Nova Movie: Absolute Zero

On a scale of 1 to 5 (1 being the best), how do you rank the Nova movie Absolute Zero compared to all other Nova presentations you have watched?

A. 1
B. 2
C. 3
D. 4
E. 5

Gas Expansion Cooling

Helium as an example
Flynn Ch. 6

Fundamentals of refrigeration

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

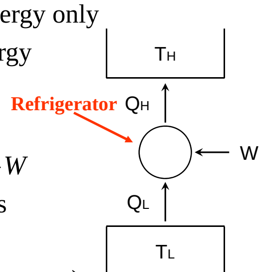
$$Q_H = Q_L + W$$

- 2nd law of thermodynamics

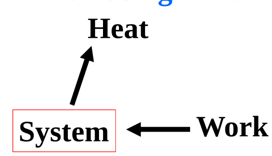
$$\frac{Q_H}{T_H} \geq \frac{Q_L}{T_L}$$

- 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

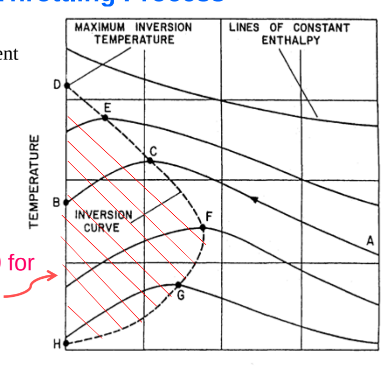
Ref. Temp T_L (K)	Work / Refrigeration W/Q_L (W/W)	
	Carnot (minimum)	Actual
270	0.11	0.3 ~ 0.5
100	2	10 ~ 20
20	14	100 ~ 200
4	74	700 ~ 1500
1	299	> 6000

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

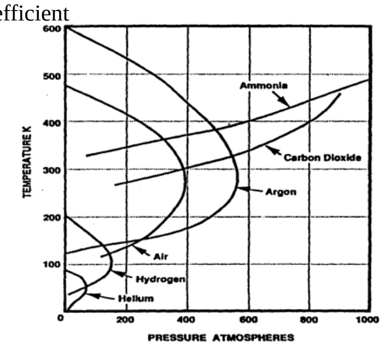
Inversion curve for various gases

Joule-Thomson Coefficient

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

Note: The maximum Inversion T for hydrogen is 202 K at 0 atm.

Expansion must start at P > 0 so for Hydrogen start at T < 100 K



Cooling comes from conversion of Kinetic → Potential Energy

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

From the previous graph, can carbon dioxide 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

Bobsleigh Track

- Total number of evaporators: 122
- Total evaporator load: 1,400 tons of refrigeration (TR)
- Total flow rate of refrigerant going up to tracks: 305 US GPM
- Total hp of compressors: 2,100 hp
- Refrigerant condition:
  Low side: Working: 16 psi and 0F; Design pressure: 300 psi
  Intermediate side: Working: 41 psi and 27F; Design pressure: 300 psi
  High side: Working: 160 psi and 90F; Design pressure: 300 psi

http://www.ammonia21.com/content/articles/2009-03-05-ammonia-use-in-2010-canada-winter-olympics.php

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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)

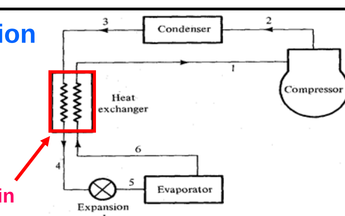
$$PV = nRT \qquad \mu_{J-T} = \left(\frac{\partial T}{\partial P}\right)_H$$

Joule Thomson Coefficient for an Ideal Gas = ?

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

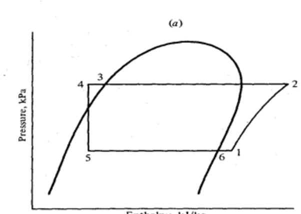
Hint: If you don't know thermodynamics, think about where the change in temperature comes from in an isenthalpic expansion, in which total energy is conserved.

General refrigeration cycle and its components



Very important in cryogenic refrigeration !

P-H diagram of refrigeration cycle



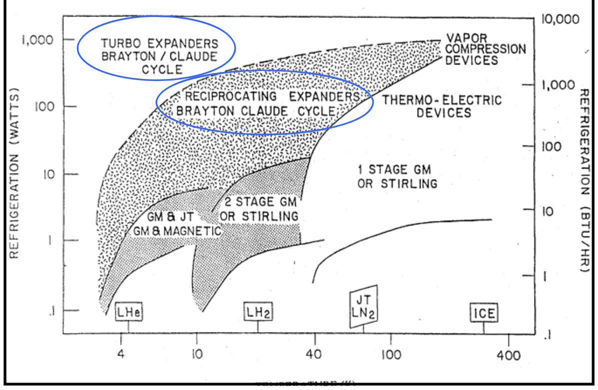
Two heat exchanger types in cryogenic refrigerator

- **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

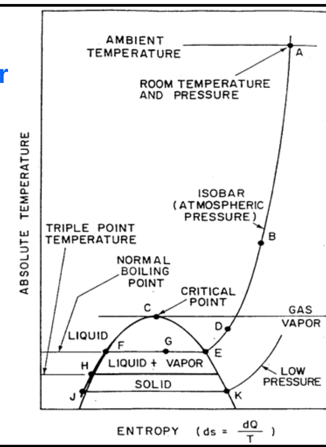
Cryogenic refrigeration system

- 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

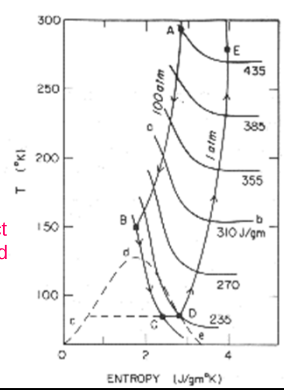
Temperature range of commercial refrigerators



Temperature Entropy Diagram for Cryogenic Fluid

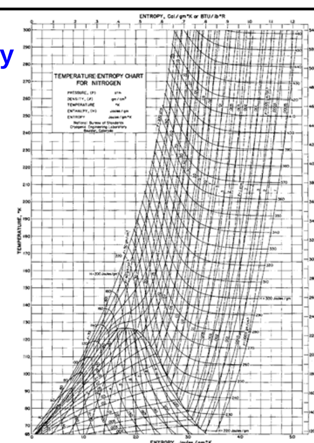


Isenthalpic lines in T-s diagram

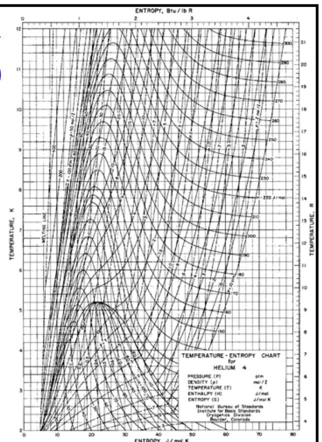


Gases are imperfect at low enough T and high enough P.

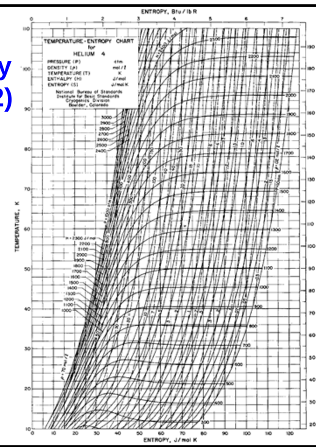
Temperature-Entropy Chart for Nitrogen



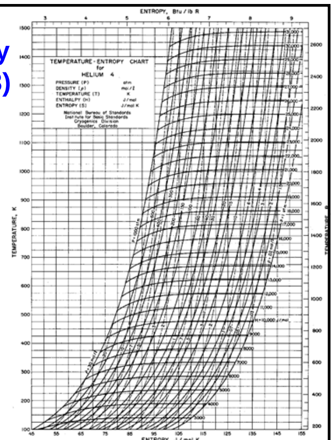
Temperature-Entropy Chart for Helium 4 (1)



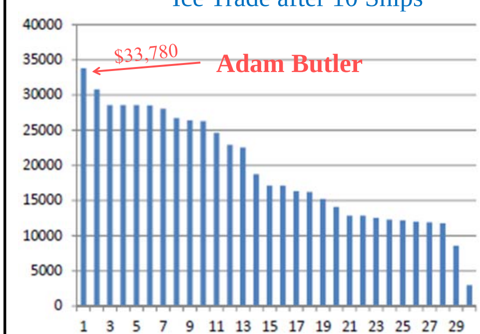
Temperature-Entropy Chart for Helium 4 (2)



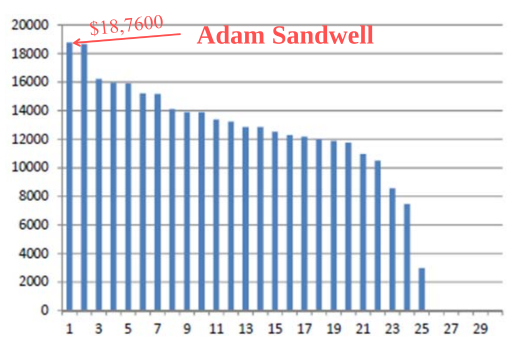
Temperature-Entropy Chart for Helium 4 (3)



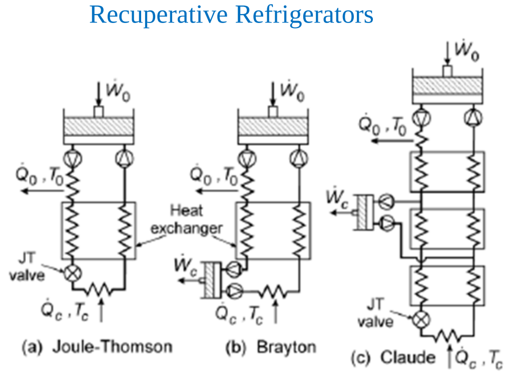
Ice Trade after 10 Ships



Ice Trade after 5 Ships



Recuperative Refrigerators



J-T (expansion) refrigerator

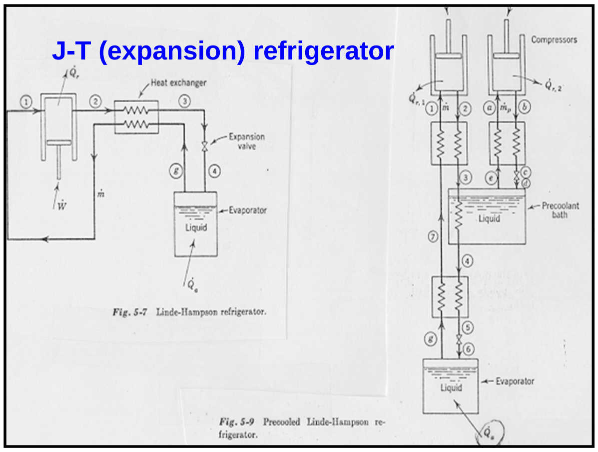
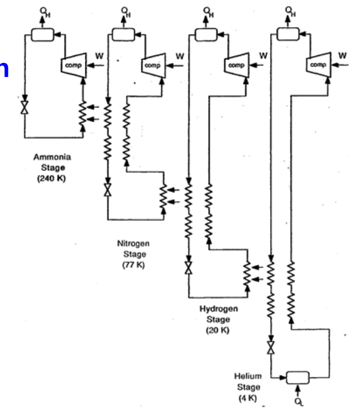


Fig. 5-7 Linde-Hampson refrigerator.

Fig. 5-9 Precooled Linde-Hampson refrigerator.

Cascade cooling of J-T refrigeration system



J-T expansion liquefier

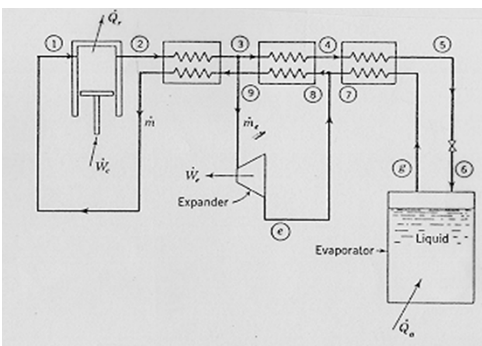
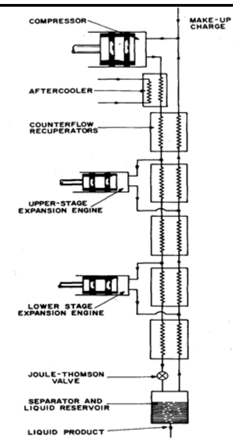
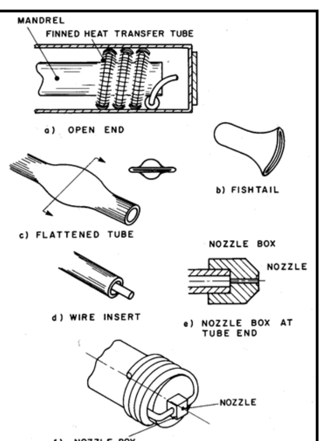


Fig. 5-12 Claude refrigerator.

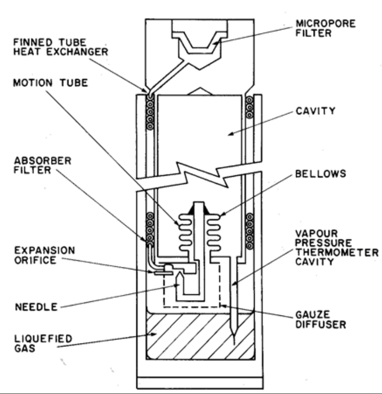
Schematic diagram of the Collins-Claude cycle multiple-expansion gas (helium) liquefier



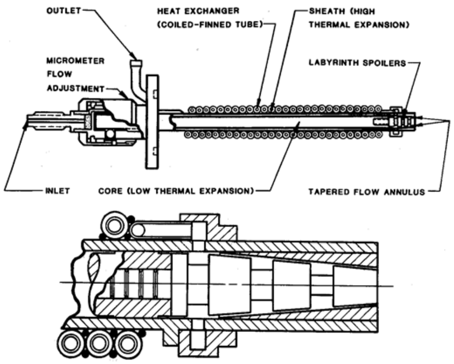
Fixed-orifice J-T expansion nozzles



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

Isentropic Expansion—Doing External Work

Adiabatic expansion

$\mu_s = (\partial T/\partial p)_s = (T/c_p)(\partial v/\partial T)_p > 0$

Always cooling effect

perfect gas $\mu_s = v/c_p$

real gases van der Waals gas

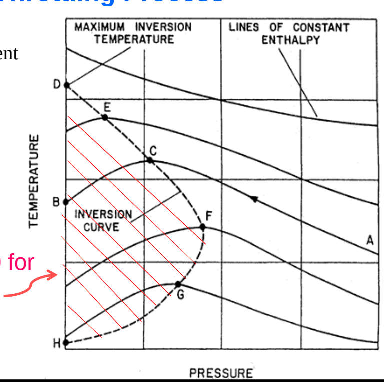
$\mu_s = (v/c_p)(1-b/v)/[1-(2a/vRT)(1-b/v)^2] > 0$

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



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

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.

Linde-Hampson Cycle
Turbine does External Work

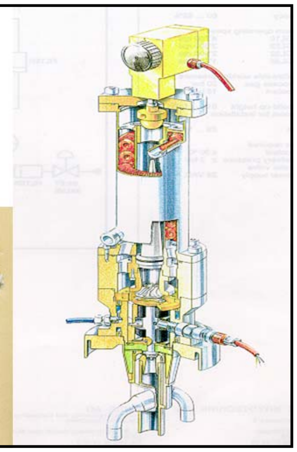
ADVANTAGES

- 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

Turboexpander
Where the work goes

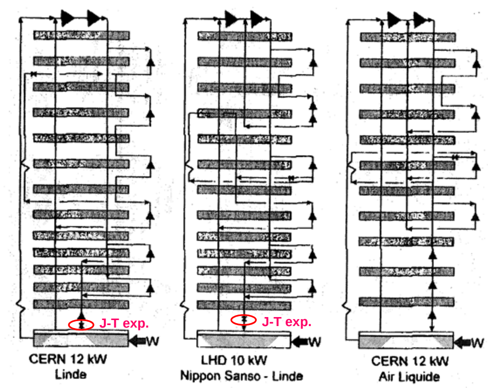


Turbocharger

It came off a Cosworth engined Formula 1 car, back in the days when they were turbocharged (1986). The turbo is manufactured by Garrett.

http://www.users.zetnet.co.uk/gas/theturbo.htm

Turbo Claude Refrigerators (4.2 K)



Linde-Hampson Cycle

***USES* (*Current and Potential*)**

- IR sensors for satellites (such as NICMOS)
  - → **both in large or small refrigeration systems**
- HTS applications such as motor cooling

RECENT DEVELOPMENTS

- Small turbo expanders and compressors
- 3.2 mm dia. expander rotor
- 5 W at 65 K with 43 W/W
- Heat exch. : 90 mm dia. 533 mm long

NICMOS (Near Infrared Camera and Multi-Object Spectrometer) cooler test

Work extraction mechanism ?

NICMOS cooler will cool the instrument and its detectors to temperatures around 78 K. http://www.stsci.edu/cgi-bin/NICMOS/si.pl?nav=nichistory

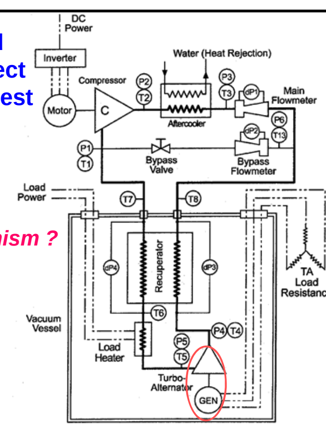
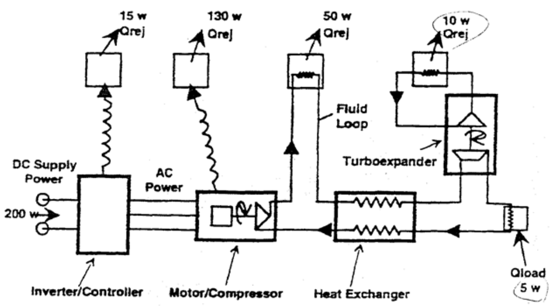
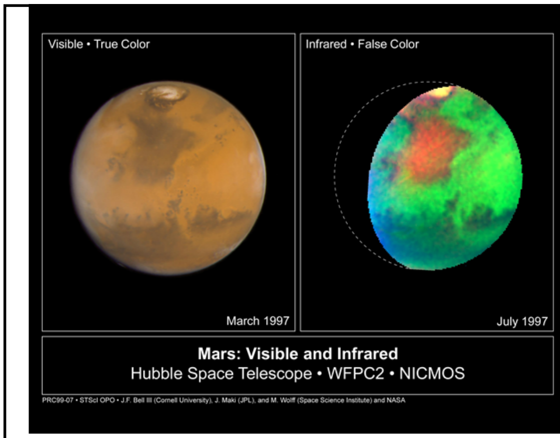


Figure 3. Schematic of reverse Brayton test assembly.

Single Stage Linde-Hampson Cycle (SSLH) system schematic
Heat and power flow are shown for individual components



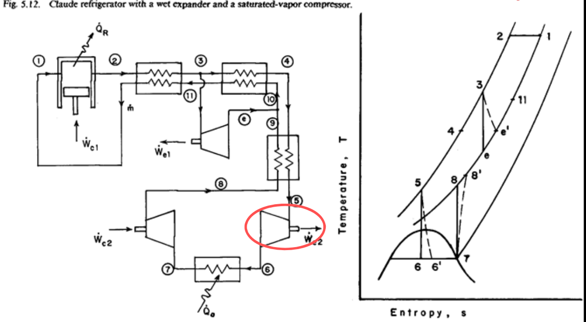


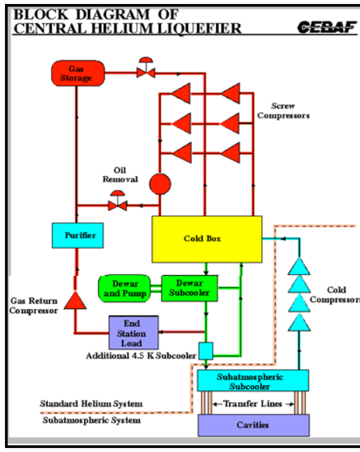
Wet expander system
Two phase system

Which is the "Wet" Expander?

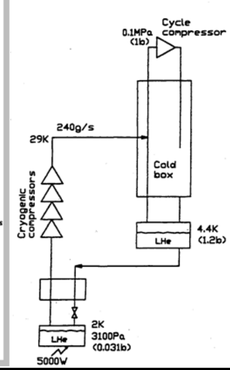
Helium only !

Fig. 5.12. Claude refrigerator with a wet expander and a saturated-vapor compressor.





Cooling system for superconducting cavity (Nb)



Specific power of commercial cryogenic refrigerators

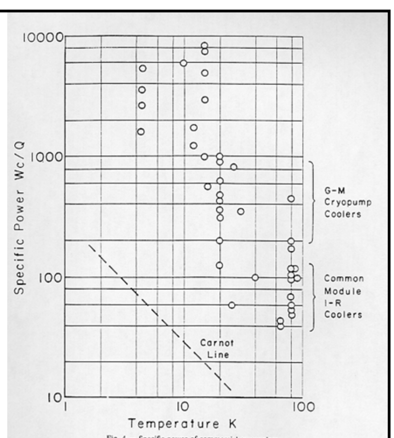
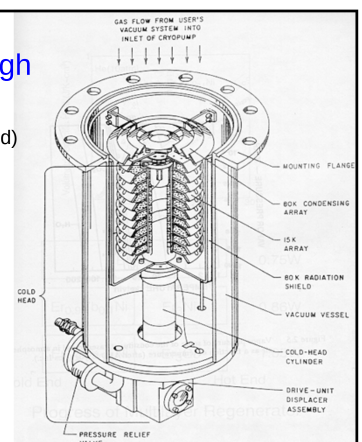


Fig. 4 — Specific power of commercial cryocoolers

Cryopump for high vacuum

(G-M cryocooler mounted)



Weight of commercial cryogenic refrigerators

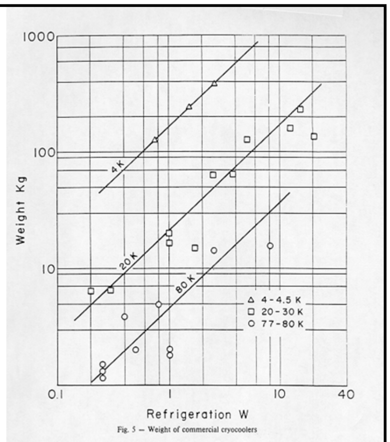
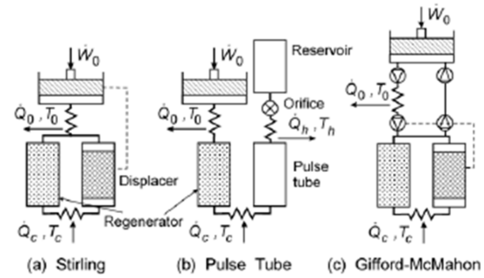


Fig. 5 — Weight of commercial cryocoolers

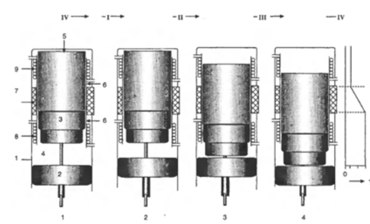
Regenerative Refrigerators



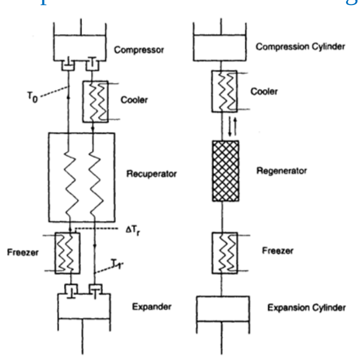
A regenerative heat exchanger-

A. Mixes the hot and cold fluid streams
B. Uses a "counter-flow" heater exchanger
C. Is inherently a bad idea
D. Maintains a separation between hot and cold fluid flows
E. I just have no idea!!!!

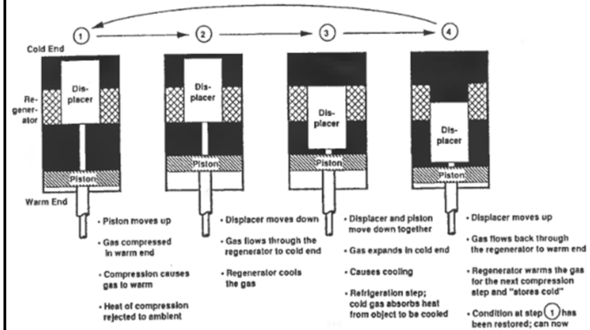
Stirling Cycle



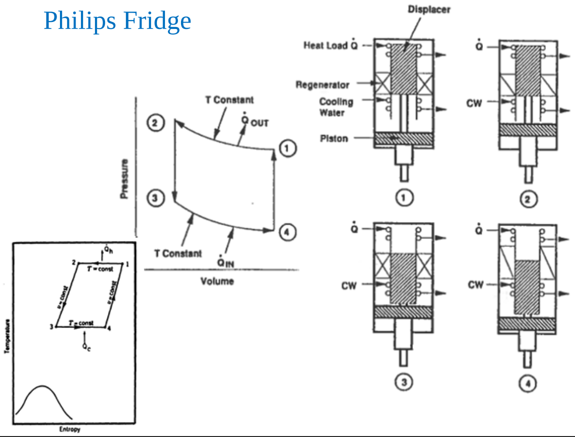
Comparison of Claude and Stirling



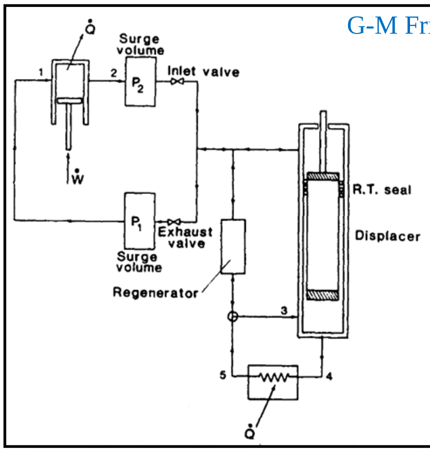
Stirling Integral CryoCooler



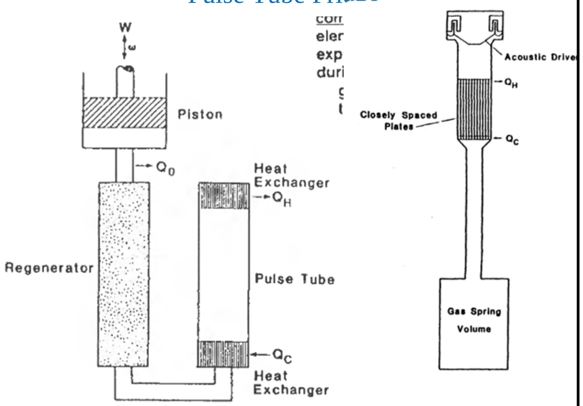
Philips Fridge

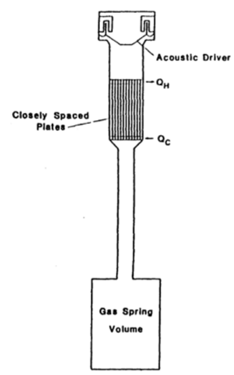


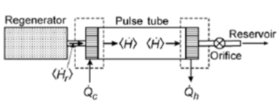
G-M Fridge



Pulse Tube Fridge







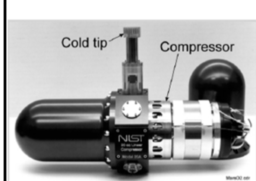
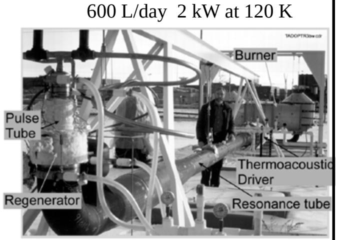
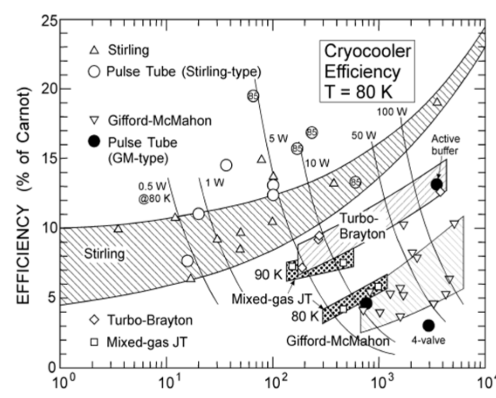


Figure 10. Pulse tube refrigerator for studies of liquefying oxygen on Mars (580 mm total length)

Natural Gas Liquefier
600 L/day 2 kW at 120 K



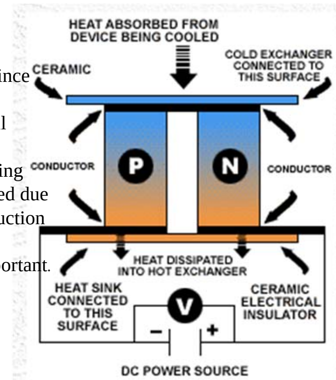


Special refrigeration method

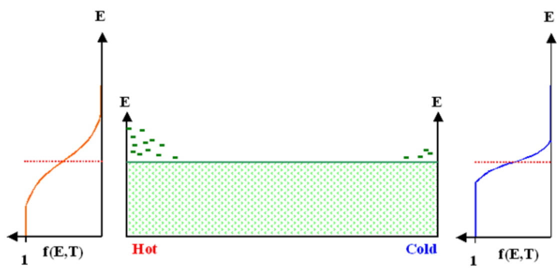
1. **Thermoelectric cooling**
2. **Vortex tube cooling**
3. **Evaporative cooling**
4. **Radiative cooling**
5. Magnetic refrigeration
6. Thermoacoustic refrigeration
7. **Elastic cooling**

Thermoelectric cooling

No moving part at all.
Utilizing Peltier effect
Opposite of Thermoelectric generator (e.g. Voyager since 1980)
Semiconductor cooling, small refrigerator, drink water dispenser, IR sensor cooling
Temperature difference limited due to parasitic thermal conduction loss
Cooling of hot surface is important.

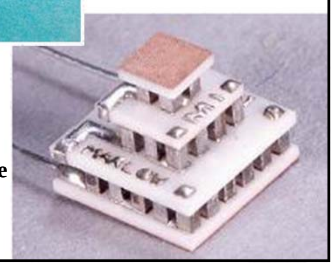


Temperature Difference across a Conductor Kelvin Effect



Single stage thermoelectric module

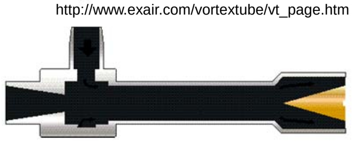
Multi stage thermoelectric module



•Vortex tube cooling

Compressed air supply : Hot and cold air separation at low pressure
No moving parts : Min. T ~ -45 °C, Max. T ~ 126 °C
Tangential inflow of compressed air
→ Passing down the hot tube in spinning shell (like tornado)
→ Some warm air escapes through one end.
→ Other air heads back down inside the low pressure area of the larger vortex.
→ Inner stream loses angular momentum, giving thermal energy to outer swirl.
→ Inner stream escapes at low temperature.

http://www.exair.com/vortextube/vt_page.htm



- **Thermo-acoustic refrigeration**
  Pressure wave generation by speaker
  High resonance frequency such as 500 Hz
  Due to standing resonant wave, surface heat pumping occurs.

- **Elastic cooling**
  Stretching a rubber band reduces the entropy.
  Similar to volume compression work input
  Restoring to the original shape generates temperature drop.
  Several degrees of temperature change can be obtained adiabatically.