Lecture 10
Cryocoolers (Part I)

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Goals

- Introduce the characteristics and applications of cryocoolers
- Discuss reculpretive vs. regenerative heat exchangers
- Describe regenerator materials
- Describe the Stirling cycle cryocooler and give examples

Introduction to Cryocoolers

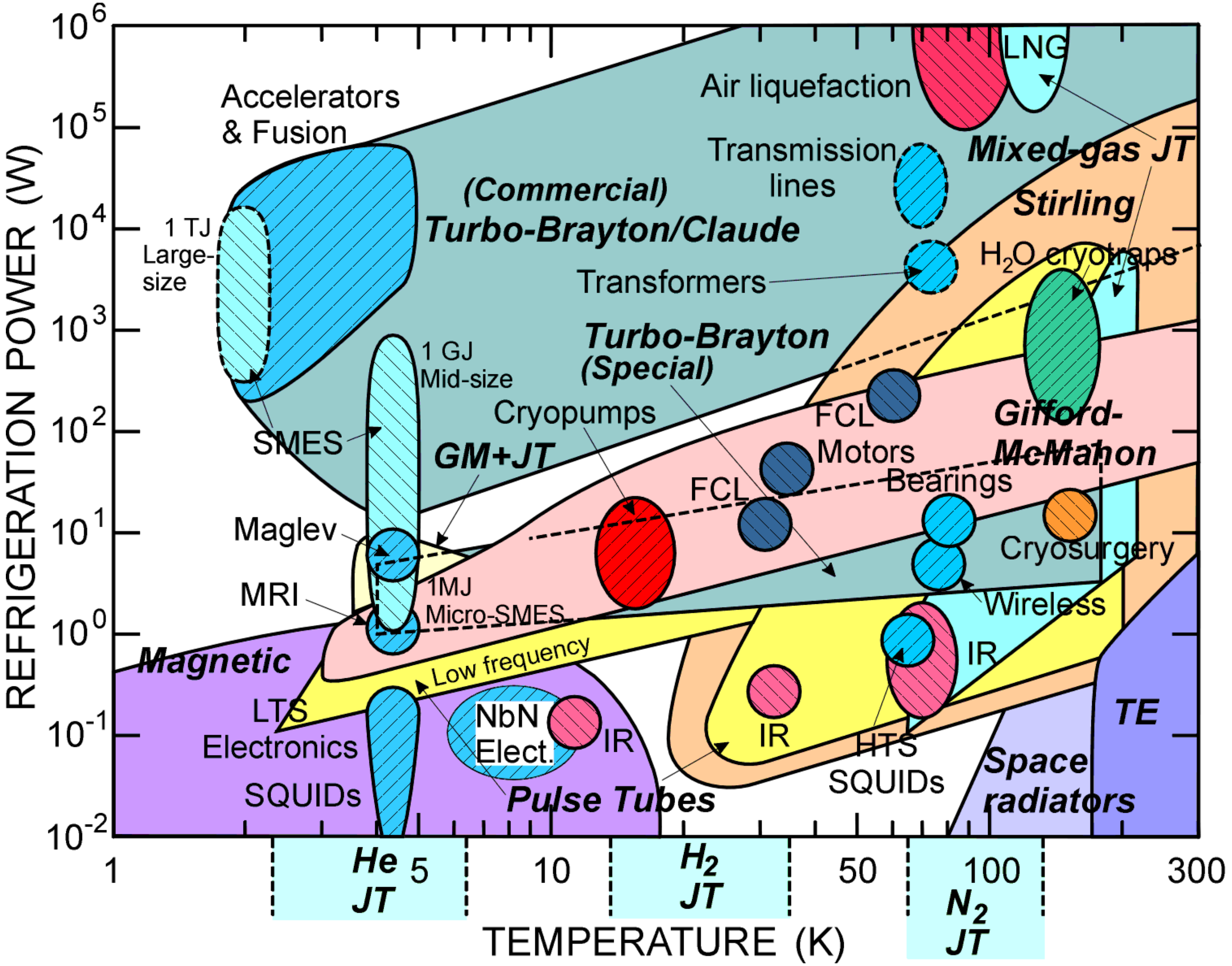
- Cryocoolers are smaller closed cycle mechanical refrigeration systems
  - There is no official upper size for a cryocooler but typically these provide less than few 100 W of cooling at 20 – 100 K and less than 10 W at 4.2 K
  - Cryocoolers do not use the Claude/Collins cycles used by large refrigeration plants but use alternative cycles
  - Working fluid is almost always helium – some exceptions exist
  - All the laws of thermodynamics still apply
  - Improved technology (bearings, miniaturized compressors, better materials, CFD, better reliability etc) has lead to the development of a large number of practical cryocooler designs in the past 10 – 20 years
  - We will concentrate on 3 types: Stirling, Gifford McMahon & Pulse tube

Cryocooler Applications

- Cryocoolers are most useful in applications that:
  - Have smaller heat loads (< 1 kW)
  - Operate above 10 K (though there are significant 4.2 K applications)
  - Require small size, weight, portability or operation in remote locations – space and military applications
  - Are single cryogenic applications within a larger system – reliquefiers for MRI magnets, sample cooling, “cooling at the flip of a switch"

- Application examples
  - Cooling of infrared sensors for night vision, missile guidance, surveillance or astronomy
    - » Much IR astronomy requires < 3 K and thus can’t be met by cryocoolers
  - “Cryogen free” superconducting magnets or SQUID arrays
  - Reliquefing LN_2,LHe or other cryogens
  - Cooling of thermal radiation shields
  - Cooling of HiTc based electronics e.g. microwave filters for cell phone towers
  - Cooling of electronics for superconductivity or low noise (radio astronomy)
  - Cryopumps for high vacuum (down to about 15 K)

Crycooler Types and Applications



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R. Radebaugh

Potential Disadvantages of Cryocoolers

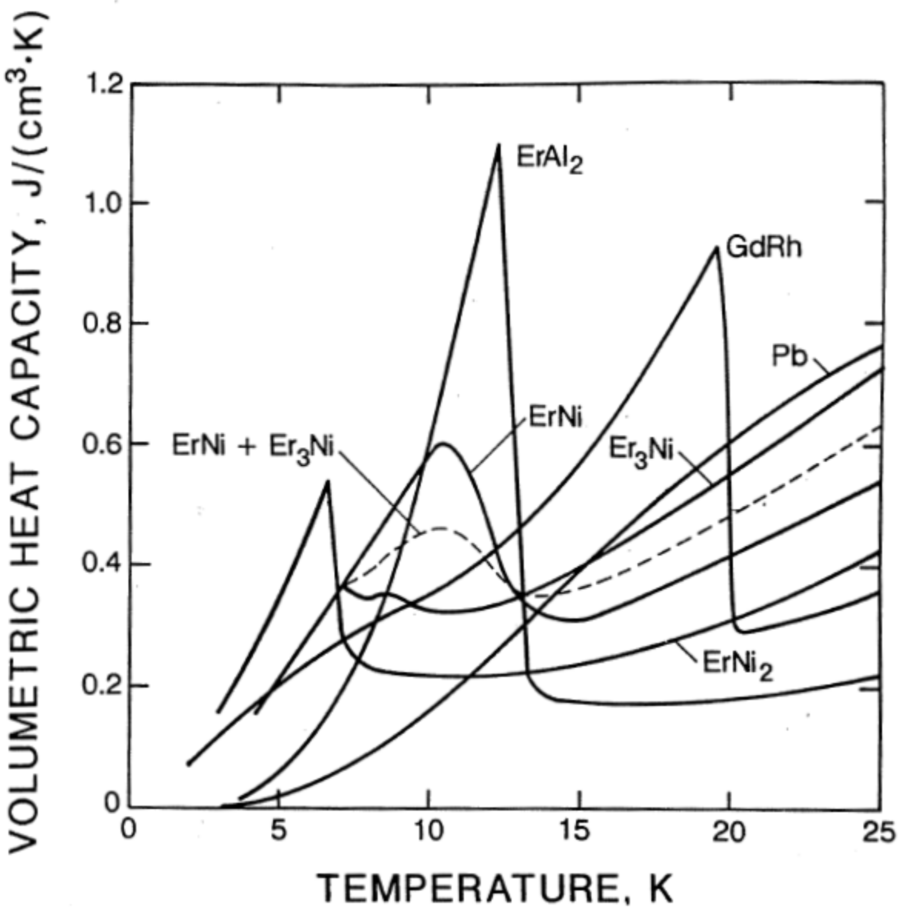
- Smaller capacity at lower temperatures
- Vibrations
- Reliability
- Efficiency
  - Can be as low as 1 % Carnot at 4 K (compared to > 20% for large Collins cycle plants)
- Cost (in particular as compared to bulk liquid)

Recuperative & Regenerative Heat Exchangers

- Recuperative
  - Flows are separated by a wall and only heat is transferred
    - » Plate fin or shell and tube heat exchangers are the most common examples
    - » Very common in large cryogenic refrigerators and in everyday life
    - » Allows continuous flows
- Regenerative
  - Warm and cold flows pass through the same material (known as a regenerator) at different phases of the cycle. The regenerator absorbs the heat from the warm stream and releases it into the cold stream
    - » Very common in cryocooler cycles
    - » Generally results in oscillating flows
    - » Required advances in regenerator materials
- Cycles that use these different types of heat exchangers can be classified at recuperative or regenerative

Regenerators

- Efficient regenerators should
  - Contain a large amount of surface area for heat transfer
    - » Thus are typically made of fines divided wire mesh or spheres
    - » Have a large specific heat over their operating temperatures
    - » Produce a low pressure drop in the working fluid
- Pb, Er and Gd compounds are frequently used as regenerator materials
  - In some designs, the regenerator material is optimized by temperature & position within the regenerator



Stirling Cycle Cryocoolers

- The cryocooler consists of a compressor, regenerator and displacer
- This is an oscillatory cycle
  - frequencies ~ 10 – 60 Hz
- Steps:
  - a-b isothermal compression
    - » Heat rejected to outside
  - b-c regenerative cooling
    - » constant volume expansion
    - » Heat transferred to regenerator
  - c-d isothermal expansion
    - » Heat absorbed from cold sink
  - d-a regenerative heating
    - » constant volume compression
    - » Heat absorbed from regenerator

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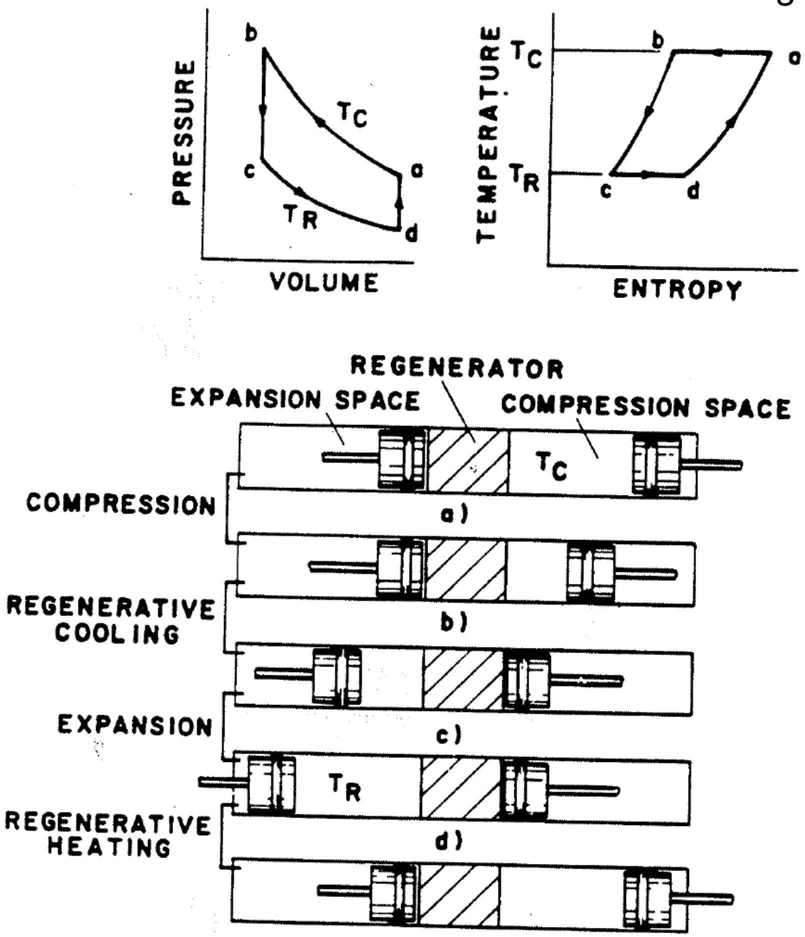


Coefficient of Performance for an ideal Stirling Cryocooler

- Heat rejected to ambient is given by: $Q_r = mT_c(s_b - s_a)$
- Heat absorbed at the cold end is given by: $Q_a = mT_r(s_d - s_c)$
- By the first law $W_{net} = Q_r + Q_a$
- COP = $- Q_a / W_{net}$ or

$$COP = \frac{T_r}{T_c\left({(s_a - s_b)}\big/{(s_d - s_c)} \right) - T_r}$$

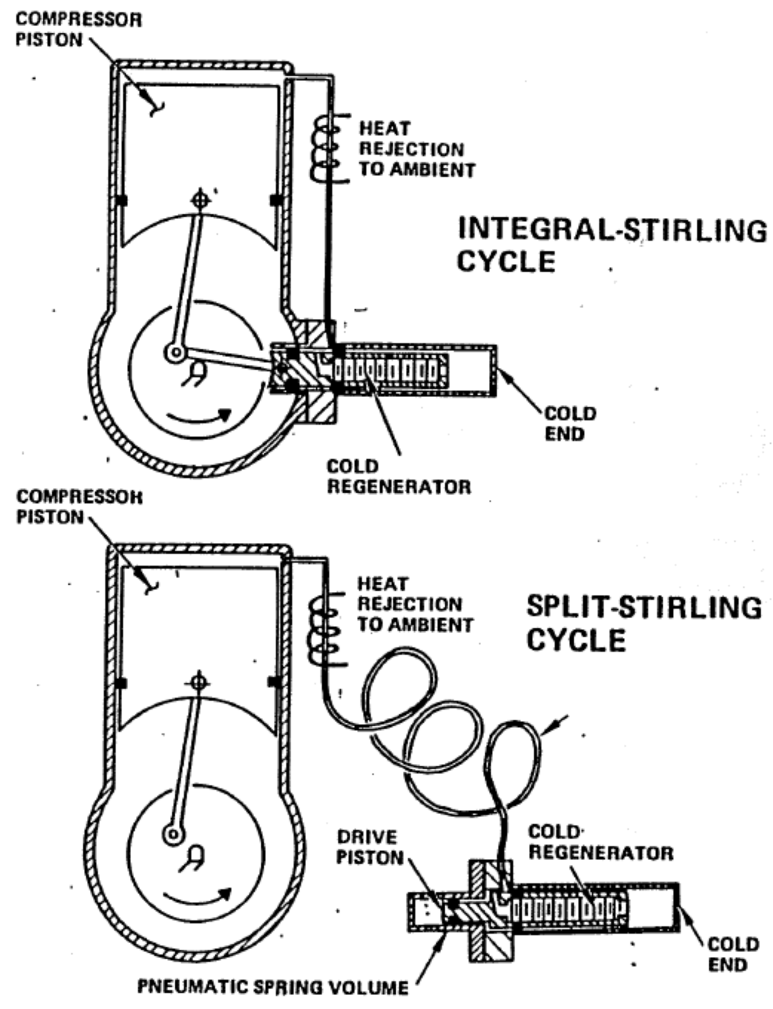
- For an ideal gas, the entropy differences are equal and the Stirling COP equals that of the Carnot cycle : COP = $T_r /(T_c – T_r)$
  - Don't be confused, subscripts here refer to previous slide

Real Stirling Cryocoolers

- In the real world, cryocoolers are not ideal and typical Figures of Merit are more like 30% Carnot or less
- Losses include friction in the compressor motor or displacer, pressure losses in the regenerator and finite temperature differences during heat rejection, absorption and heat transfer within the regenerator.
- Advantages of Stirling cycle cryocoolers include:
  - Relatively high efficiency
  - Small size and weight with the ability to be miniaturized
    - » very important for military and aerospace applications)
  - Moderate cost
  - Large production history - more than 140,000 produced to date

Stirling Crycoolers can be Divided Between Integral and Split

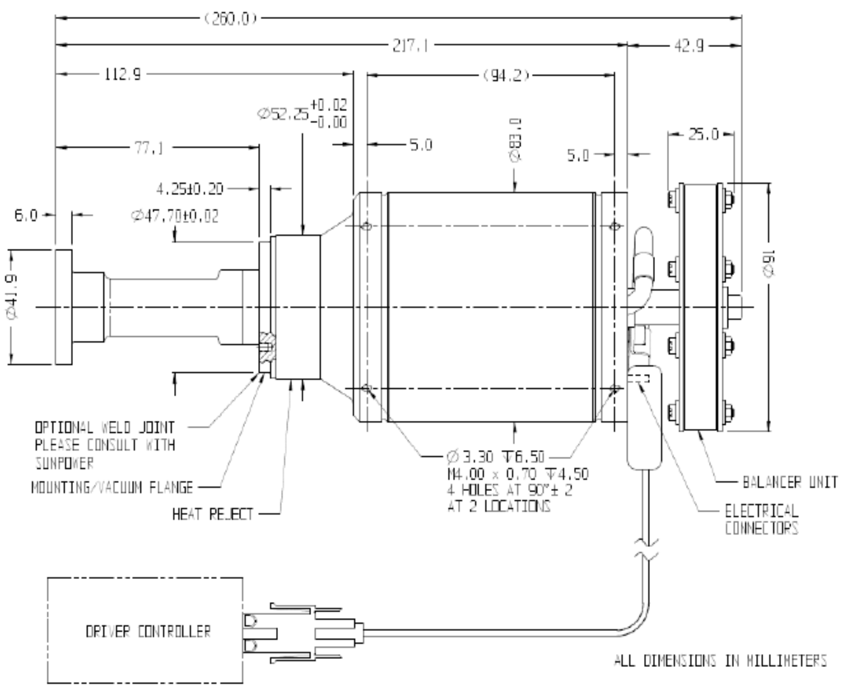
- Integral systems can be made very small
- Split systems separate out compressor vibrations from the cold end
  - However the connecting gas line adds additional frictional losses
- Other developments in Stirling cryocoolers include:
  - Use of linear motors for compressor
  - Development of flexure or gas bearings for moving parts (less chance of contamination & freezing)
  - Advanced regenerator materials



Examples of Stirling Cycle Machines

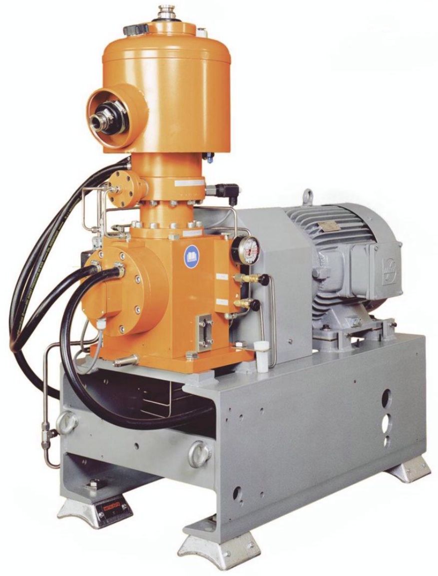
CryoTel® CT

SUNPOWER



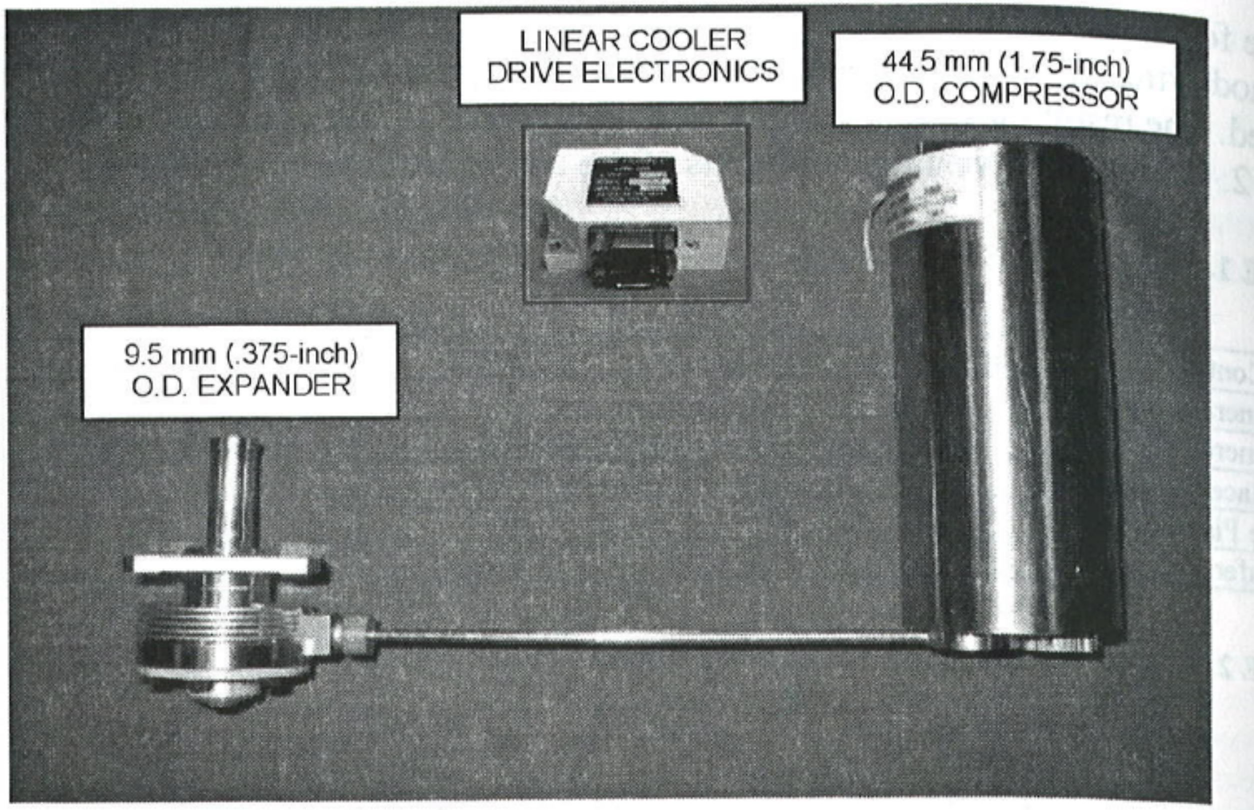
- 10 W @ 77 K
- 3 kg mass
- Nominal input power is 160 W
- Roughly 18% Carnot

Examples of Stirling Cycle Machines



- Model SPC1 produced by Stirling Cryogenics
- Roughly 1 kW capacity @ 80 K
- Requires 11 kW electrical power for 80 K work
  - Roughly 25% Carnot
- Not a miniature system, generally used for reliquefaction of LN_2 or process cooling to LN_2
- 3 were recently ordered to provide reliquefaction of LN_2 as part of the DEAP 3600 experiment at SNOLAB

Examples of Stirling Cycle Machines



From:D.T. Kuo et al. "Performance Optimization of L-3 CE 0.6 W Linear Cryocooler" Adv. Cryo Engr. Vol 53 (2008)

- Miniaturized split Stirling cycle cryocooler for FLIR sensor applications
- 2 W at 80 K capacity, requires 70 W input power ~ 8% Carnot
- Total mass 800 g