Refrigeration Techniques and Liquefaction of Gases

Hydrogen and Helium as an example

Read Flynn Ch. 6

Fundamentals of refrigeration

- Work (W) – transport of energy only
- Heat (Q) – transport of energy and entropy
- 1st law of thermodynamics

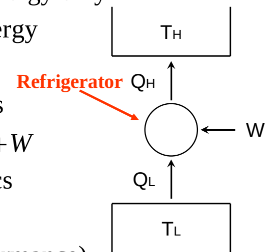
$$Q_H = Q_L + W$$

- 2nd law of thermodynamics

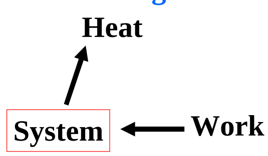
$$\frac{Q_H}{T_H} \geq \frac{Q_L}{T_L}$$

- COP (Coefficient Of Performance)

$$COP \equiv \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} \leq \frac{T_L}{T_H - T_L} = \frac{1}{T_H / T_L - 1}$$



Principle of refrigeration
Removing Heat



- **Work is transformed to elastic energy, or potential energy, or kinetic energy, or magnetic energy, quantum energy, etc.**
- **Internal energy is increased.**
- **Heat is transferred to environment with entropy transfer along with it.**

As T_L decreases
more work per unit refrigeration (W/Q_L) is required

Ref. Temp T_L (K)	Work / Refrigeration W/Q_L (W/W)	
	Carnot (minimum)	Actual
270	0.11	0.3 ~ 0.5
100	2	10 ~ 20
20	14	100 ~ 200
4	74	700 ~ 1500
1	299	> 6000

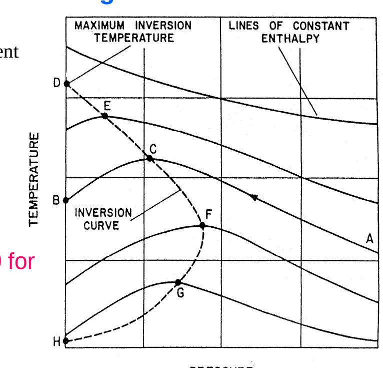
As T_L decreases, the Carnot efficiency goes down.

Usual method to obtain low temperature → Throttling Process

Joule-Thomson Coefficient

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_h$$

J-T coefficient > 0 for cooling effect



Inversion curve for various gases

Joule-Thomson Coefficient

$$\mu_{J-T} = \left(\frac{\partial T}{\partial P}\right)_H$$

Note: The maximum T to begin hydrogen liquefaction is 202 K at 0 atm.

Since expansion must begin at a higher pressure, it is usually Started below 100 K.

Cooling comes from kinetic energy → potential energy

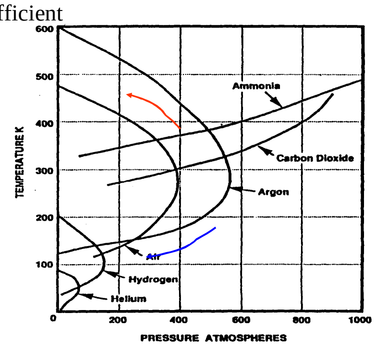


Figure adapted from *Cryogenic Engineering* by Thomas M. Flynn, Dekker:NY (1997), p. 284

From the previous graph, can ammonia be used as an expansion refrigerator at room temperature?

A. Yes
B. No
C. Can not be determined from the graph

2010 Olympics

- Energy efficiency initiatives to minimize refrigeration plant energy use include:
  – ammonia refrigeration system — ammonia is one of the most energy-efficient refrigerants producing no chlorofluorocarbons (which contribute to ozone-layer depletion and global climate change)
  – track shading and weather protection system
  – tree retention to cast shade
  – track painted white to minimize heat absorption
  – capture and reuse of waste heat from refrigeration plant

Maximum inversion temperature

Gas	Maximum Inversion Temperature [K]
Helium-4	45
Hydrogen	205
Neon	250
Nitrogen	621
Air	603
Carbon monoxide	652
Argon	794
Oxygen	761
Methane	939
Carbon dioxide	1500
Ammonia	1994

RT (dashed line between Neon and Nitrogen)

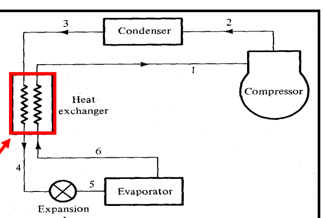
$$PV = nRT \qquad \mu_{J-T} = \left(\frac{\partial T}{\partial P}\right)_H$$

Joule Thomson Coefficient for an Ideal Gas = ?

A. 0
B. V / nR
C. V
D. Can not be determined

Hint: If you don't know thermodynamics, think about where the change in temperature comes from in an isenthalpic expansion, in which total energy is conserved.

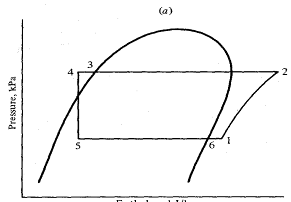
General refrigeration cycle and its components



(a)

Very important in cryogenic refrigeration !

P-H diagram of refrigeration cycle



Two heat exchanger types in cryogenic refrigerator

- **Recuperator type** :
  Separate channels for the warm and cold fluids which flow continuously, usually in counterflow
- **Regenerator type** :
  A single matrix of finely divided material subject to alternate flows of the warm and cold fluids periodically

Cryogenic refrigeration system

- Recuperator type

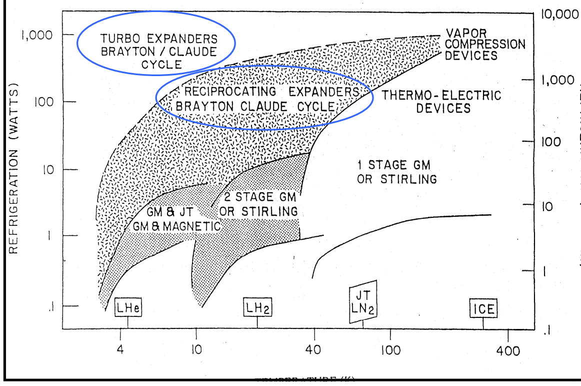
➔J-T expansion refrigerator, reverse-Brayton type (mechanical expander) refrigerator

- Regenerator type

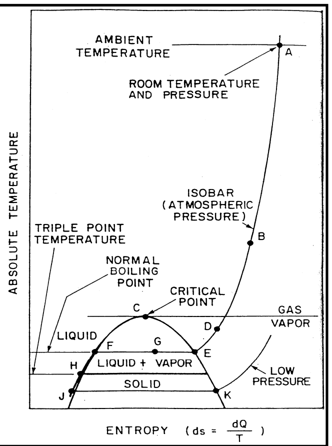
➔Ericsson, Stirling, Pulse tube refrigerator (or cooler or cryocooler)

- Magnetic refrigerator
- Dilution refrigerator
- Nuclear cooling system, Laser cooling system

Temperature range of commercial refrigerators

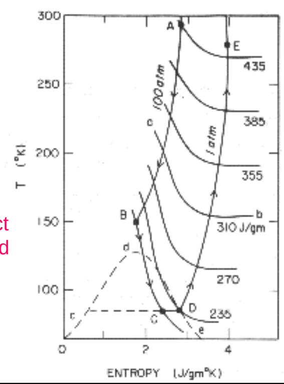


Temperature Entropy Diagram for Cryogenic Fluid

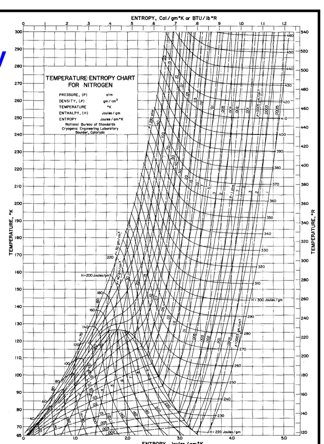


Isenthalpic lines in T-s diagram

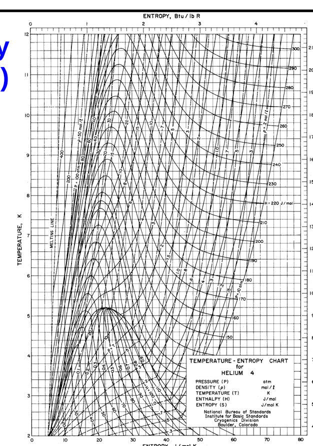
Gases are imperfect at low enough T and high enough P.



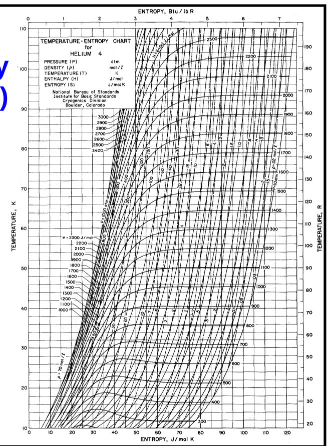
Temperature-Entropy Chart for Nitrogen



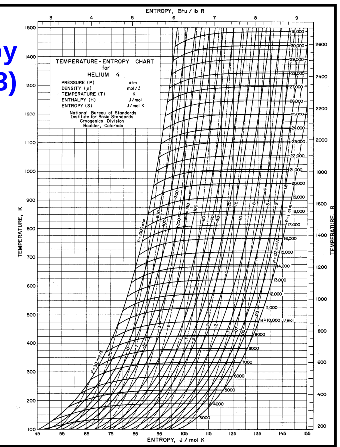
Temperature-Entropy Chart for Helium 4 (1)



Temperature-Entropy Chart for Helium 4 (2)



Temperature-Entropy Chart for Helium 4 (3)



J-T (expansion) refrigerator

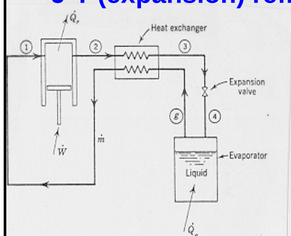


Fig. 5-7 Linde-Hampson refrigerator.

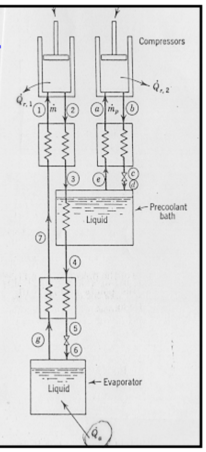
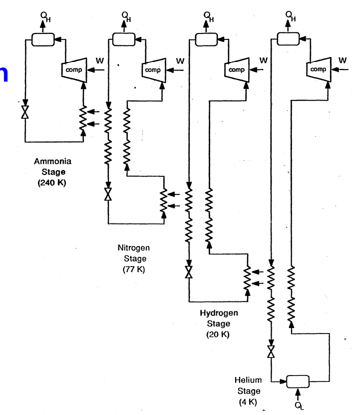


Fig. 5-9 Precooled Linde-Hampson refrigerator.

Cascade cooling of J-T refrigeration system



J-T expansion liquefier

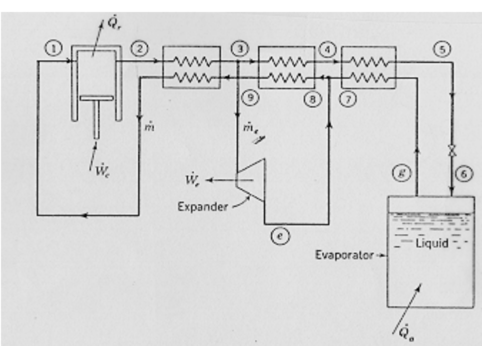
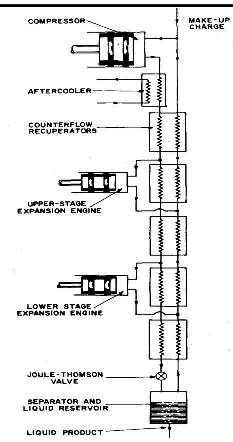
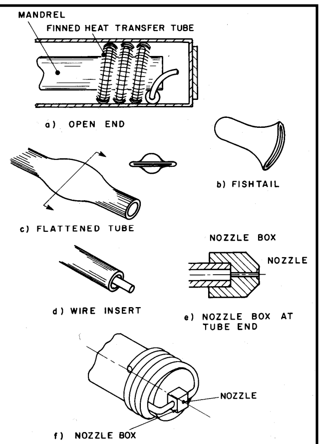


Fig. 5-12 Claude refrigerator.

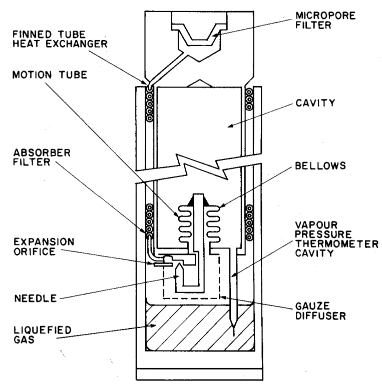
Schematic diagram of the Collins-Claude cycle multiple-expansion gas (helium) liquefier



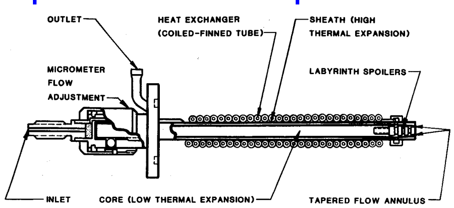
Fixed-orifice J-T expansion nozzles

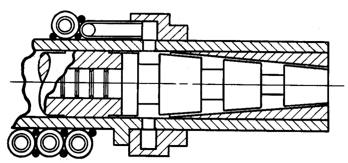


Hymatic self-regulating minicooler



General Pneumatics variable-area temperature-sensitive expansion nozzle





JOULE-THOMSON CYCLE (Throttle cycle)

ADVANTAGES

- No cold moving parts
- Steady flow (no vibration)
- Transport cold long distance
- Cold end can be miniaturized.

DISADVANTAGES

- Relies on real-gas behavior
- Requires high pressures (compressor wear)
- Small orifice susceptible to clogging

JOULE-THOMSON CYCLE (Throttle cycle)

- ***USES*** **(*Current and potential*)**
  - Cooling IR sensors on missiles
  - Cooling IR sensors for surveillance (10 K)
  - Cooling semiconducting electronics
  - Cryogenic catheter (heart arrhythmias)
  - All gas-liquefaction systems
- ***RECENT DEVELOPMENTS***
  - Mixed refrigerants
  - Sorption compressors
  - Electrochemical compressors

Linde-Hampson Cycle

ADVANTAGES

- Steady flow (low vibration, turbo-expander)
- Long lifetime (gas bearings, turbo system)
- Transport cold long distance
- Good efficiency due to work extraction except in small sizes

DISADVANTAGES

- Difficult to miniaturize
- Requires large heat exchanger
- Expensive to fabricate