Cryogenics - cycles

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European Course of Cryogenic
CERN, Geneva 30 August, 2010

Content

- Liquefaction of gases
- Processes of gas cooling
- Cryogenic cycles with recuperative heat exchangers
- Cryogenic Cycles with regenerator heat exchangers
- Classification and comparison of cryocoolers

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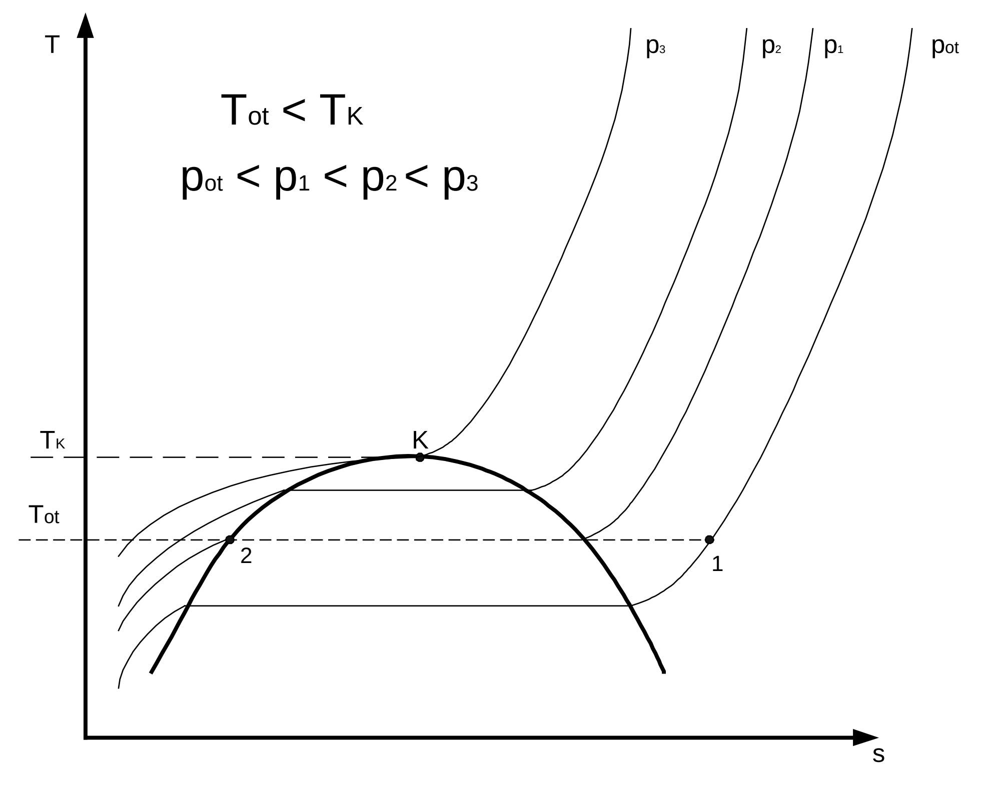
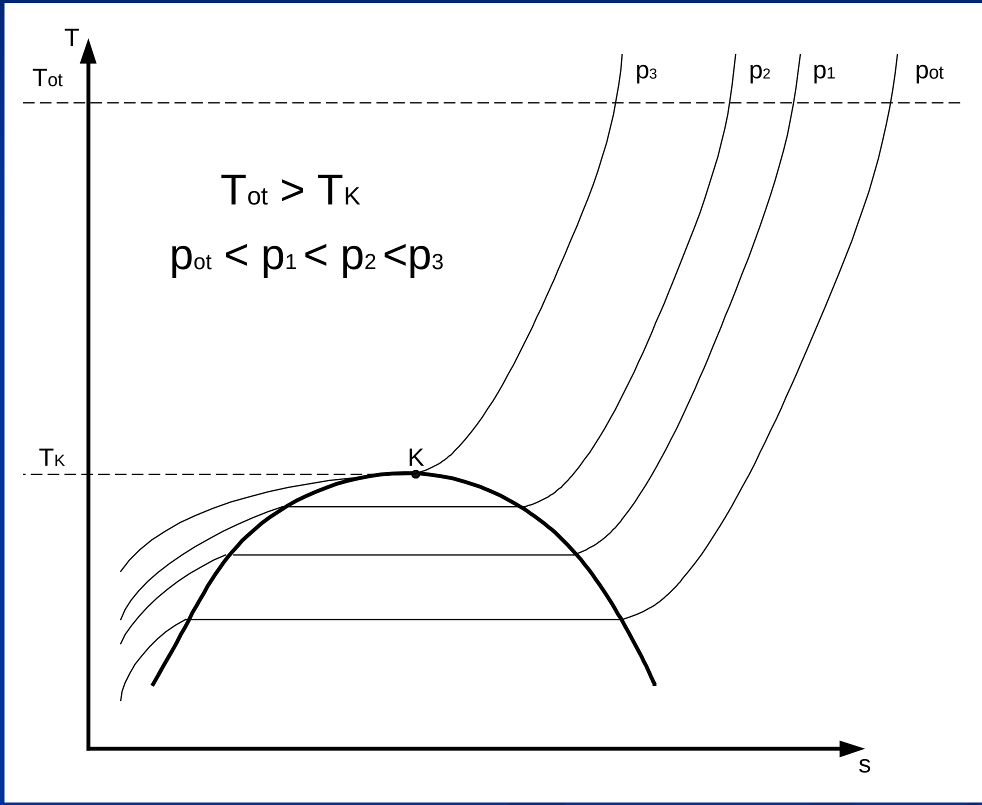
Liquefaction of gases





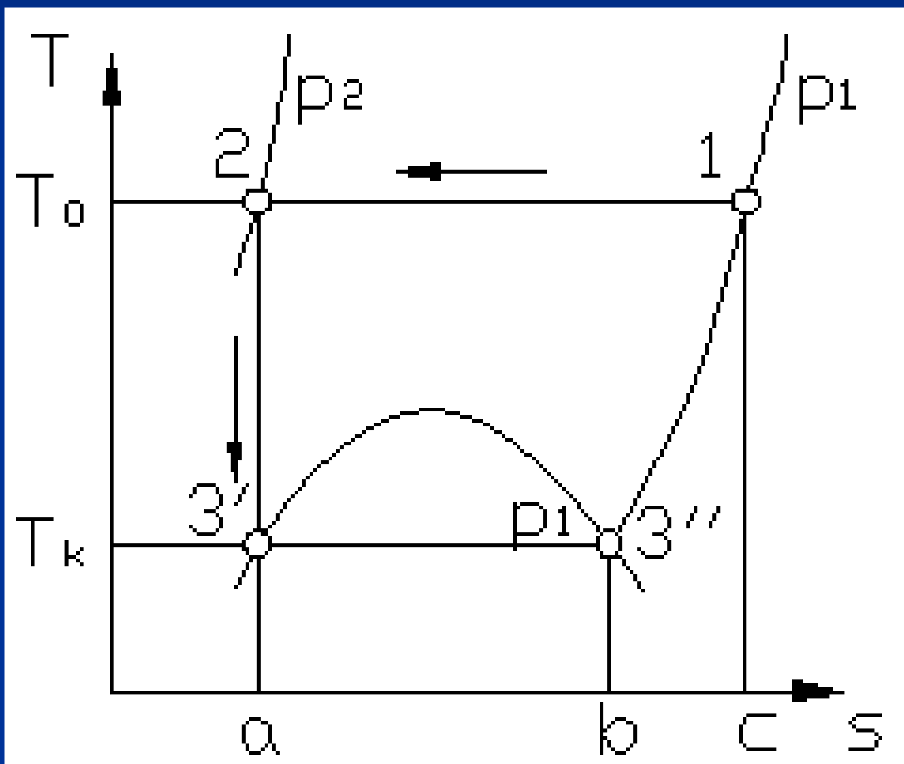
T-s diagram of the gas with the critical temperature above ambient temperature

T-s diagram of gases with the critical temperature below ambient temperature CRYOGENIC GASES!!!

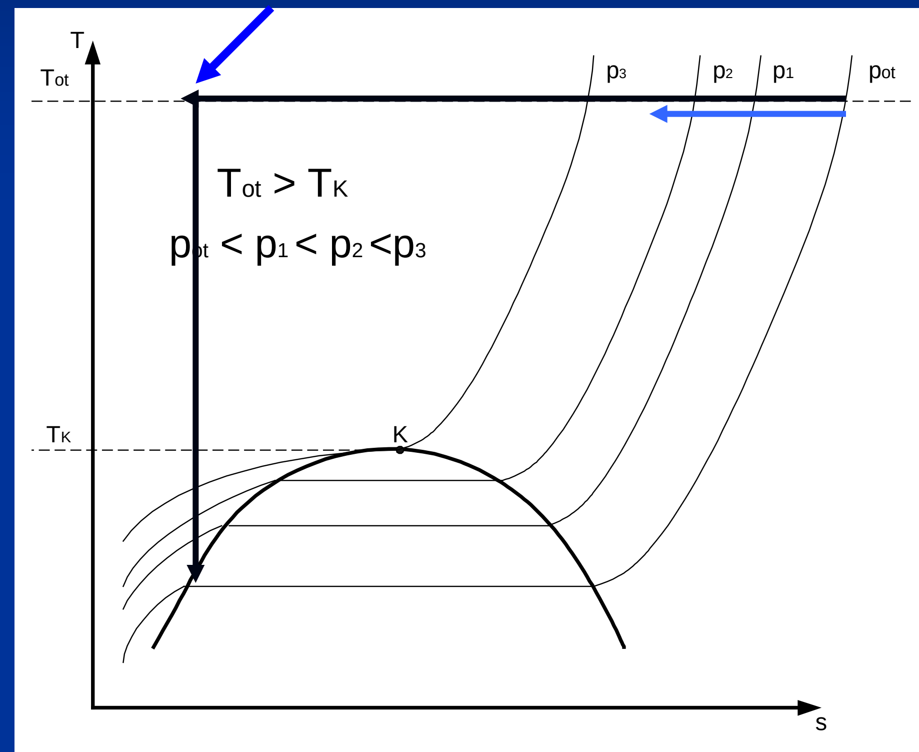
Critical parameters and boiling temperature of chosen gases

Gas	T_C, K	P_C, MPa	T_B, K
CO_2	304.2	7.38	195.2
Xe	289.8	5.84	165.0
C_2H_2 (ethyne)	237.2	6.20	193.2
Kr	209.4	5.50	119.9
CH_4	190.5	4.60	111.6
O_2	154.6	5.04	90.2
Ar	150.9	4.90	87.3
N_2	126.2	3.39	77.3
Ne	44.5	2.73	27.1
H_2	33.0	1.29	20.3
He	5.2	0.23	4.2

Ideal process of gas liquefaction



Too high pressure



$$W_{min} = T_o\left(s_1 - s_{3'}\right) - \left(h_1 - h_{3'}\right)$$

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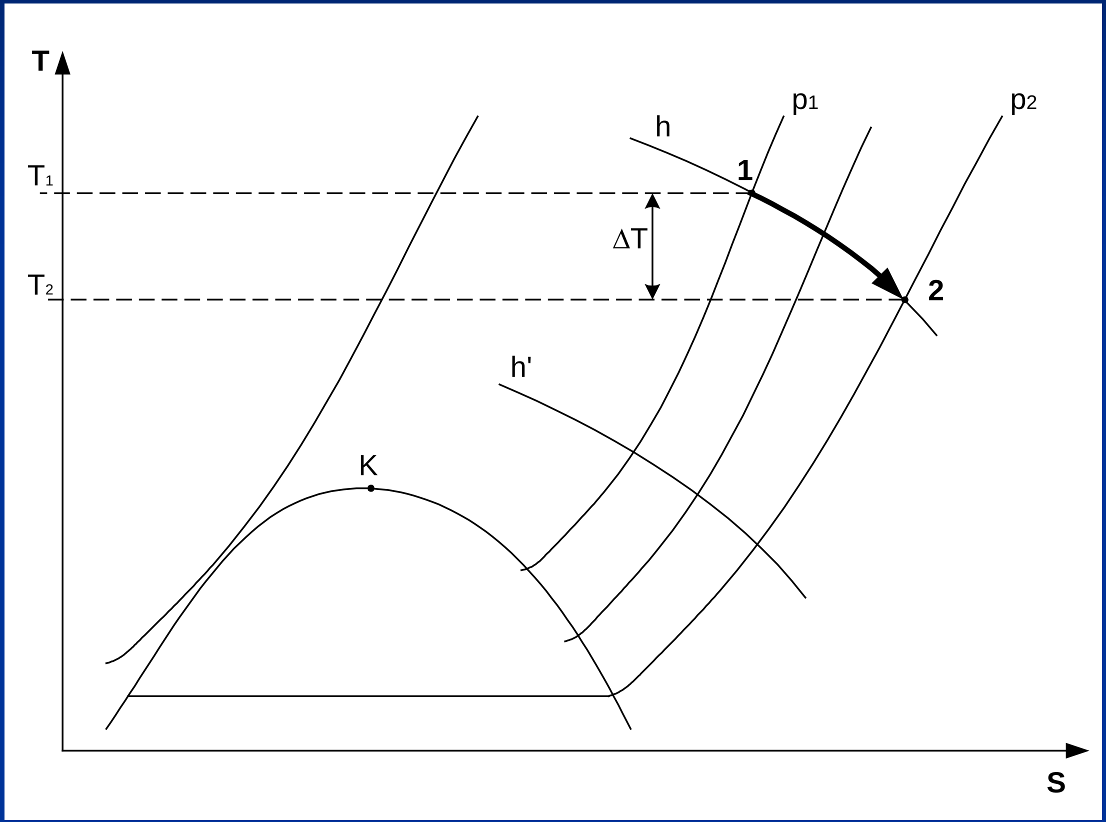
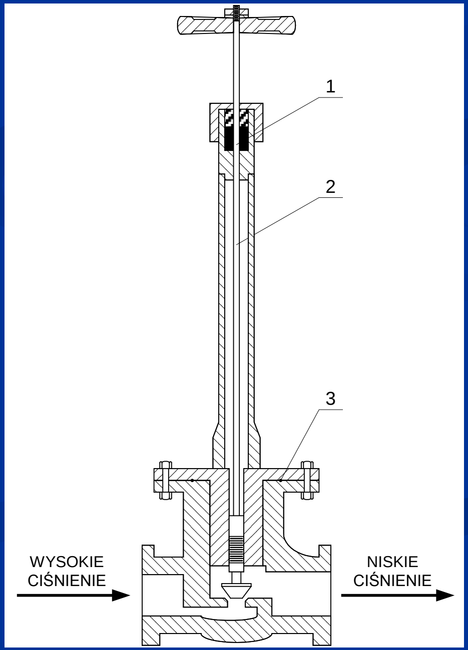
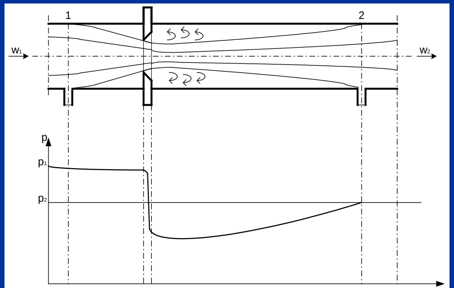
Processes of gas cooling – isenthalpic throttling

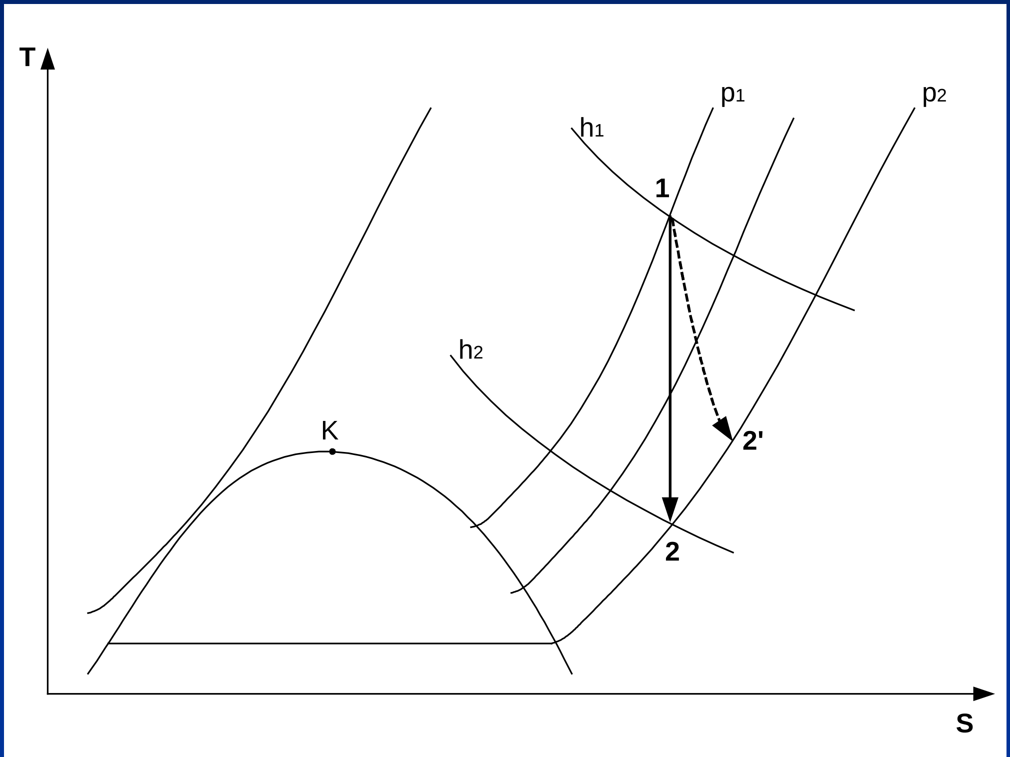


$$\mu_h = \left(\frac{dT}{dp}\right)_h = \frac{T\left(\frac{\partial v}{\partial T}\right)_p - v}{c_p}$$



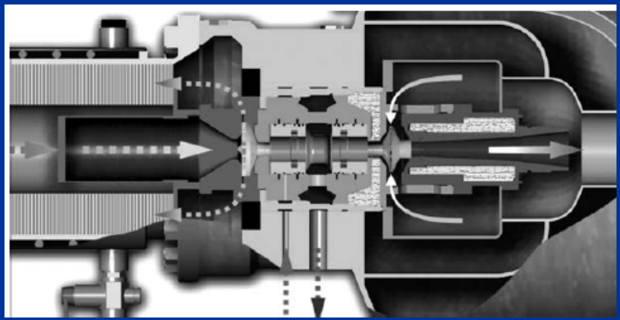


Gas cooling – isentropic expansion

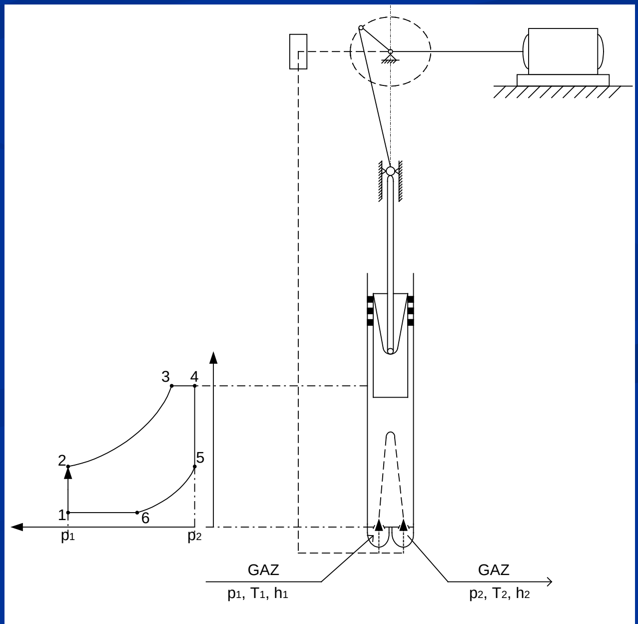


$$\mu_s = \left(\frac{dT}{dp}\right)_s = \frac{T\left(\frac{\partial v}{\partial T}\right)_p}{cp} = \frac{Tv\beta}{cp}$$

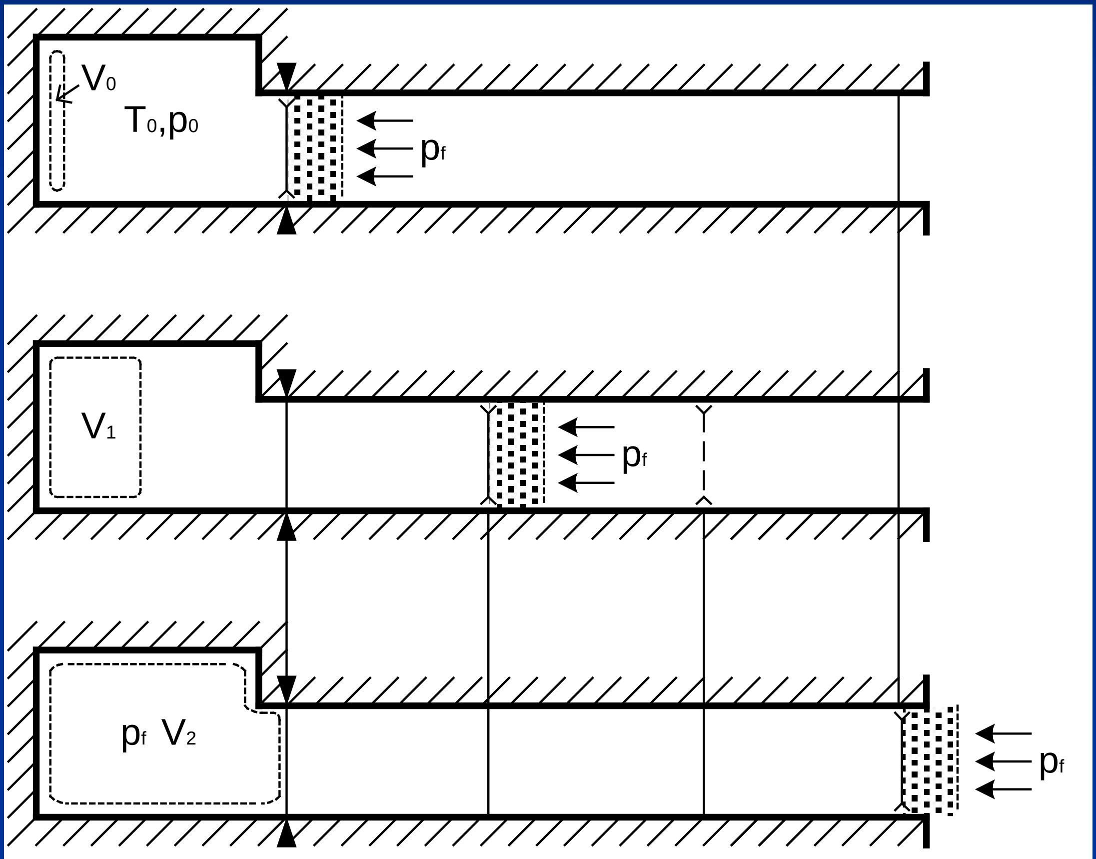
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}$$ For ideal gas



Cryogenic turbine and piston expanders



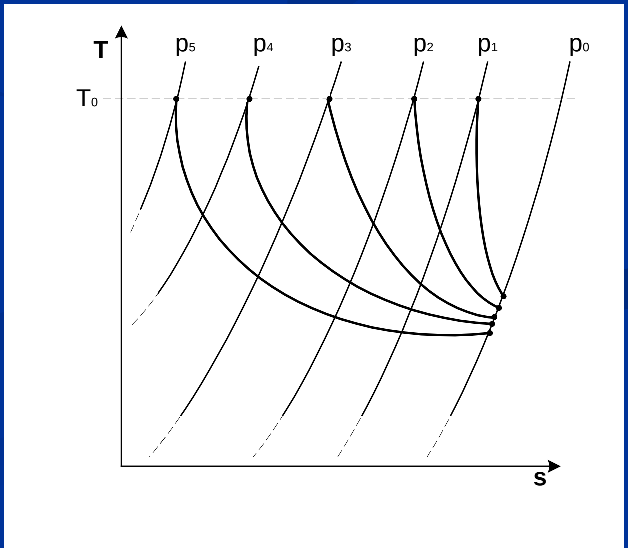
Gas cooling - free exhaustion

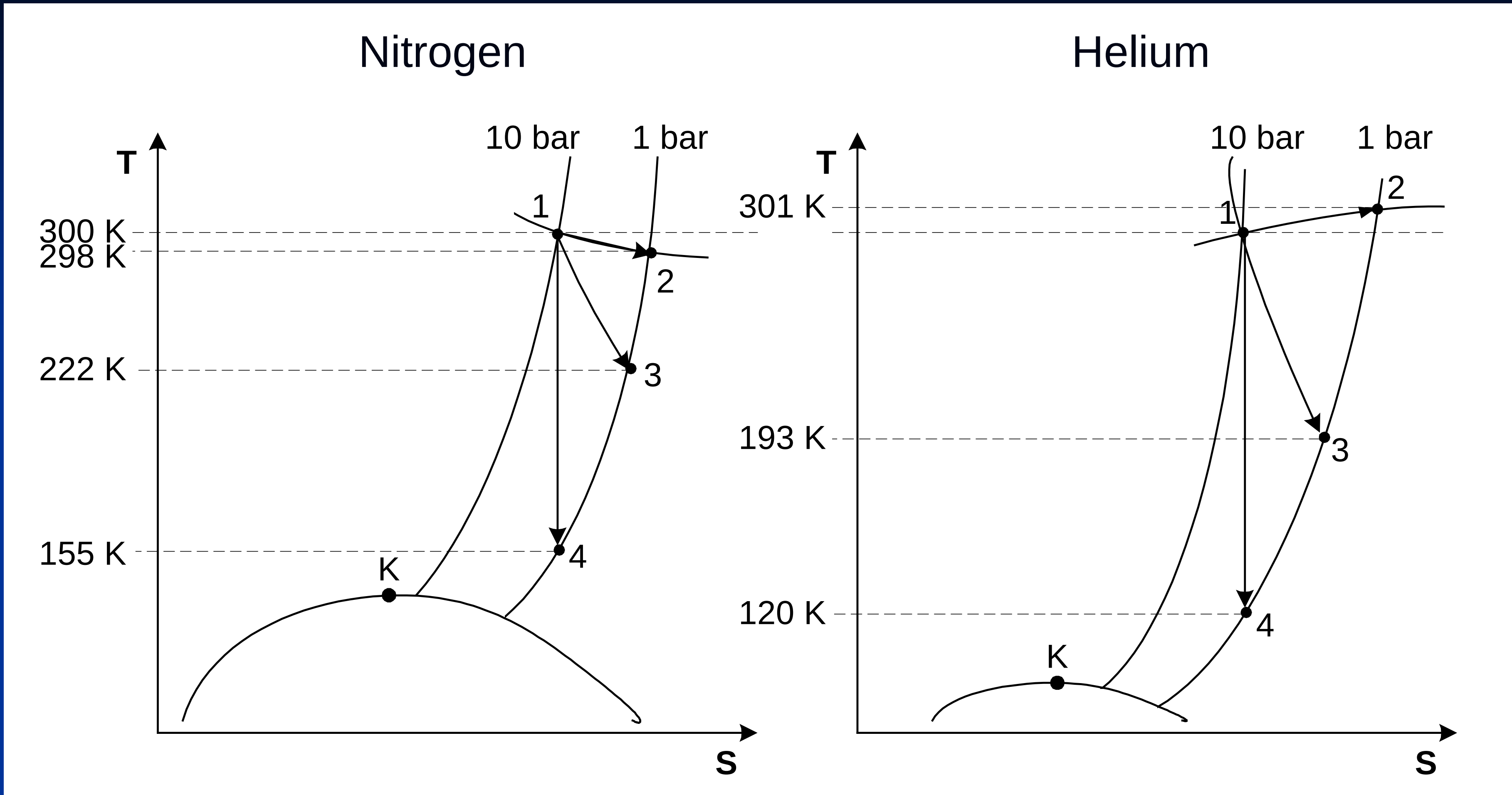


$$u_f - u_0 = -p_f (v_f - v_0)$$

The energey of the gas decreases because the exhaustng gas performs work against the external pressure

$$\frac{T_0}{T_f} = \frac{k}{1 + (p_f / p_0)(k-1)}$$





1-4 – isentropic expansion, 1 – 3 – free exhaustion, 1 – 2 - throttling

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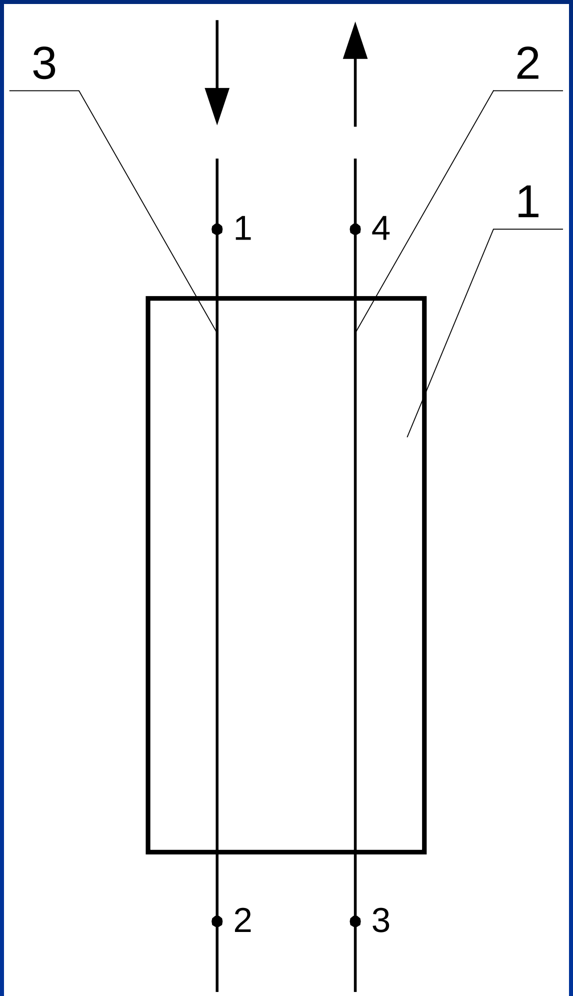
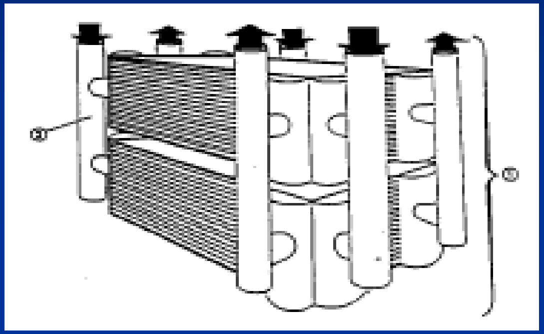
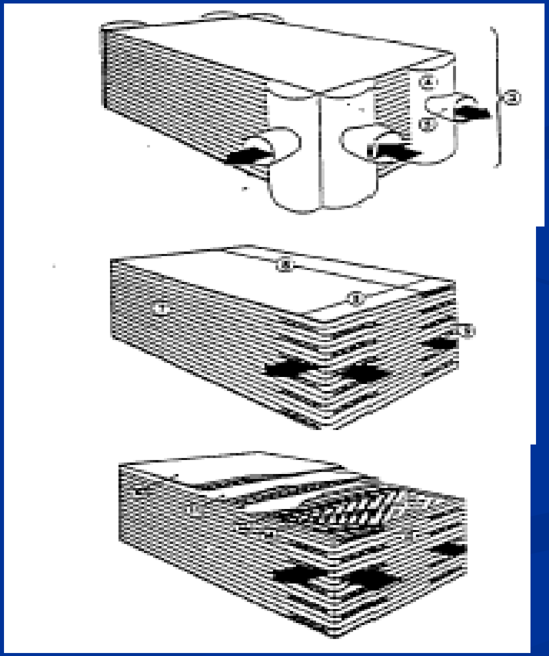
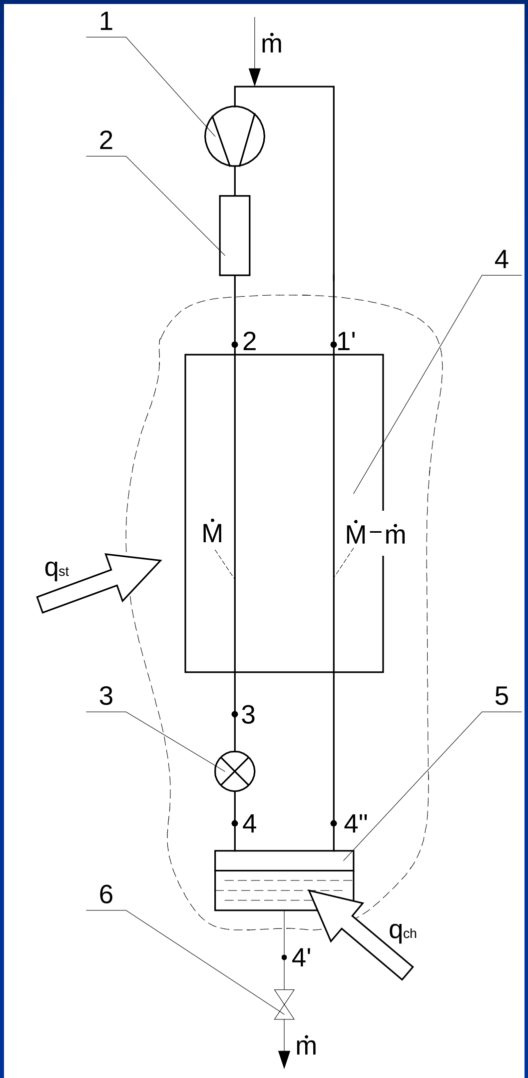
Cryogenic cycles with recuperative heat exchangers

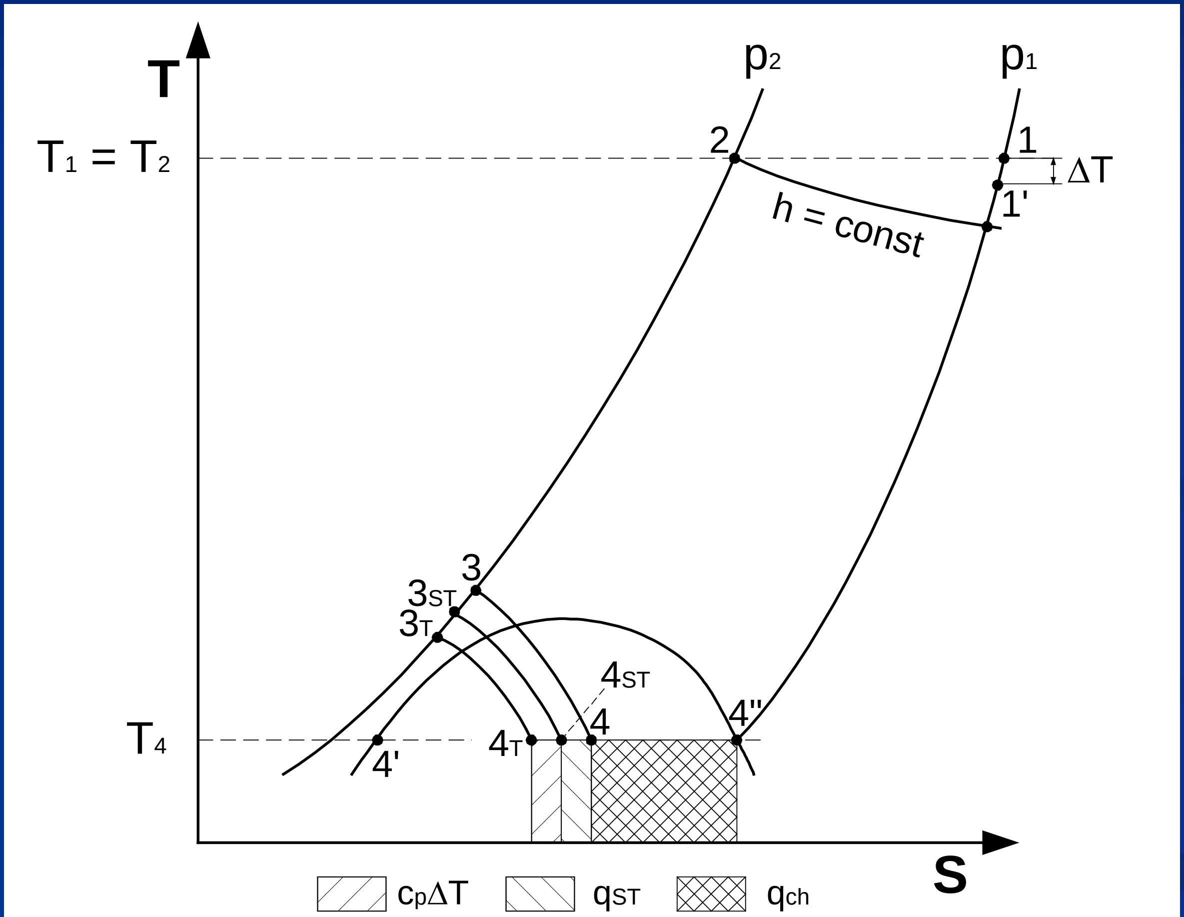




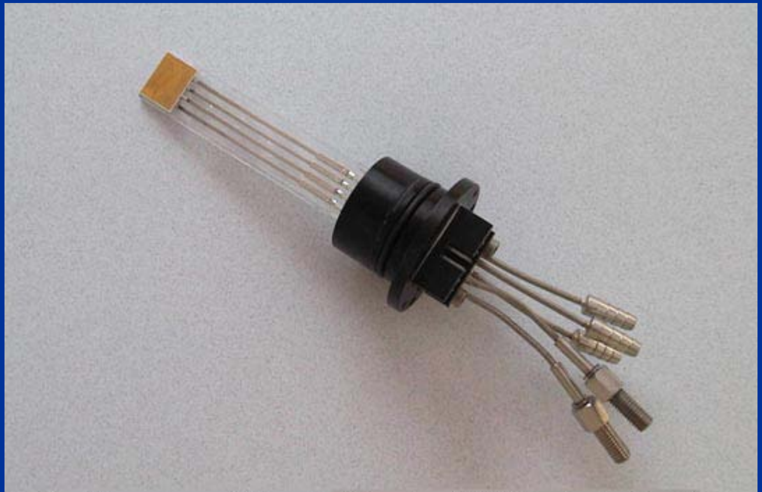


Joule-Thomson Liquefier





Joule-Thomson liquefiers



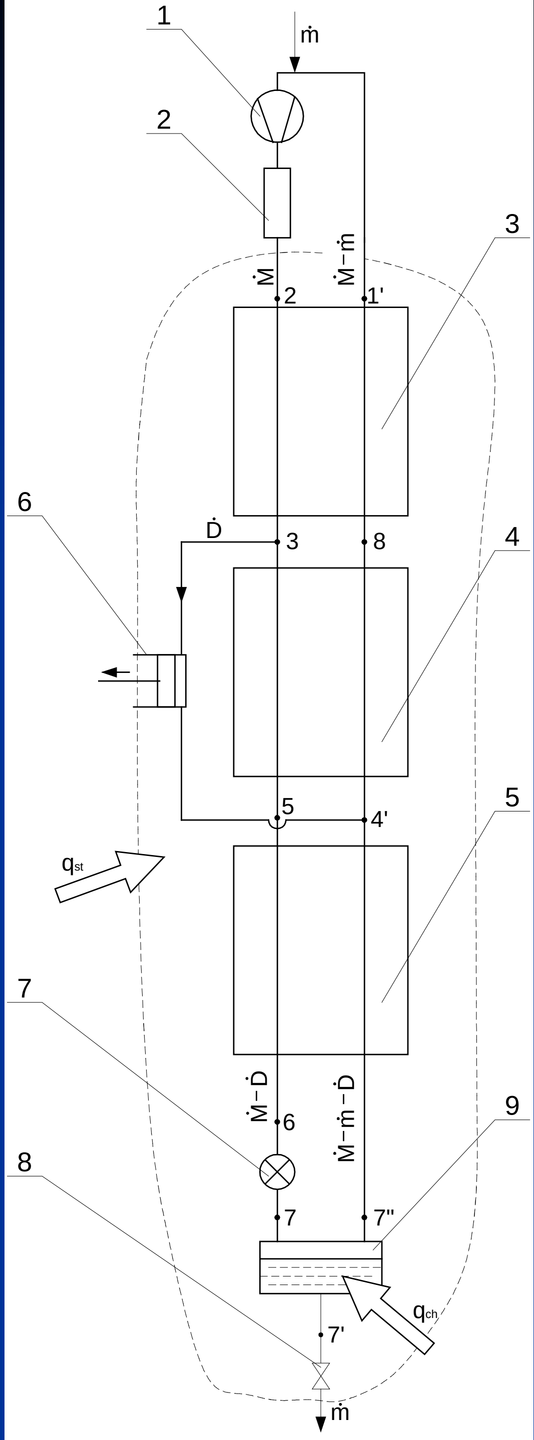
Two Stage Argon / Neon Refrigerator, MMR Technologies, Inc.

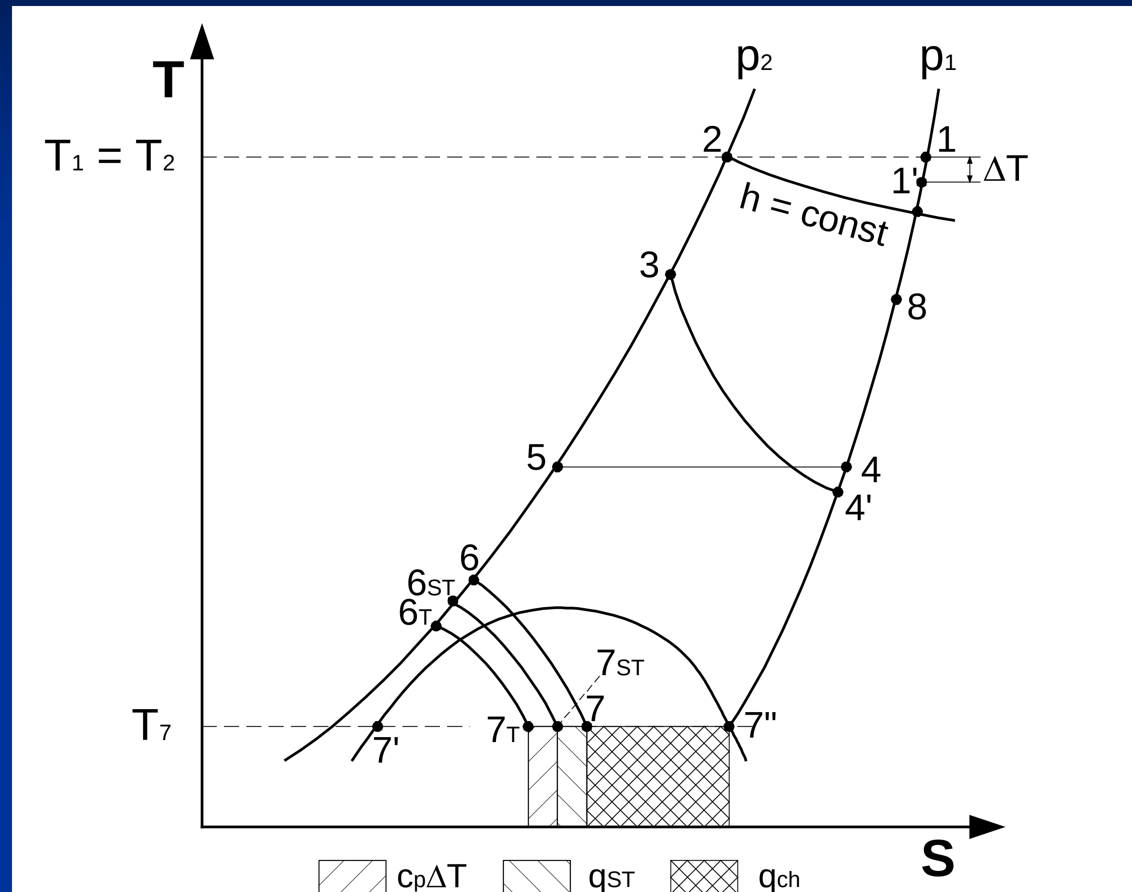
$$\dot{M}\, h_2 - \dot{m}\, h_{4'} - \left(\dot{M} - \dot{m} \right) h_{1'} + q_{st} = 0$$

$$x = \dot{m} / \dot{M}$$

$$x = \frac{h_1 - h_2 - c_p \Delta T - q_{st}}{h_{1'} - h_{4'}} = \frac{\Delta h_T - c_p \Delta T - q_{st}}{h_{1'} - h_{4'}}$$

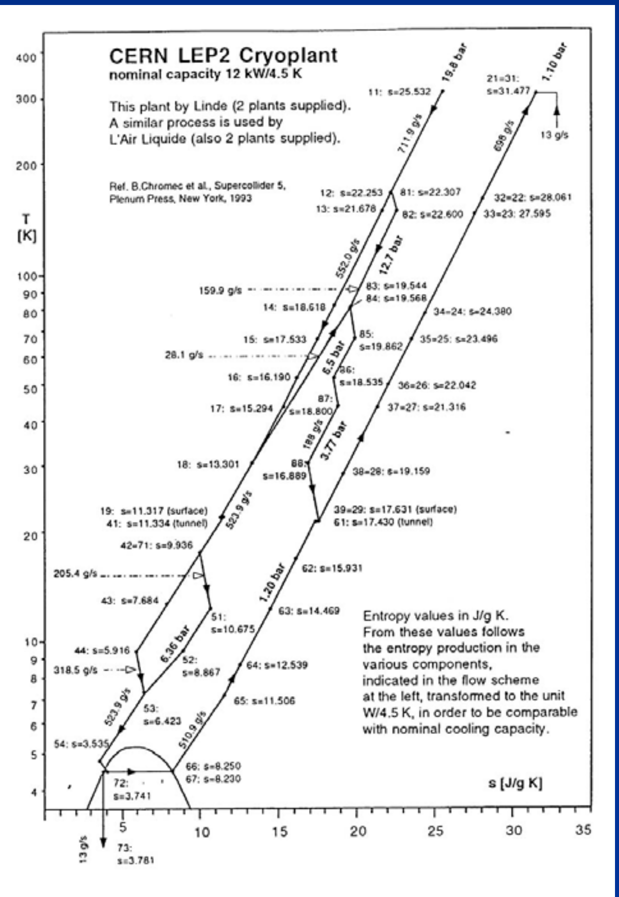
Claude liquefier

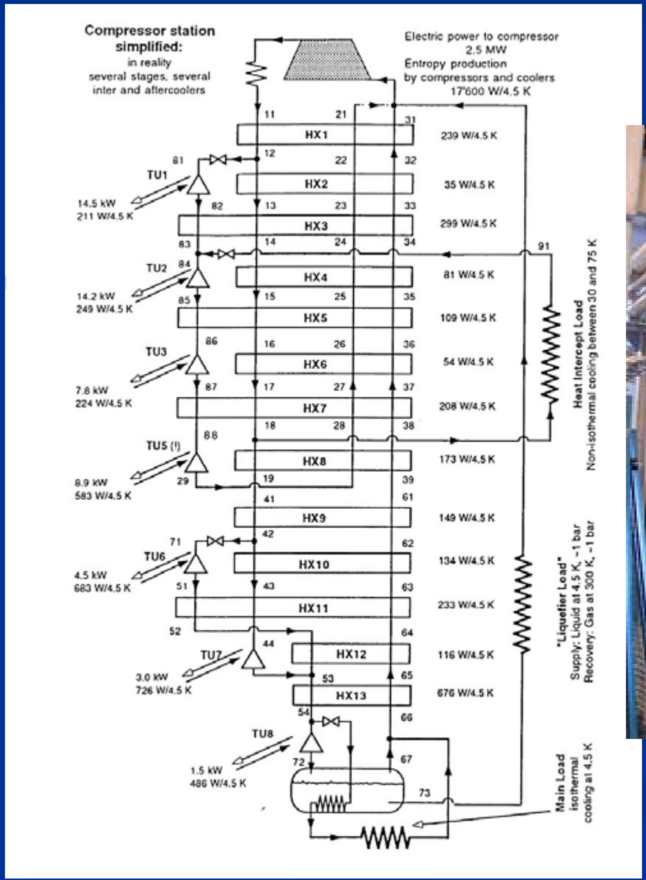




$$x = \frac{\Delta h_T + \left(\dot{M}_R / \dot{M}\right)\left(h_3 - h_{4'}\right) - c_p \Delta T_1 - q_{st}}{h_{1'} - h_{4'}}$$

Refrigerator 12 kW @ 4,5 K





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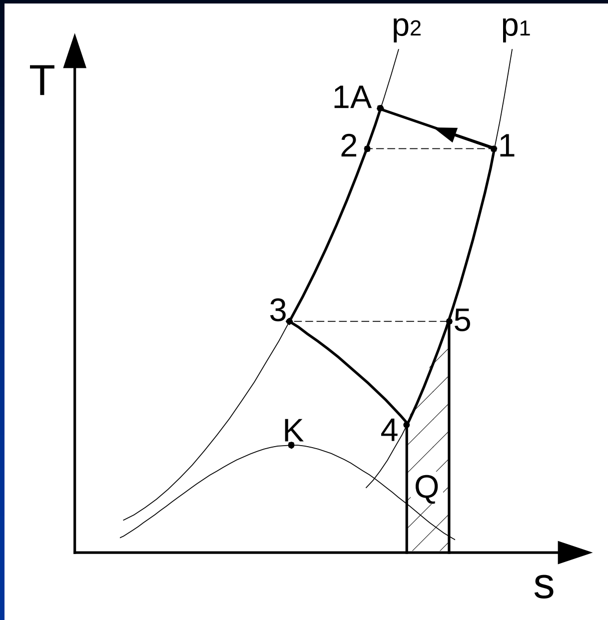
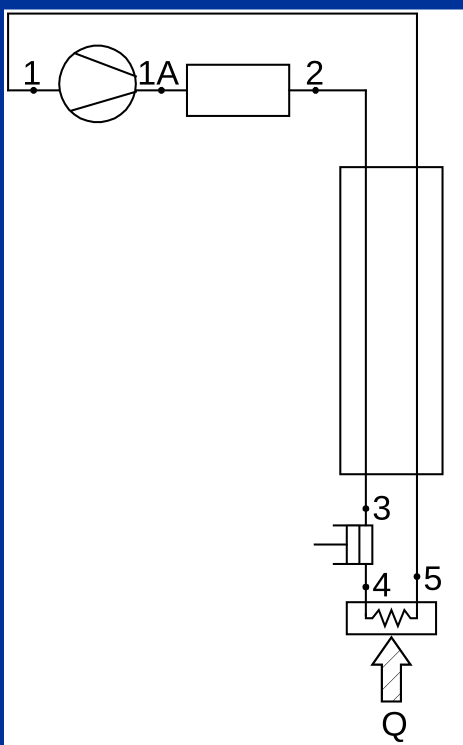
Brayton cycle





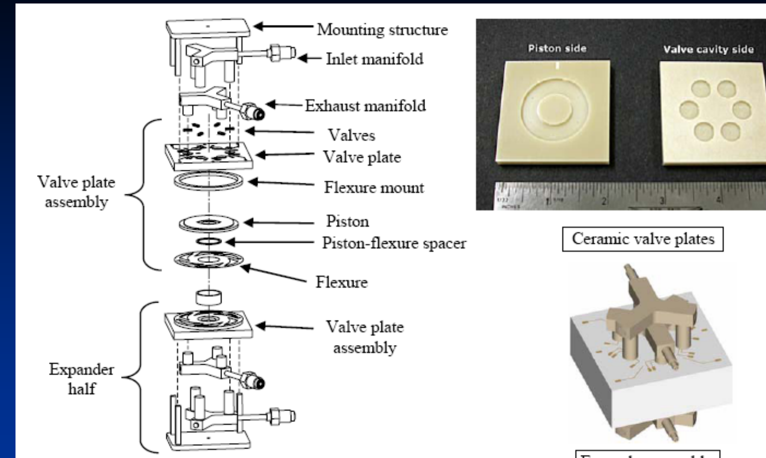
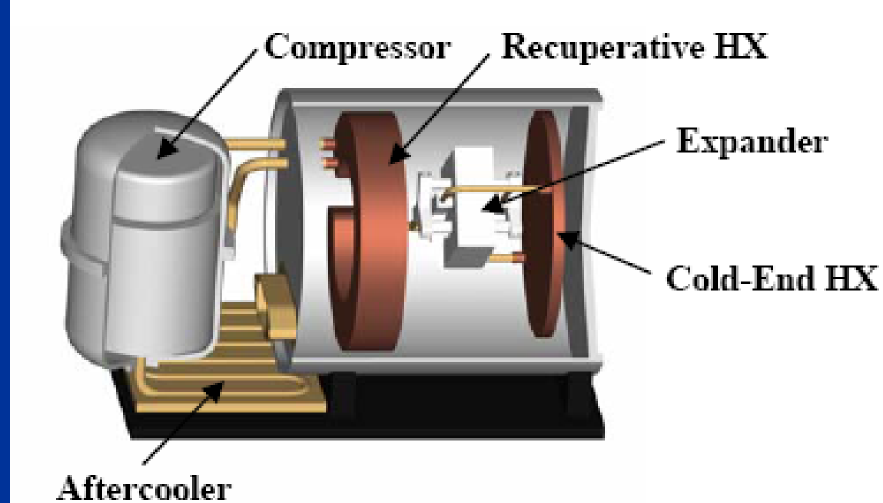
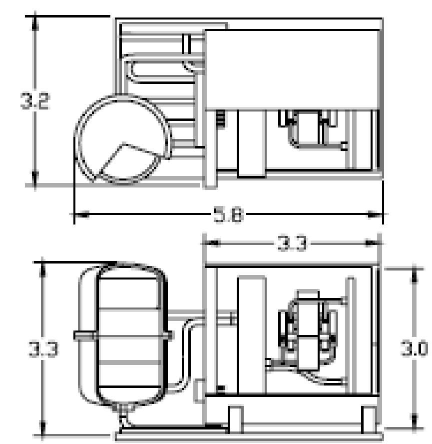


FIGURE 6. Expander components and assembly

PARAMETER	SENSITIVITY %/%	RANGE
Compressor Isentropic Efficiency	1.3	0.4< η <0.6
Expander Isentropic Efficiency	2.5	0.6< η <0.8
CFHX-1 Effectiveness	11	0.94< ε <0.98
CFHX-2 Effectiveness	24	0.94< ε <0.98





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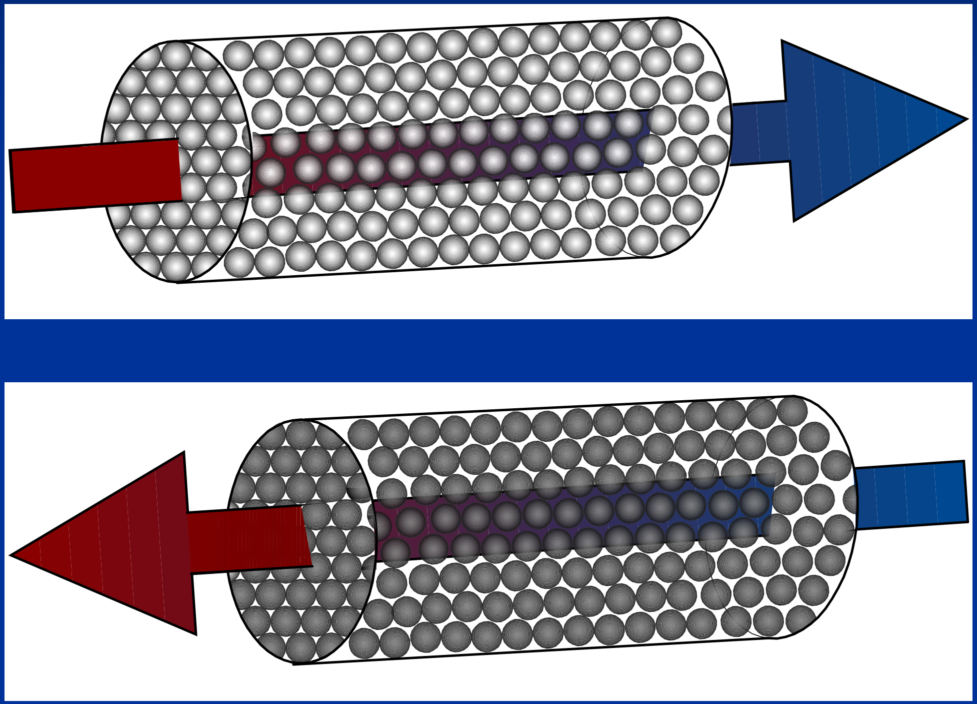
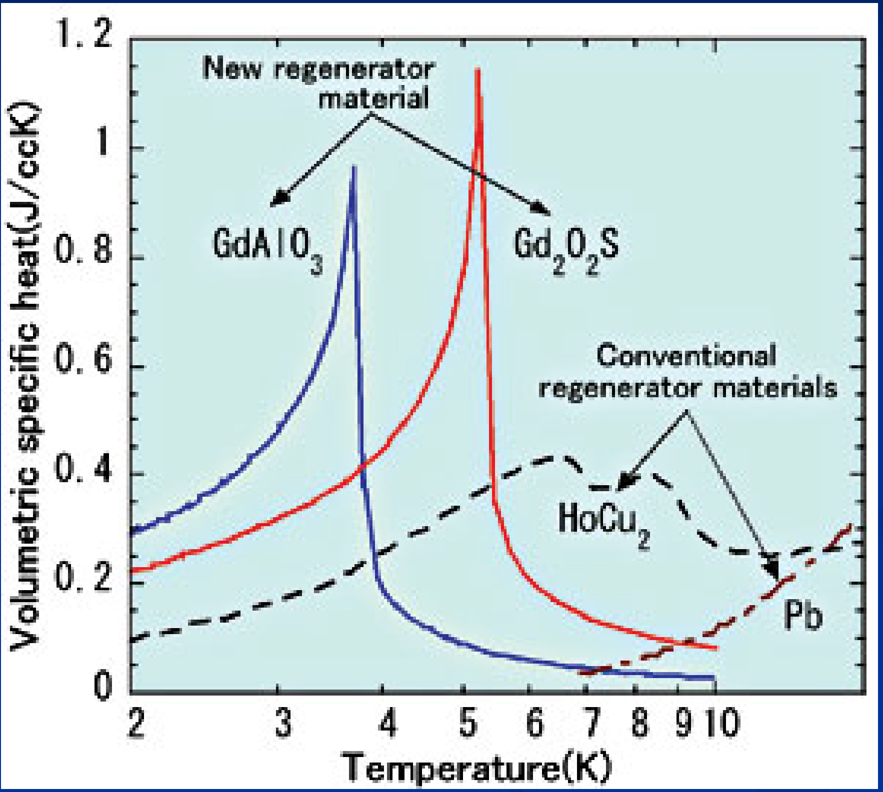
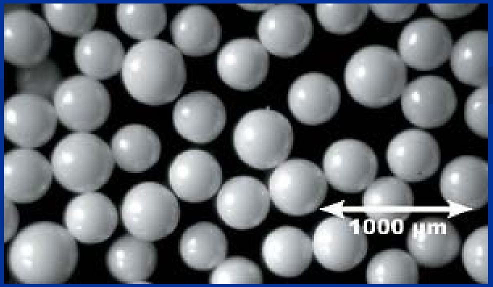
Cycles with regenerator heat exchangers

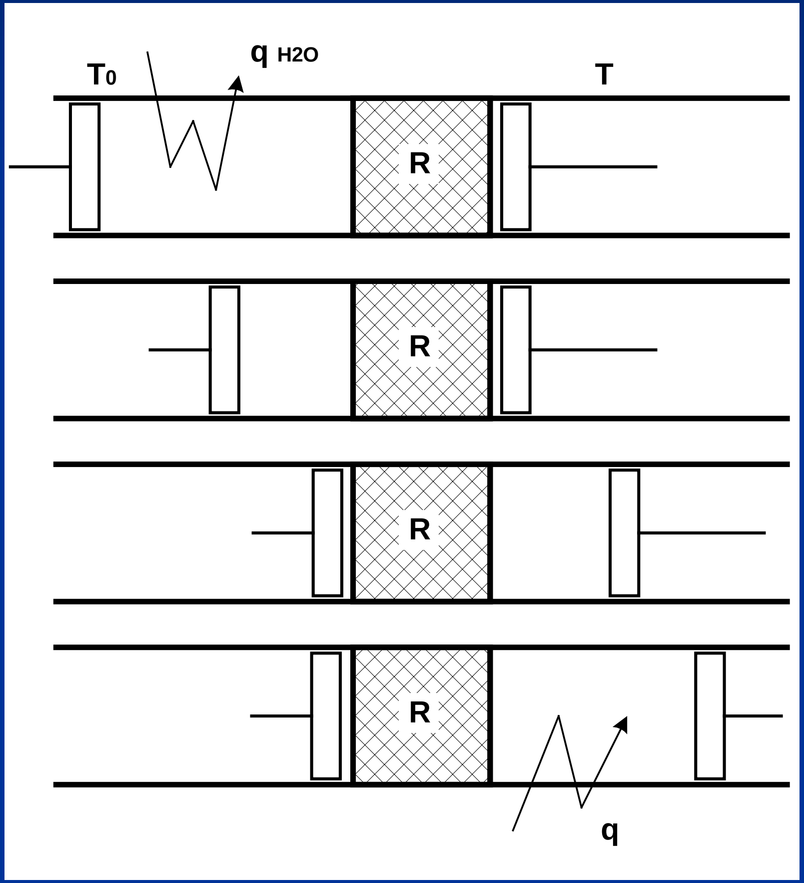


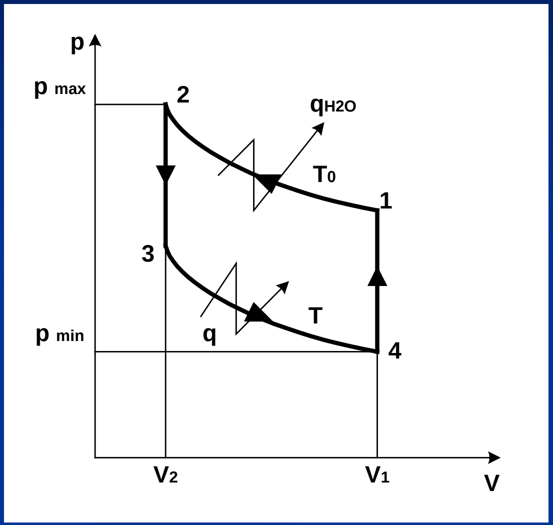


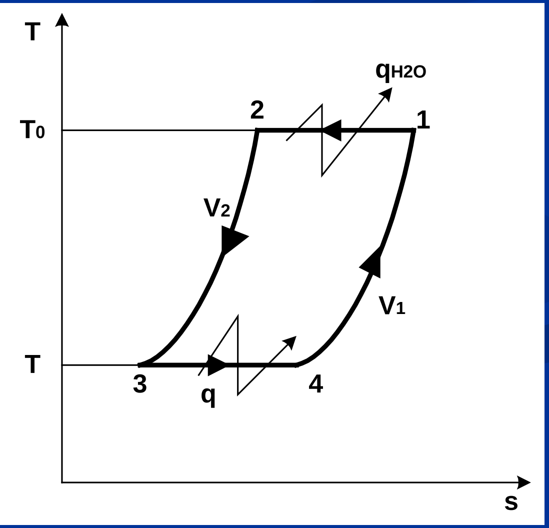
Ceramic magnetic regenerator material (Gd2O2S) (average grain size: 400µm)



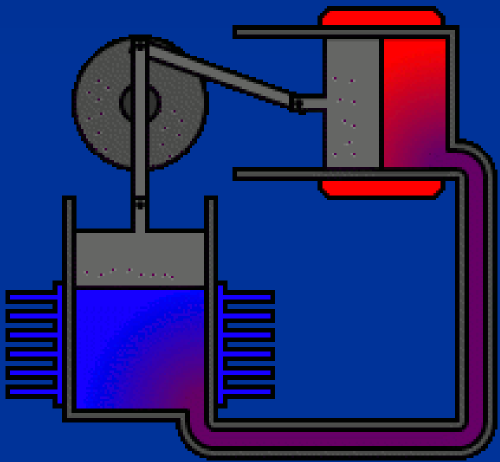
Stirling cryocooler







Stirling cryocoolers

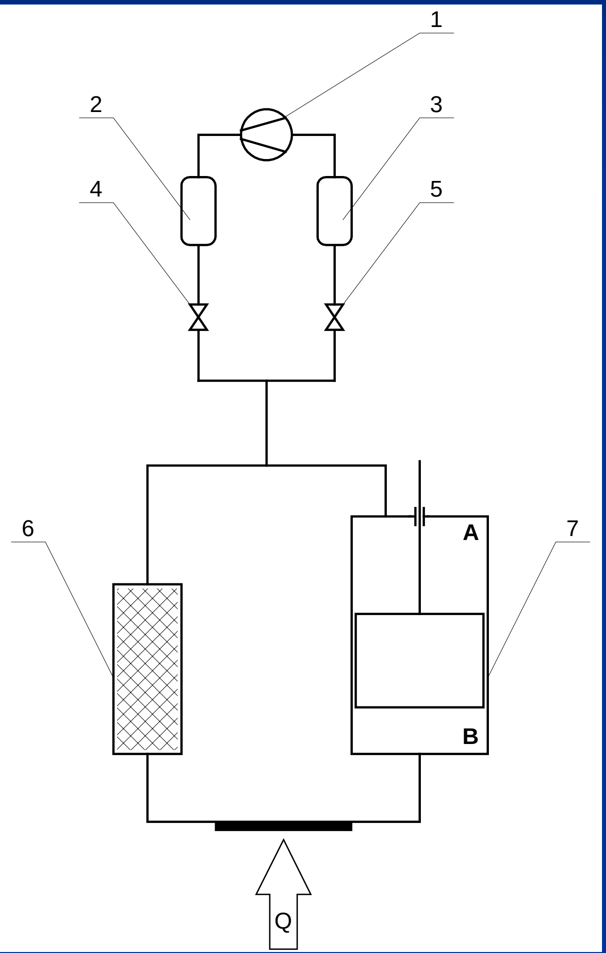


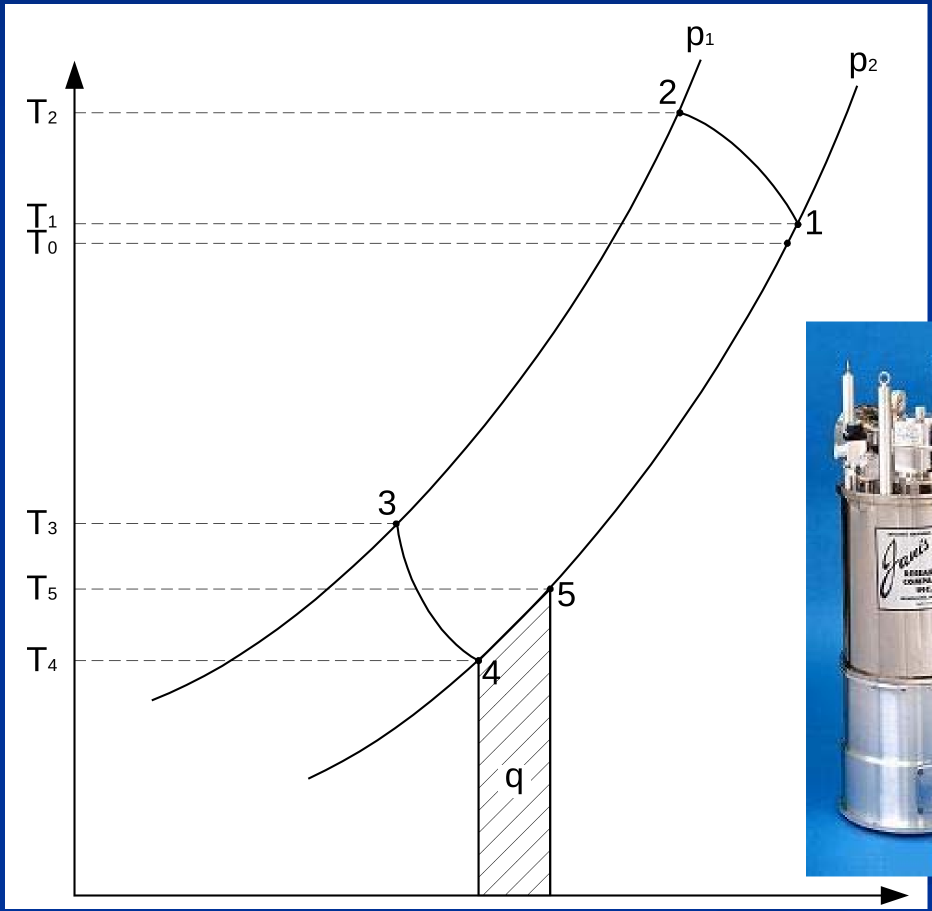
Stirlinga cryocoolers

a) Stirling Cryogenics & Refrigeration BV – liquefaction of gases,

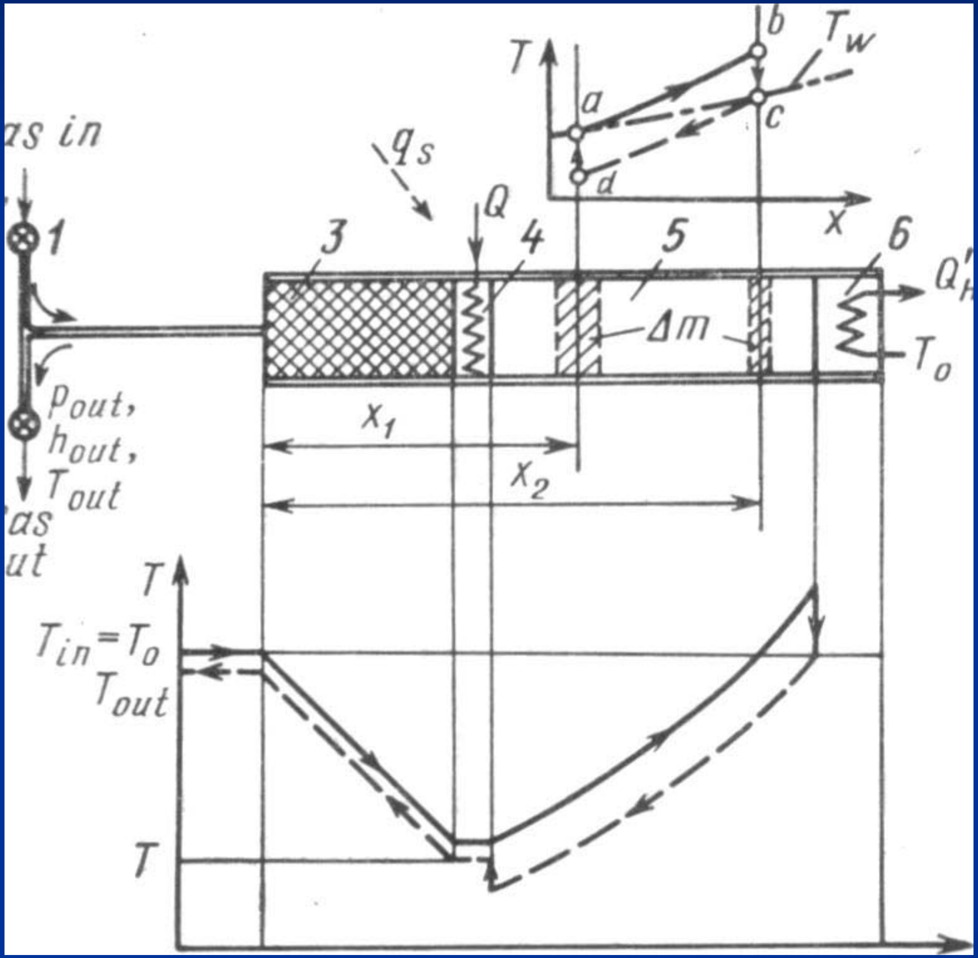
b) Miniature Stirling - 1 W @ 80 K, power consumption 55 W, 2 kg, in cryoelectronics (IR detectors) Janis Research Company.

Gifford McMahon cryocooler free exhaustion process: 3-4





Pulse tube cryocooler

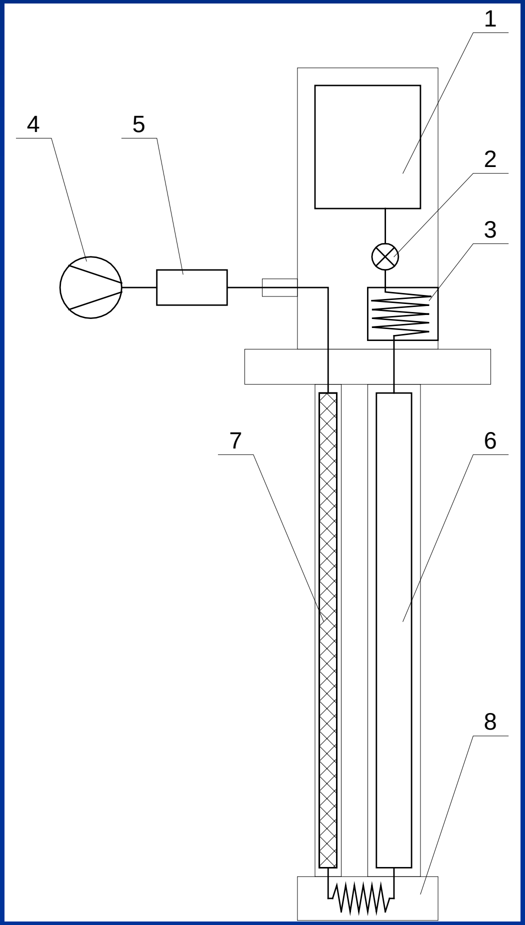


$$Q = Q^{'} - \dot{G}(h_1 - h_2) - Q_s$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} = \left(\frac{x_2}{x_1}\right)^{\frac{\kappa-1}{\kappa}}$$

1 – High pressure line
2 – Low pressure line
3 – Regenerator
4 – Low temperature heat exchanger
5 – Tube free space
6 – High temperature heat exchanger

Pulse tube cryocoolers



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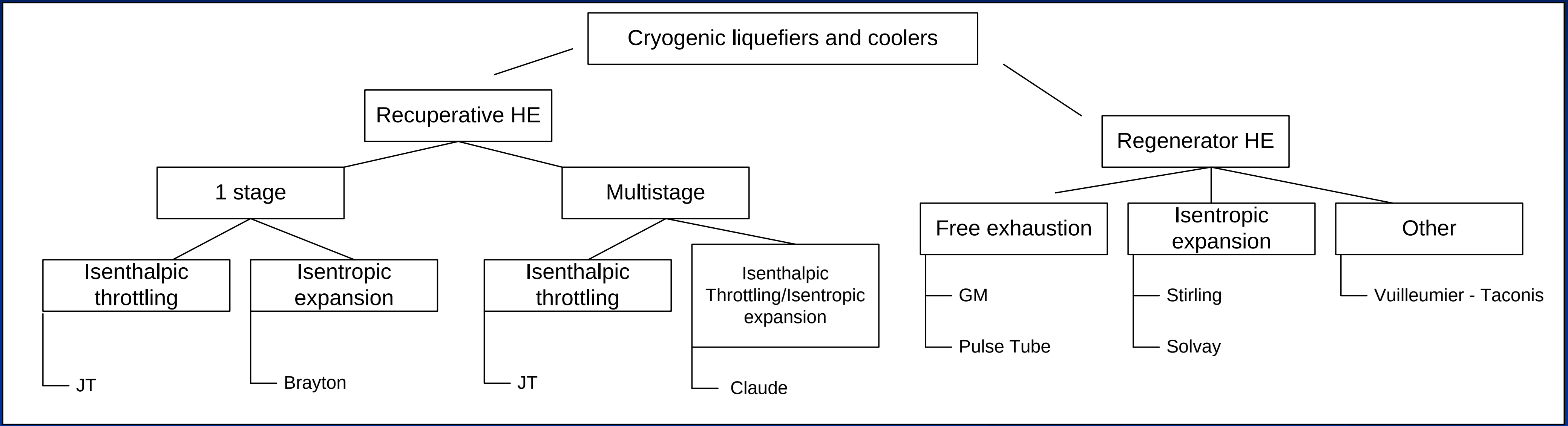
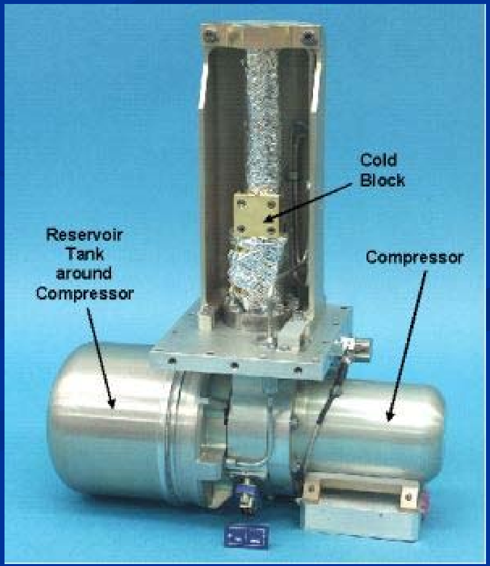
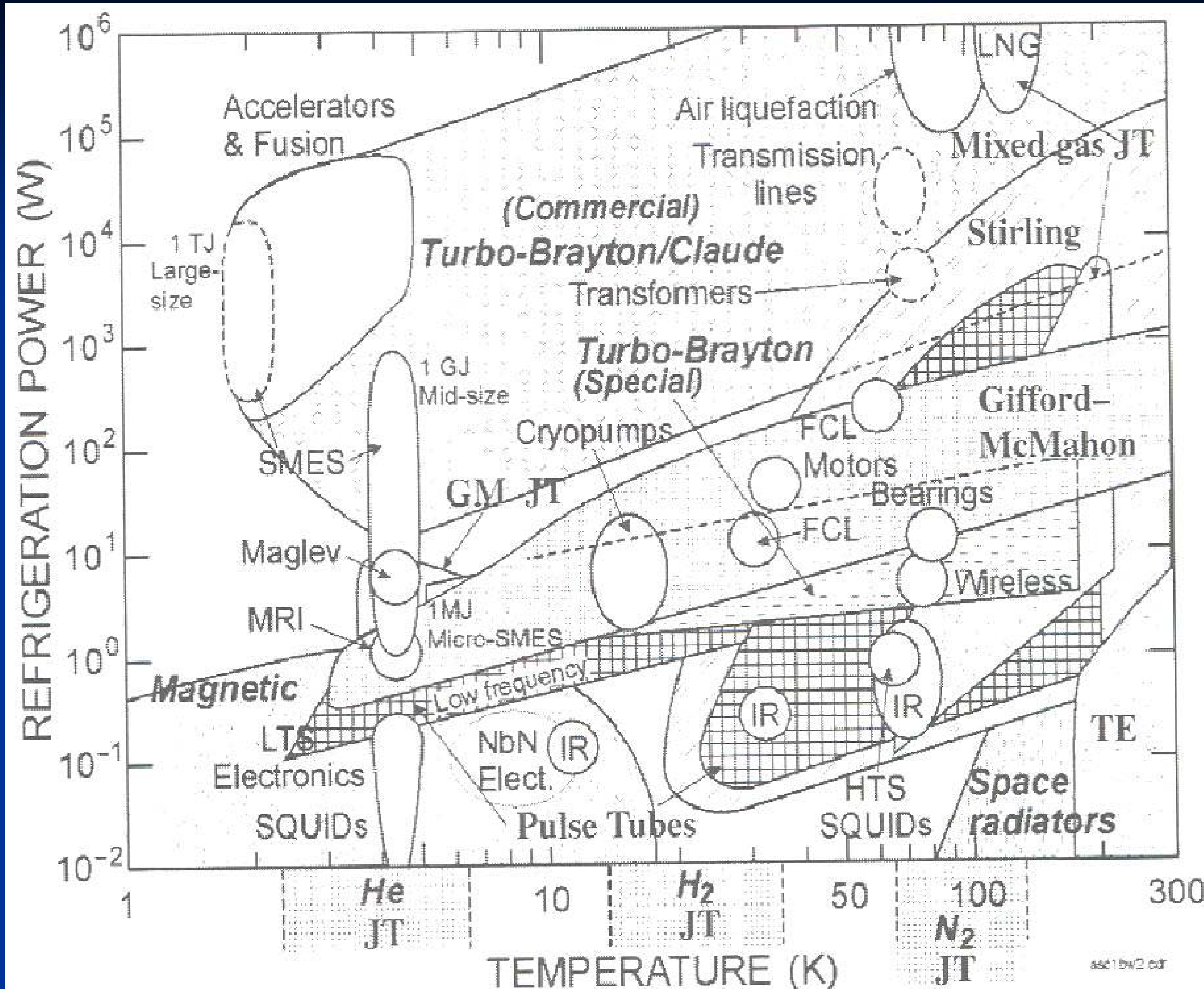
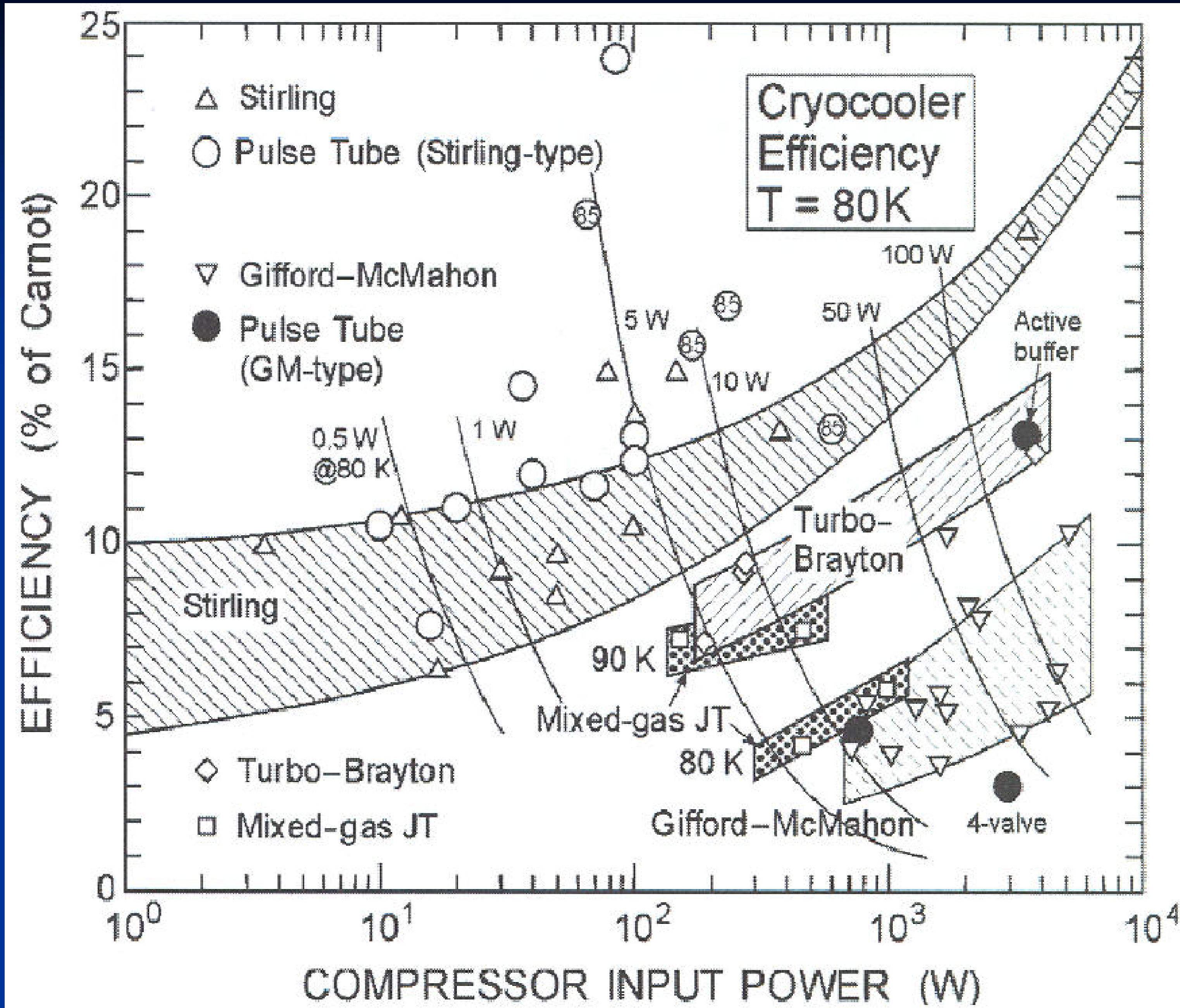
Classification of liquefiers and cryocoolers

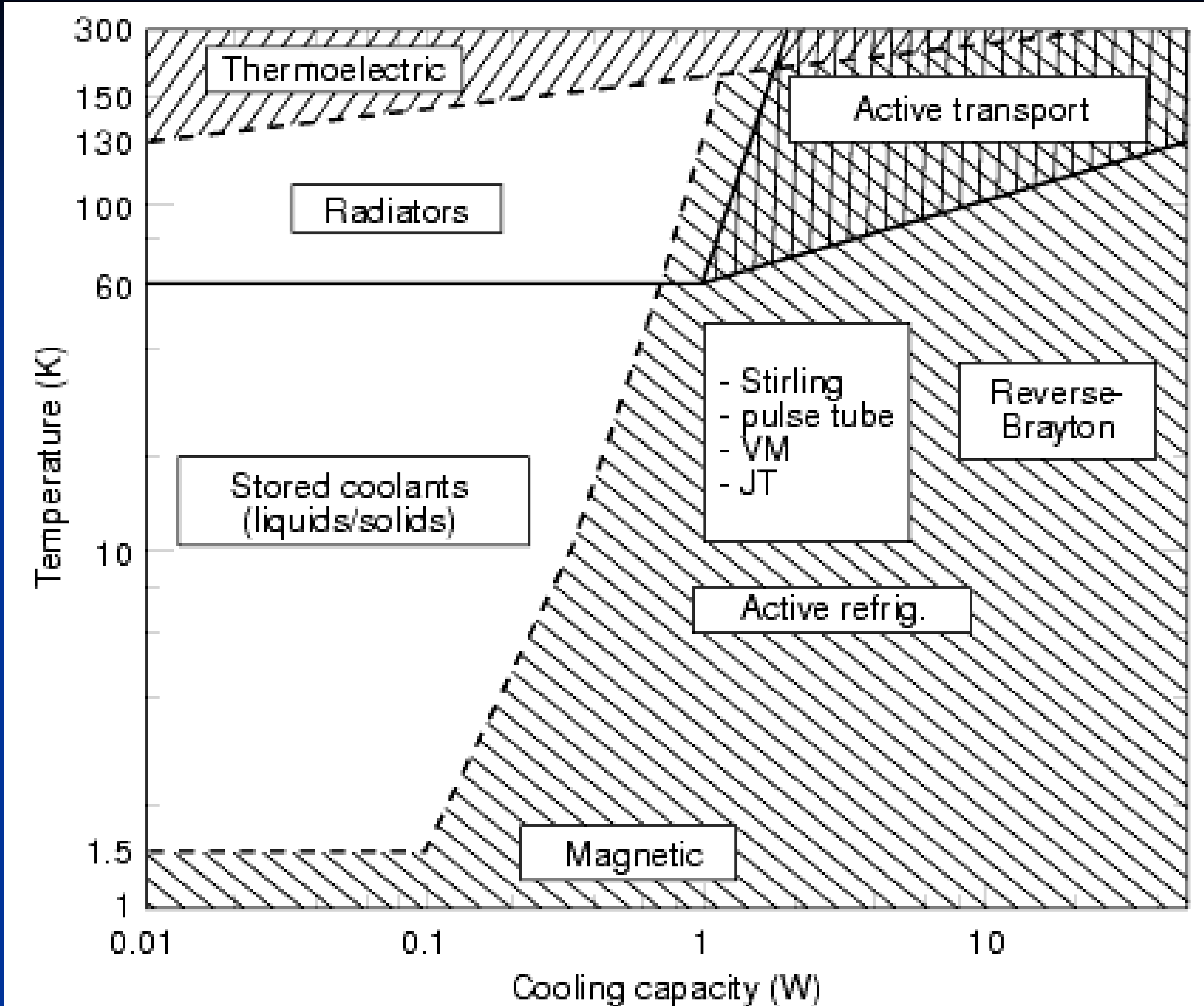



Two Stage Argon / Neon Refrigerator, MMR Technologies, Inc.




REFRIGERATION POWER (W)
TEMPERATURE (K)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
1
10
50
100
300
Accelerators & Fusion
Air liquefaction
LNG
Mixed gas JT
Transmission lines
(Commercial)
Turbo-Brayton/Claude
Stirling
1 TJ Large-size
Transformers
Turbo-Brayton (Special)
1 GJ Mid-size
Cryopumps
FCL
Gifford-McMahon
SMES
GM-JT
Motors
Bearings
FCL
Maglev
Wireless
MRI
1MJ Micro-SMES
Low frequency
Magnetic
IR
IR
LTS
NbN Elect.
IR
TE
Electronics
HTS SQUIDs
Space radiators
SQUIDs
Pulse Tubes
He JT
H_2 JT
N_2 JT


Cryocooler Efficiency T = 80K
Stirling
Pulse Tube (Stirling-type)
Gifford–McMahon
Pulse Tube (GM-type)
Turbo–Brayton
Mixed-gas JT
0.5 W @80 K
1 W
5 W
10 W
50 W
100 W
Active buffer
Turbo-Brayton
90 K
80 K
Mixed-gas JT
Gifford–McMahon
4-valve
EFFICIENCY (% of Carnot)
COMPRESSOR INPUT POWER (W)


300
150
130
100
60
10
1.5
1
0.01
0.1
1
10
Temperature (K)
Cooling capacity (W)
Thermoelectric
Radiators
Active transport
- Stirling
- pulse tube
- VM
- JT
Reverse-Brayton
Stored coolants (liquids/solids)
Active refrig.
Magnetic

Thank you for attention