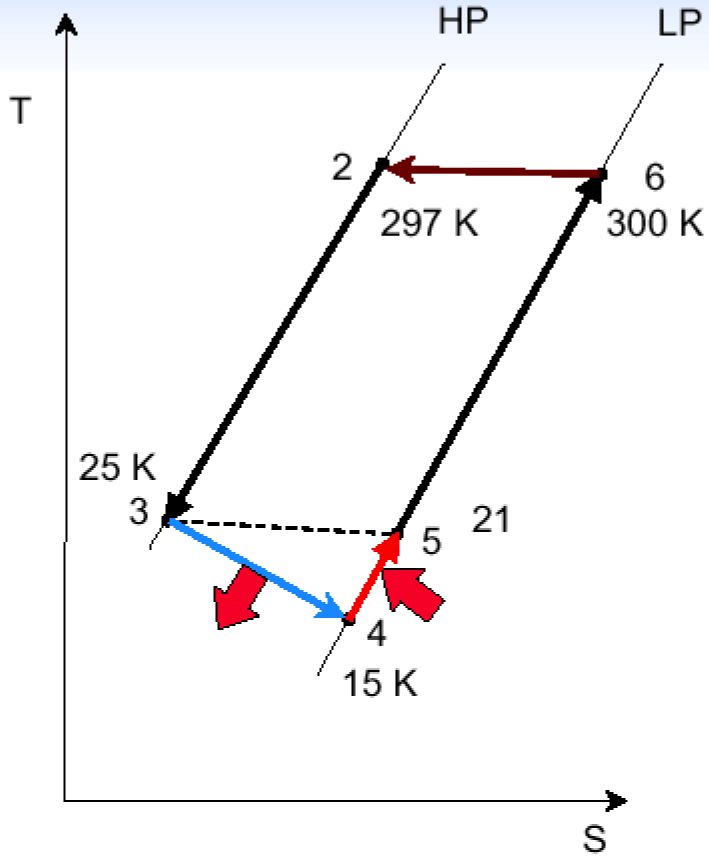
The lower part of HX1acts as a liquid nitrogen vaporiser.

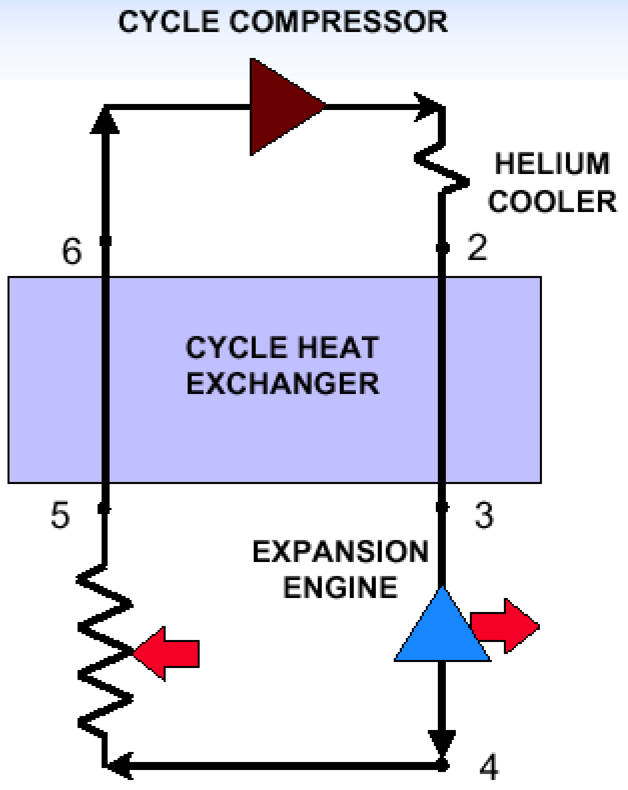


Linde-Hampson Cycle(Joule-Thompson Cycle)

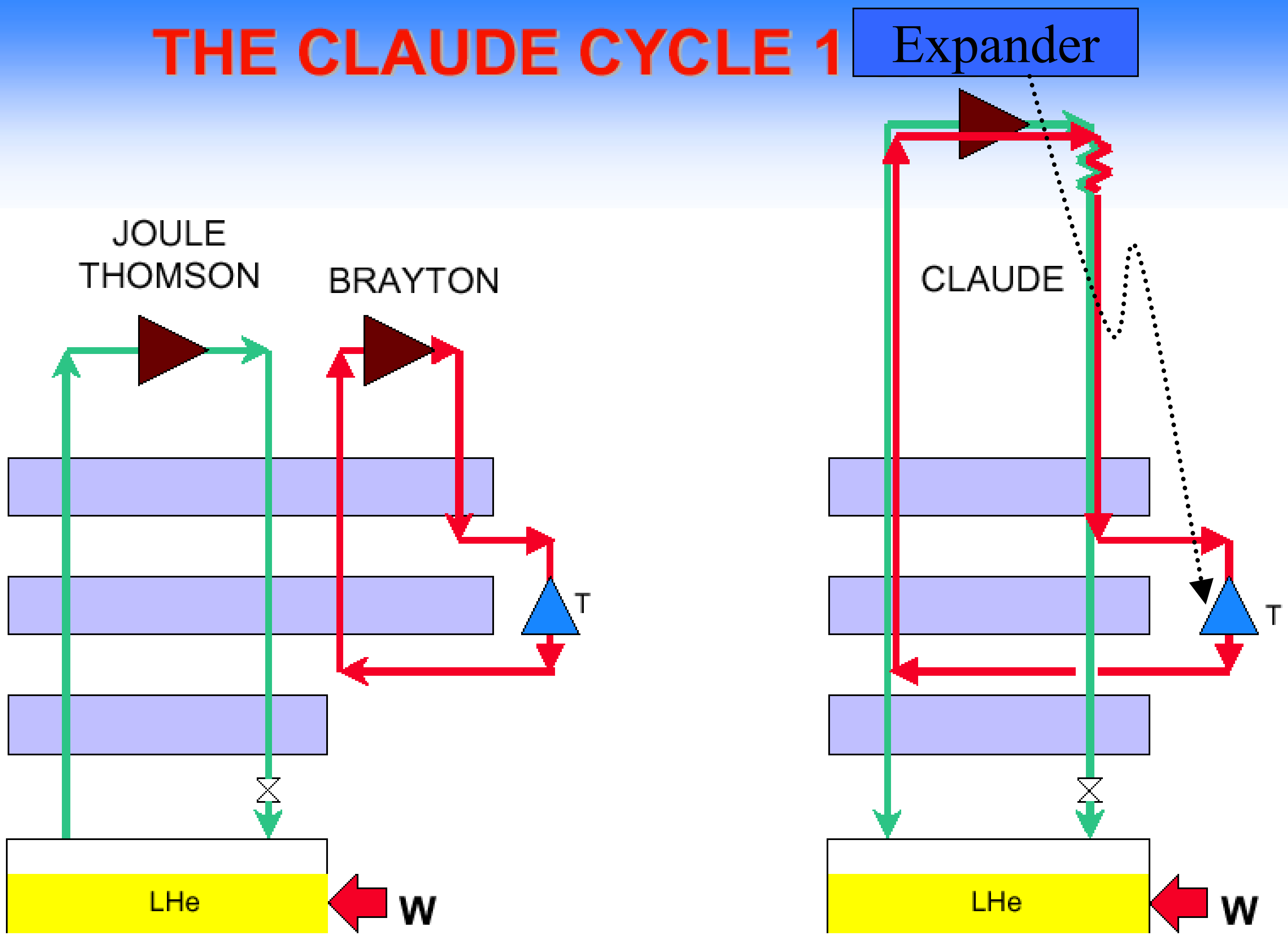


THE BRAYTON CYCLE

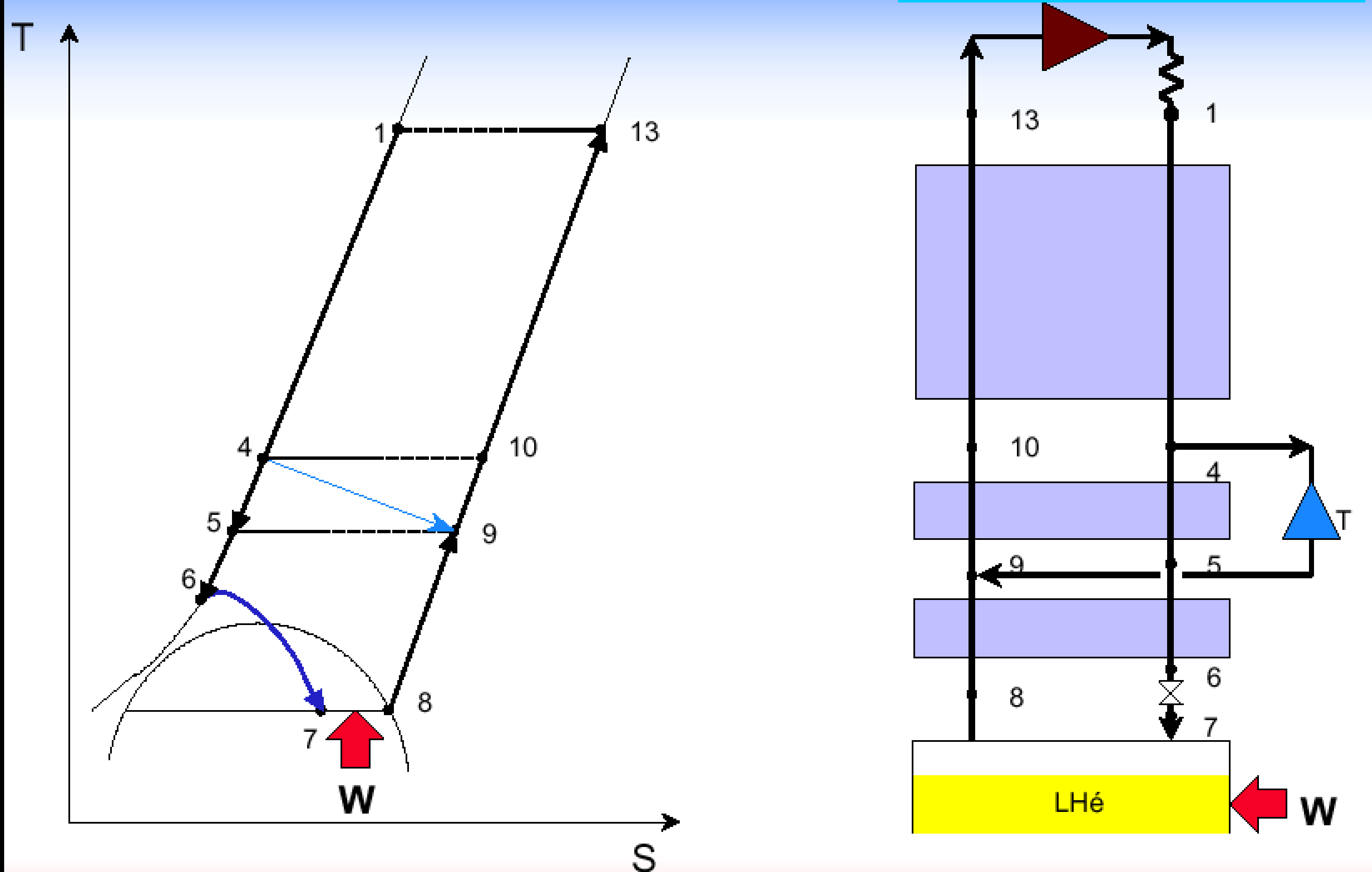




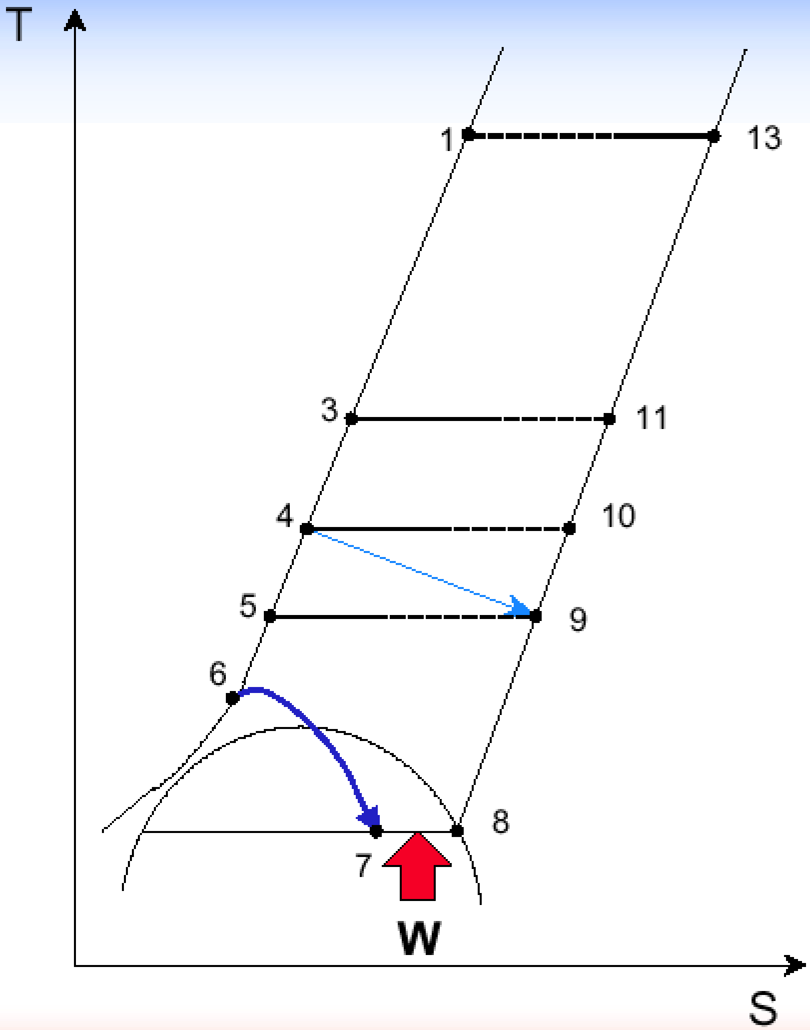
THE CLAUDE CYCLE 1

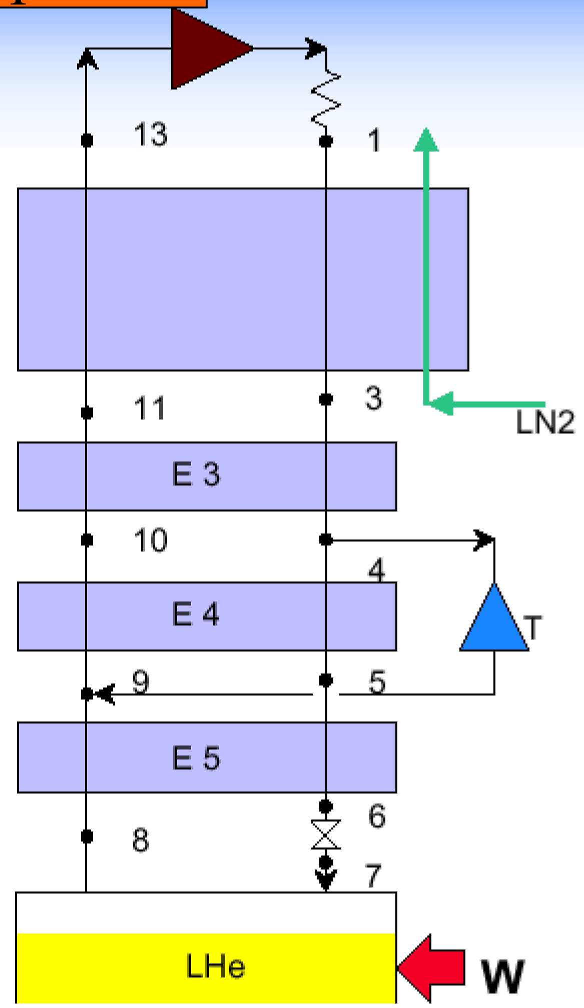


THE CLAUDE CYCLE with One Expander



THE CLAUDE CYCLE 1 Expander + LN2

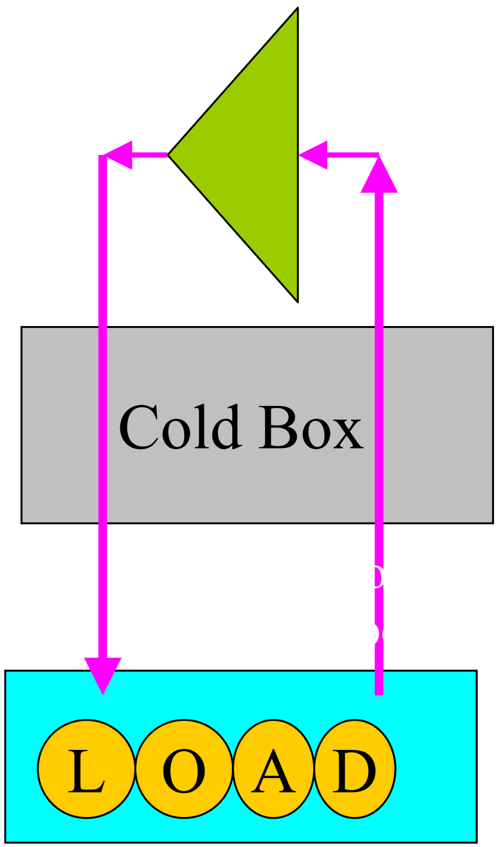




Liquefaction Vs. Refrigeration

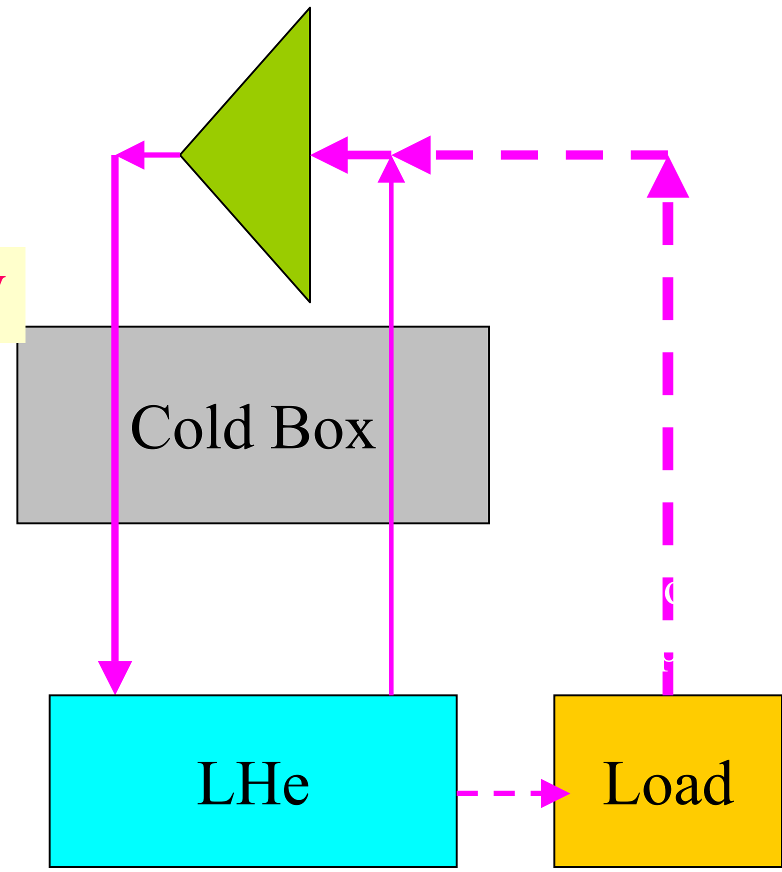
Same Technical Thermodynamical Cycle as Liquefaction Cycle. Difference in way of operation

HOW?



1 litres /hr ~ 3W

Load may be the S.C. magnets S.C. Resonators



Refrigerator Mode

Liquefaction Mode

Performance Comparisons of Helium *Refrigerators* and *Liquefiers*

$$\frac{\text{Carnot work required for liquefaction [W/(g/s)]}}{\text{Carnot work required for refrigeration [W/W]}} = \frac{W_{carnot}}{COP_{INV}} = \frac{6823\ \text{[W/(g/s)]}}{70\ \text{[W/W]}}\ ;\ 100\ \text{W/(g/s)}$$

That is, the Carnot work required for approximately 100 W of refrigeration is equivalent (on an equal Carnot work basis) as the Carnot work required to liquefy 1 g/s at 1 atm saturation condition.

Performance Comparisons of Helium *Refrigerators* and *Liquefiers* (Cont.)

If the expander output work is not recovered,

$$\frac{\text{Ideal Power required for liquefaction [W/(g/s)]}}{\text{Ideal Power required for refrigeration [W/W]}} = \frac{8387\ \text{[W/(g/s)]}}{71\ \text{[W/W]}}\ ;\ 120\ \text{W/(g/s)}$$

That is, the Carnot work required for approximately 120 W of refrigeration is equivalent (on an equal Carnot work basis) as the Carnot work required to liquefy 1 g/s at 1 atm saturation condition If the expander output work is not recovered.

Performance Comparisons of Helium Refrigerators and Liquefiers

$$\frac{\text{Ideal Power required for liquefaction [W/(g/s)]}}{\text{Ideal Power required for refrigeration [W/W]}} = \frac{8387 \text{ [W/(g/s)]}}{71 \text{ [W/W]}} ; \ 120 \text{ W/(g/s)}$$

$$= \frac{\left(\frac{w_{Carnot}}{w_C}\right)_l}{\left(\frac{w_{Carnot}}{w_C}\right)_r} = \frac{\left(\frac{6823}{8387}\right)_l}{\left(\frac{1429.5}{1449.9}\right)_r} = \frac{81.4}{98.6} ; \ 82.5\%$$

A refrigeration cycle having 30% of Carnot efficiency is expected achieve 25% in liquefaction mode

Components of Helium Liquefier

1. Compressor station
2. Oil removal module
3. Gas pressure control panel
4. Buffer tank
5. Cold Box of liquefier/refrigerator
6. Transfer siphon

Static dewar

Transfer lines

Mobile dewar

Distribution valve box

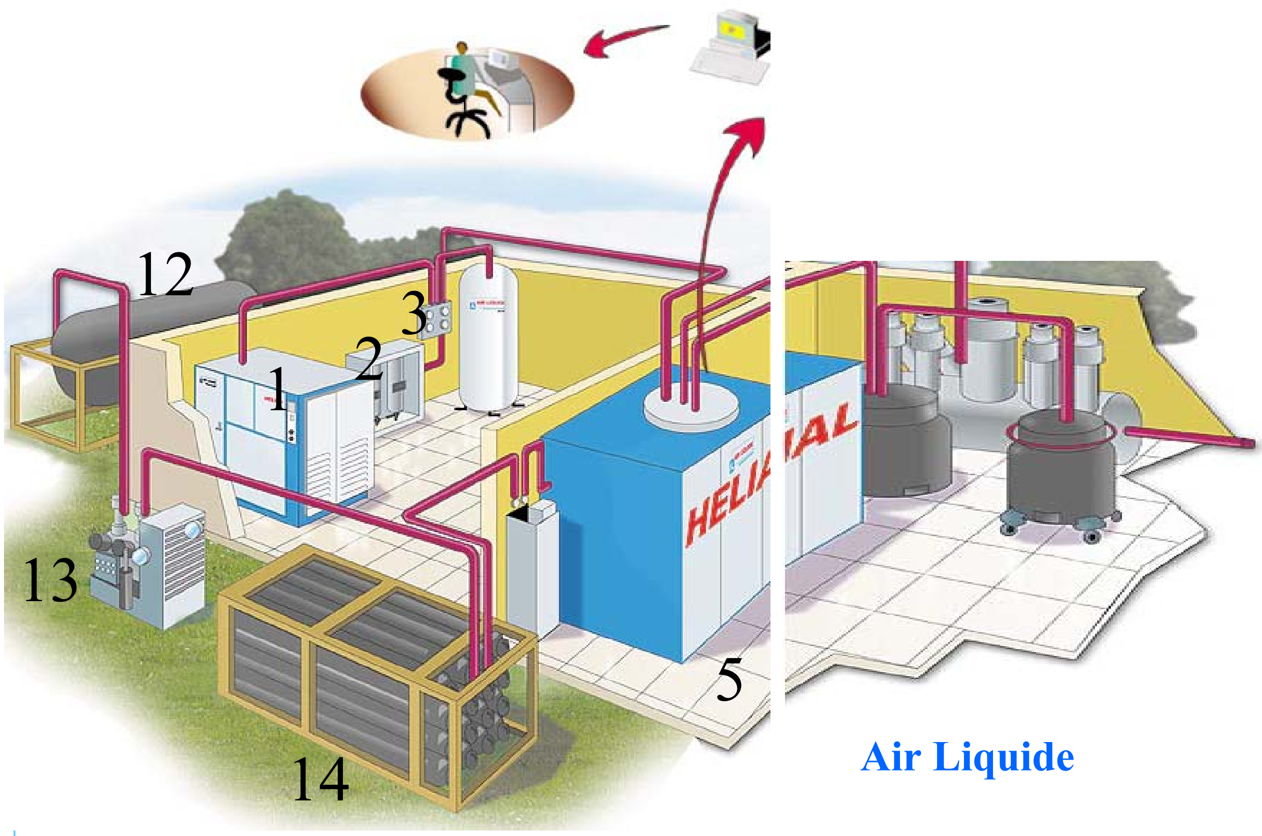
12 Recovery gas bag

13 Recovery compressor

14 HP storages

15 Drier

…



Air Liquide

Compressor

Reciprocating (High pressure, Low capacity, More Maintenance, Higher Efficiency)
Smaller Liquefier

Screw Type :(Low Pr. Higher Capacity)
Accelerator Ref.

Oil level< 0.1 PPM

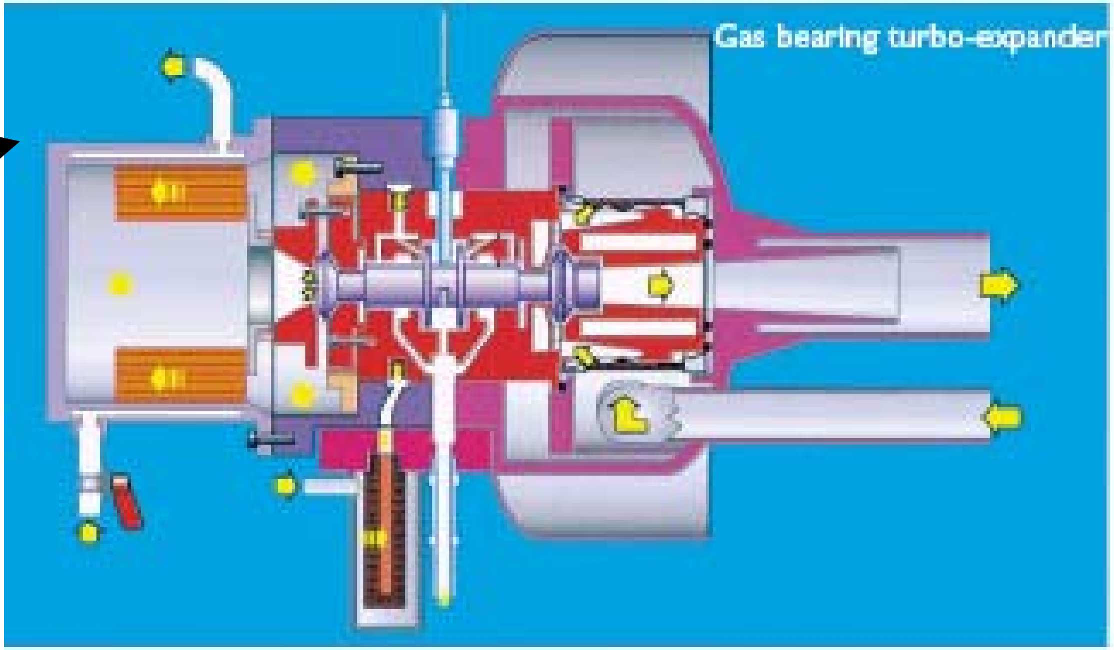
Heat Exchanger :Collins Type
Plate fin : Present

Turbine :

RPM > 1,00,000

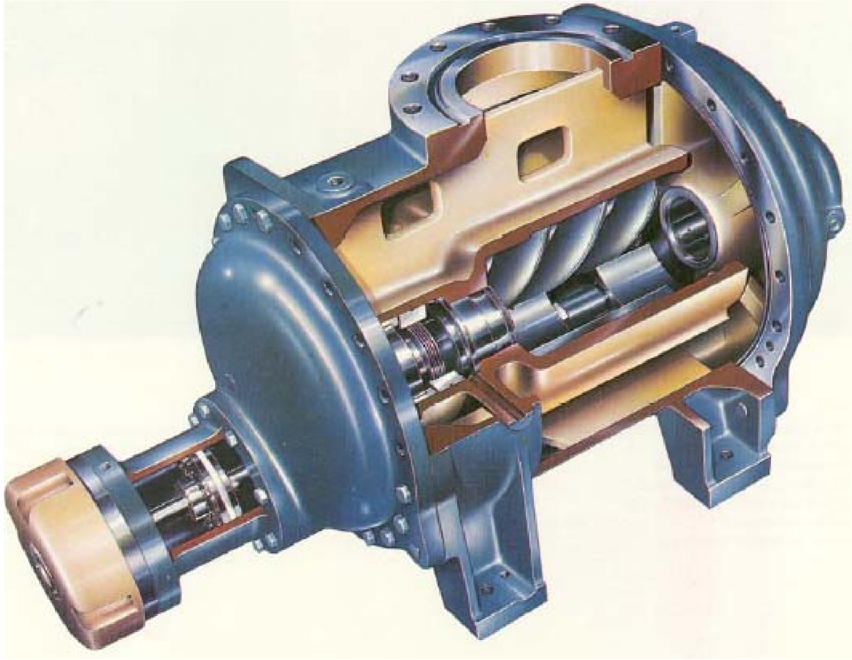
Bearing : Static/ Dynamic

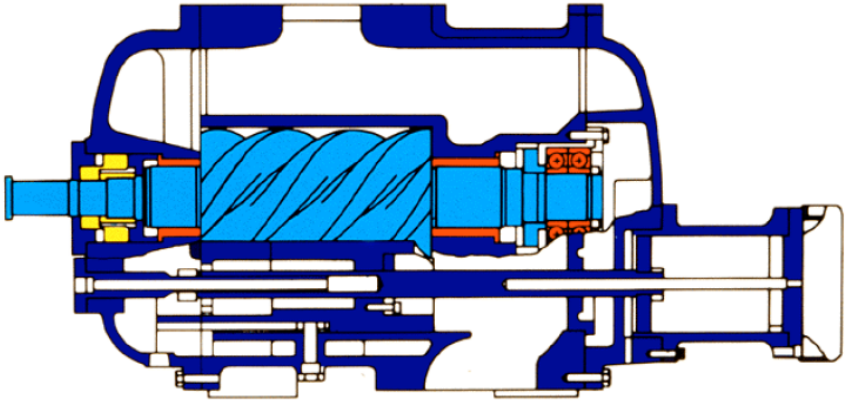
helium Gas



HELIUM COMPRESSOR (Jefferson Lab)

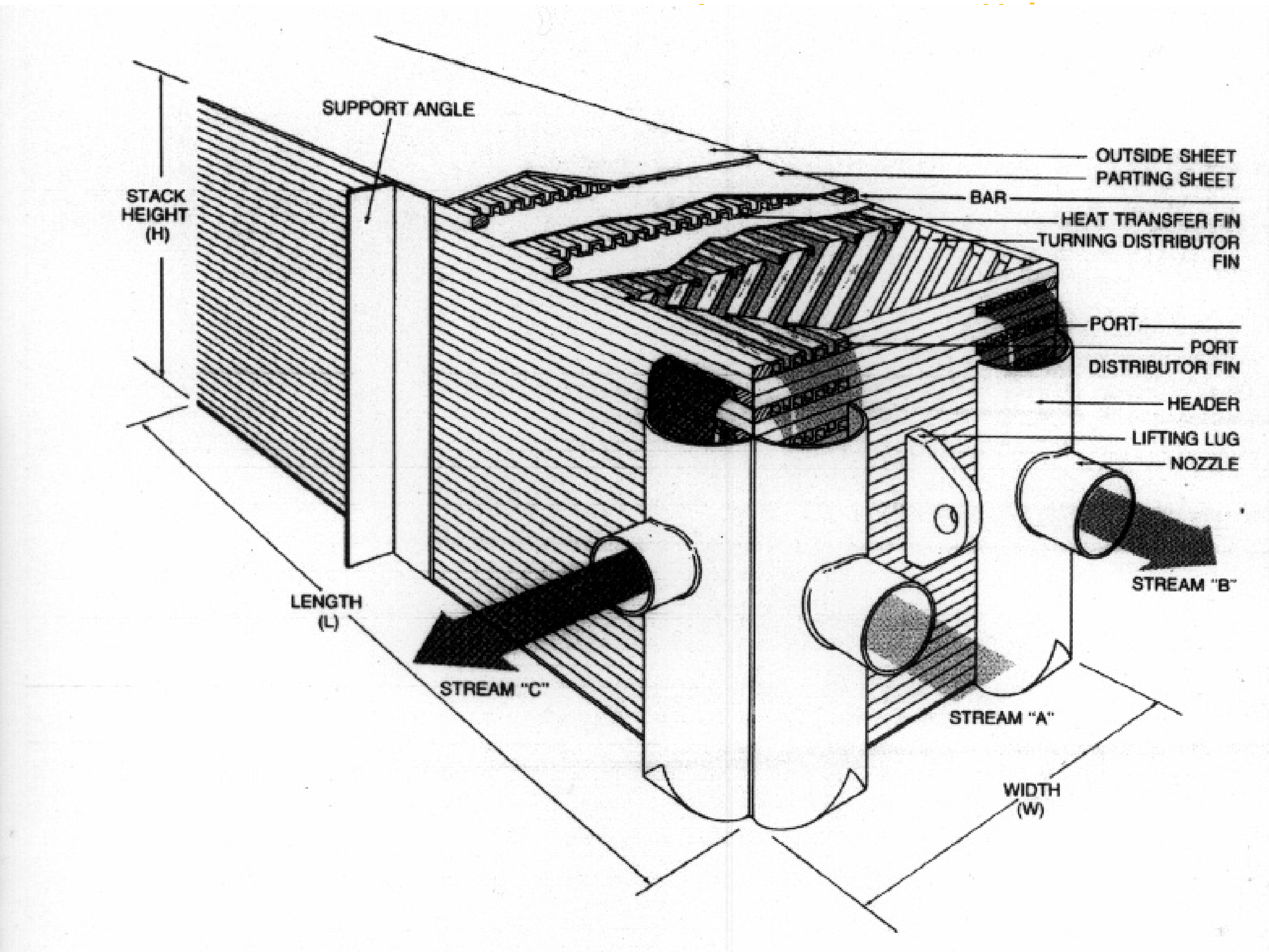
Warm Helium Compressor



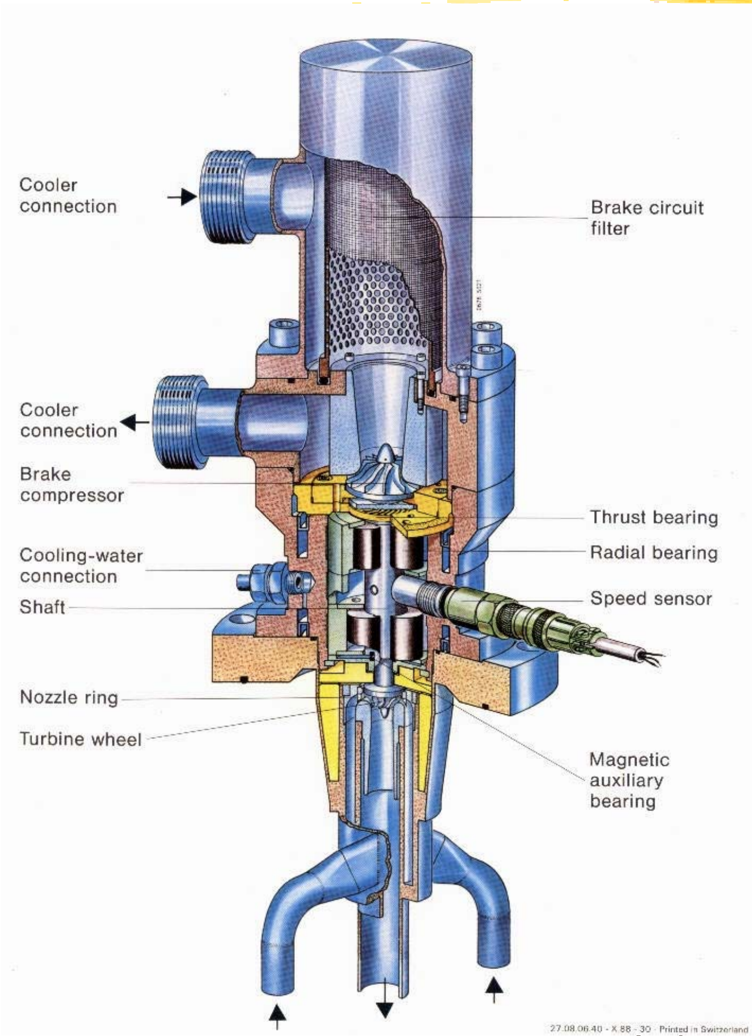


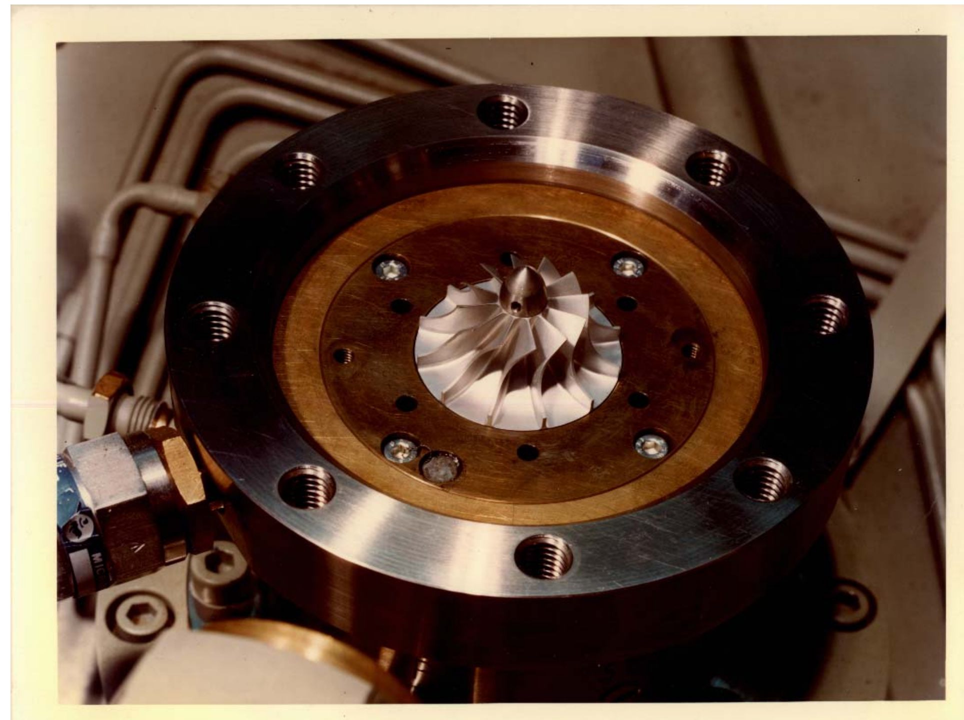
4 K Refrigerator (Cold box)

The Plate Fin Heat Exchanger



Sulzer Gas Bearing Turbine



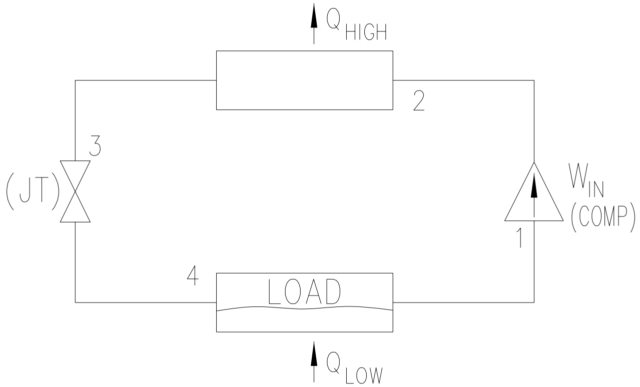


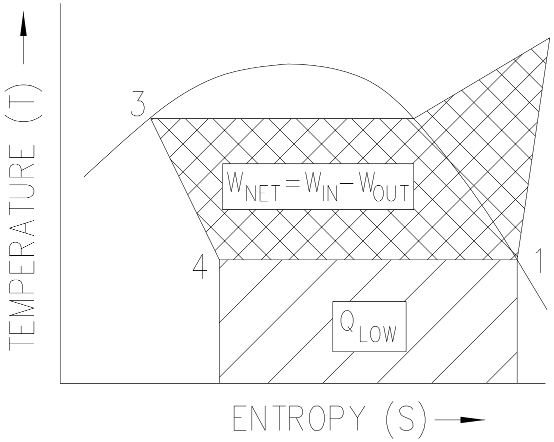
Commercial liquefier

- **Nitrogen** : Many (Stirling:Netherland , Linde , PCI 10 - 100 litres/hr)
  - Large Capacity : BOC, Air Liquide, Paraxair (Gas separation, Turbine based)
  - Laboratory : Storage Option is Preferable, subject to reliable supply
- **Helium :**
  - **Low Temp Lab : 10- 40 litrs hr (CTI/Koch/ PSI, Linde) RRCAT, TIFR, IISC), : Reciprocating/ Screw Compressor, Rec/ Turbine**
  - Accelerator Project
    - **IUAC. Delhi : 150 litres/hr M/s CCI , Two Reci Expander**
    - **VECC. Calcutta : 100 l/hr M/s Airliquide, Two Turbine**
    - **TIFR : 350W : M/s Linde , Two Turbine**
- **Outside India** : **KEK : 8 KW (~ 2500 l/hr) , LHC : 18 KW**
  - M/S Linde & M/S Air Liquide, Fermi lab :

Vapor compression process

e.g.: Typical Freon refrigerator





This process typically requires 1 kW of input power for ~3 kW of cooling load

$$\text{Carnot efficiency} \; = \; \frac{W_{Carnot}}{W_{actual}} = \frac{Q_{LOW} \cdot COP_{INV}}{W_{actual}} = \frac{3 \cdot (0.23)}{1} = 0.68$$