Lecture 20
Cryocoolers

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Goals

- Introduce the characteristics and applications of cryocoolers
- Discuss recuperative vs. regenerative heat exchangers
- Describe regenerator materials
- Describe the Stirling cycle, Gifford McMahon and pulse tube cryocoolers 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

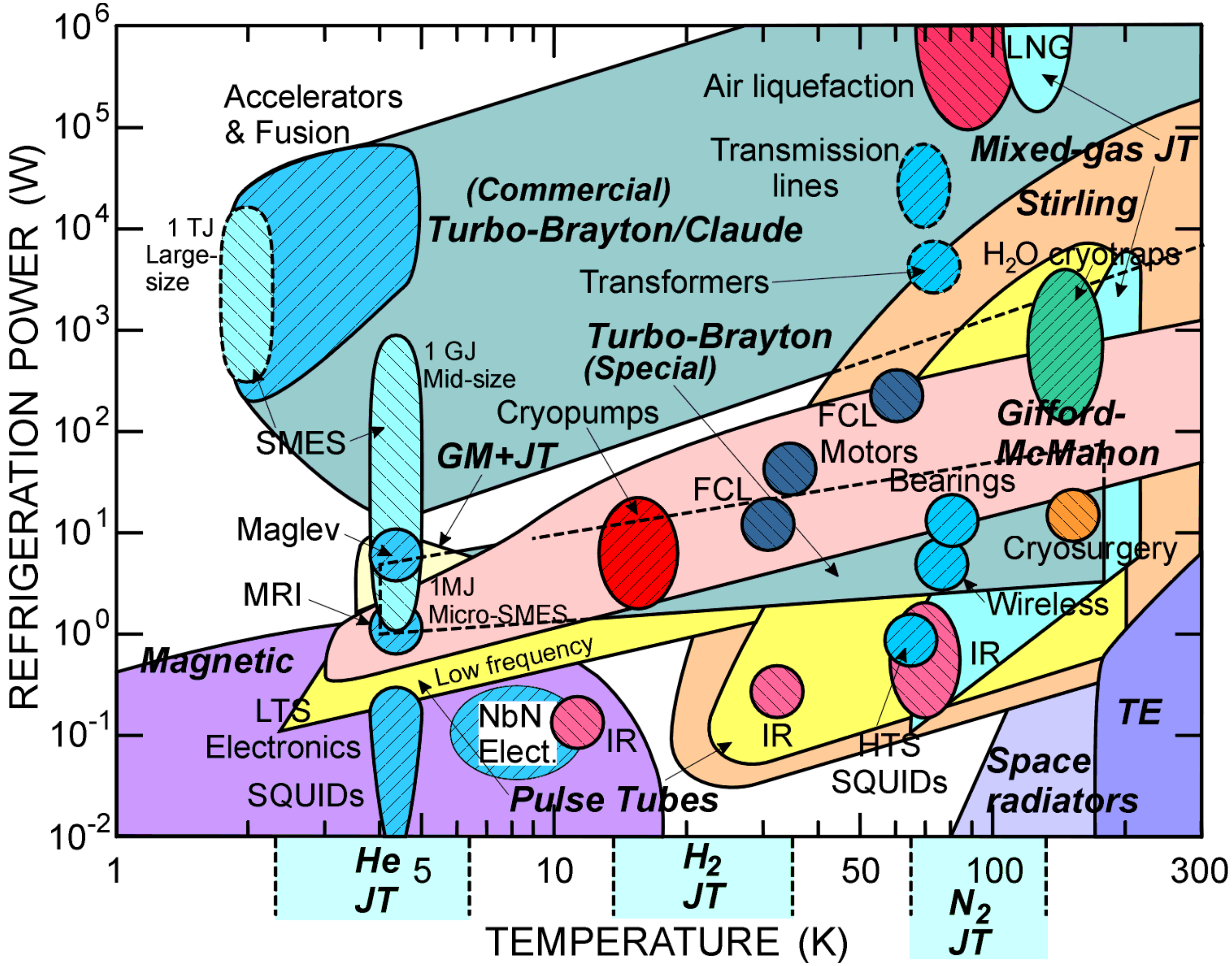
Cryocooler Applications

- 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)
    - Note synergy with HTS operating temperatures
  - 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"

Cryocooler Applications

- 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)
- Becoming more common in accelerator labs for stand alone magnets and experiments

Crycooler Types and Applications



Courtesy
R. Radebaugh

Potential Disadvantages of Cryocoolers

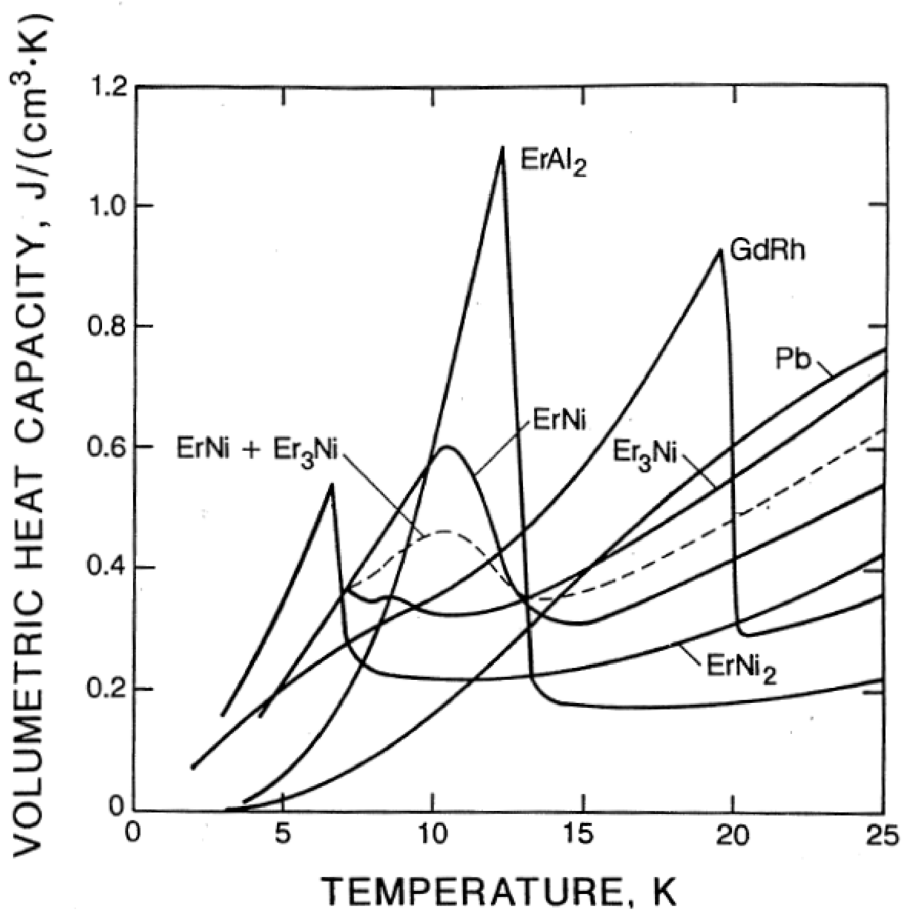
- Smaller capacity at lower temperatures
- Vibrations
- Reliability
- Efficiency
  - Can be as low as 1 % Carnot at 4 K (compared to > 20% for large Collins cycle plants)
- Cost (in particular as compared to bulk liquid)

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

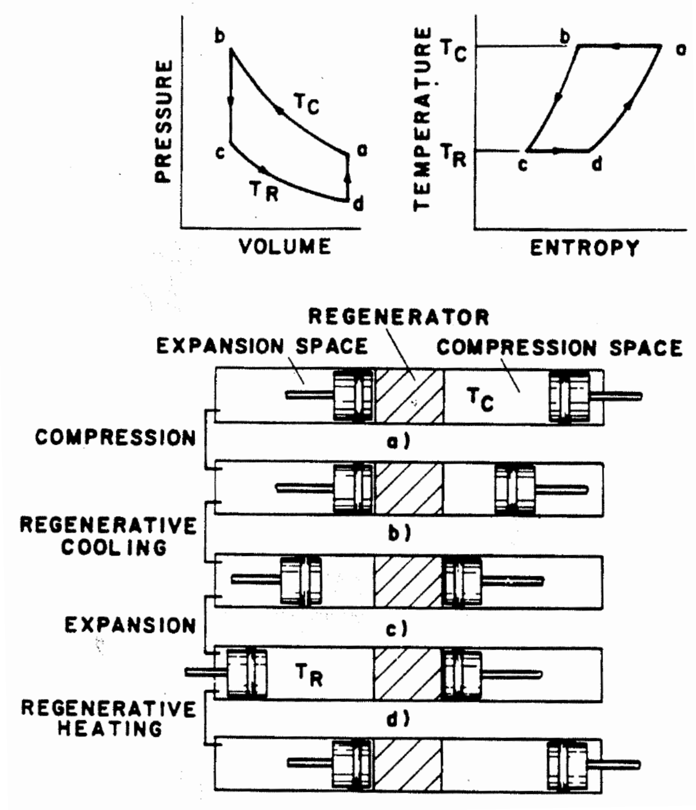
Regenerators

- 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



Courtesy R. Radebaugh

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

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

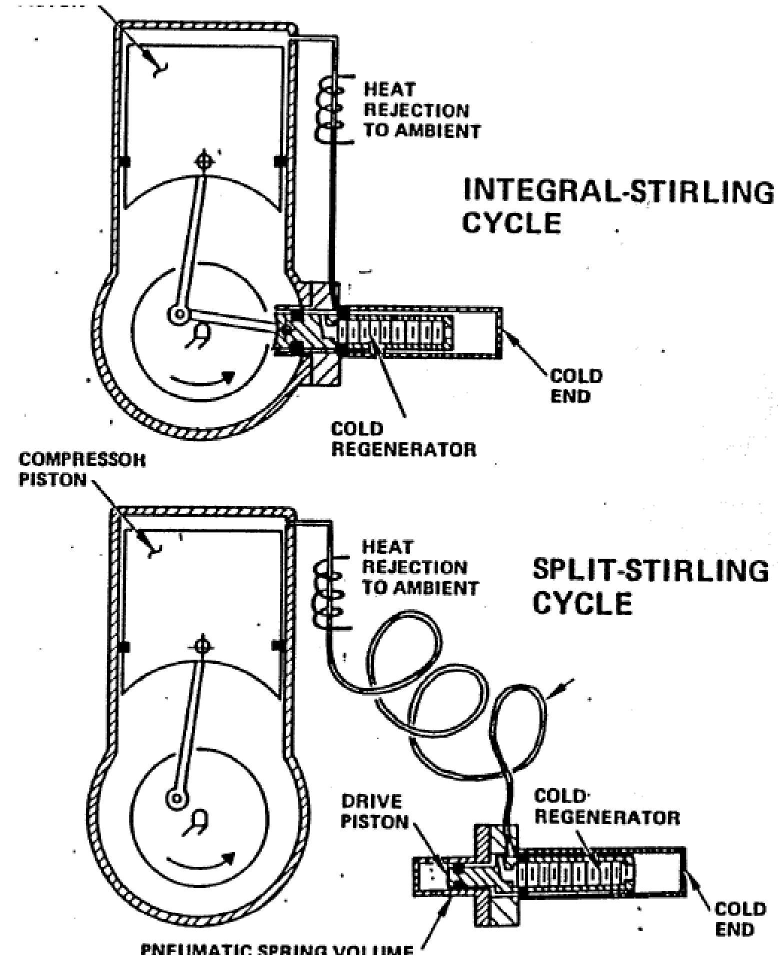
- For an ideal gas, the entropy differences are equal and the Stirling COP equals that of the Carnot cycle : $COP = T_r /(T_c – T_r)$
  - Don't be confused, subscripts here refer to previous slide

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

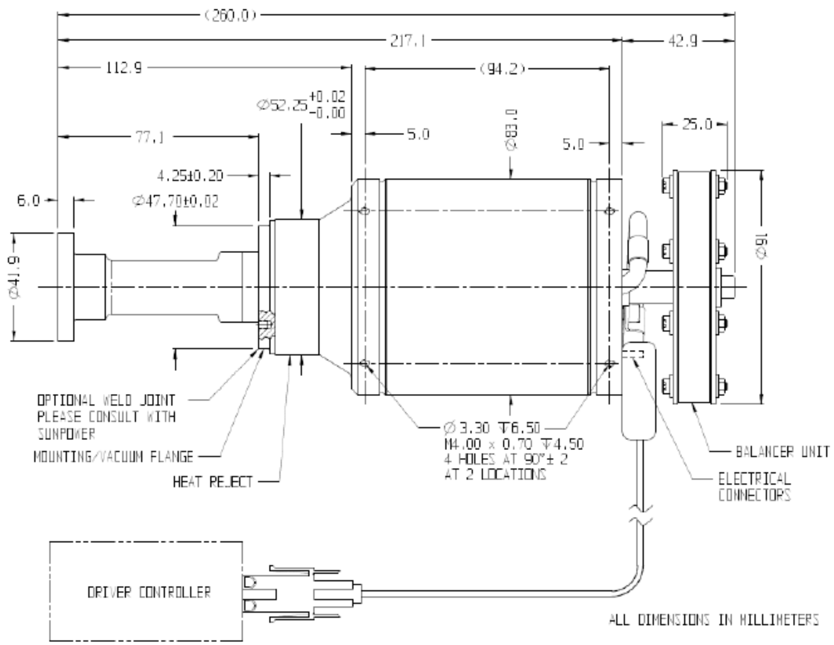
Stirling Crycoolers can be Divided Between Integral and Split

- 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



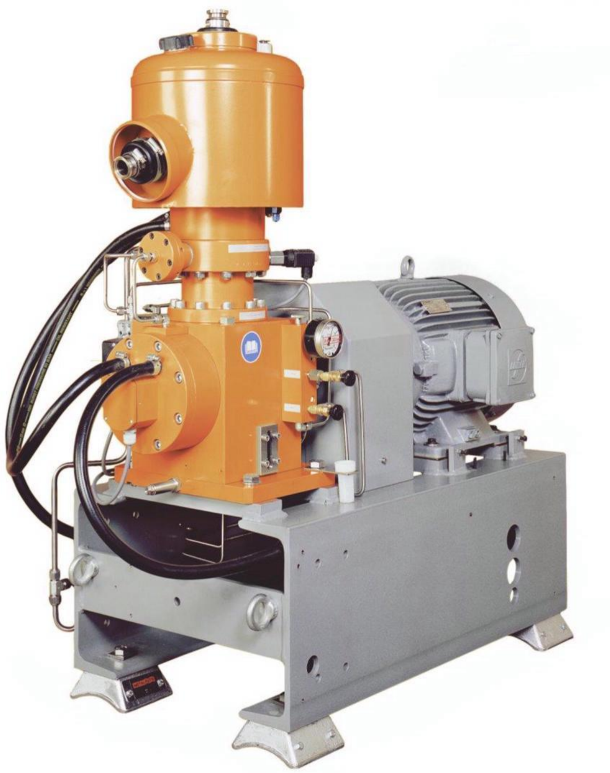
CryoTel® CT

SUNPOWER



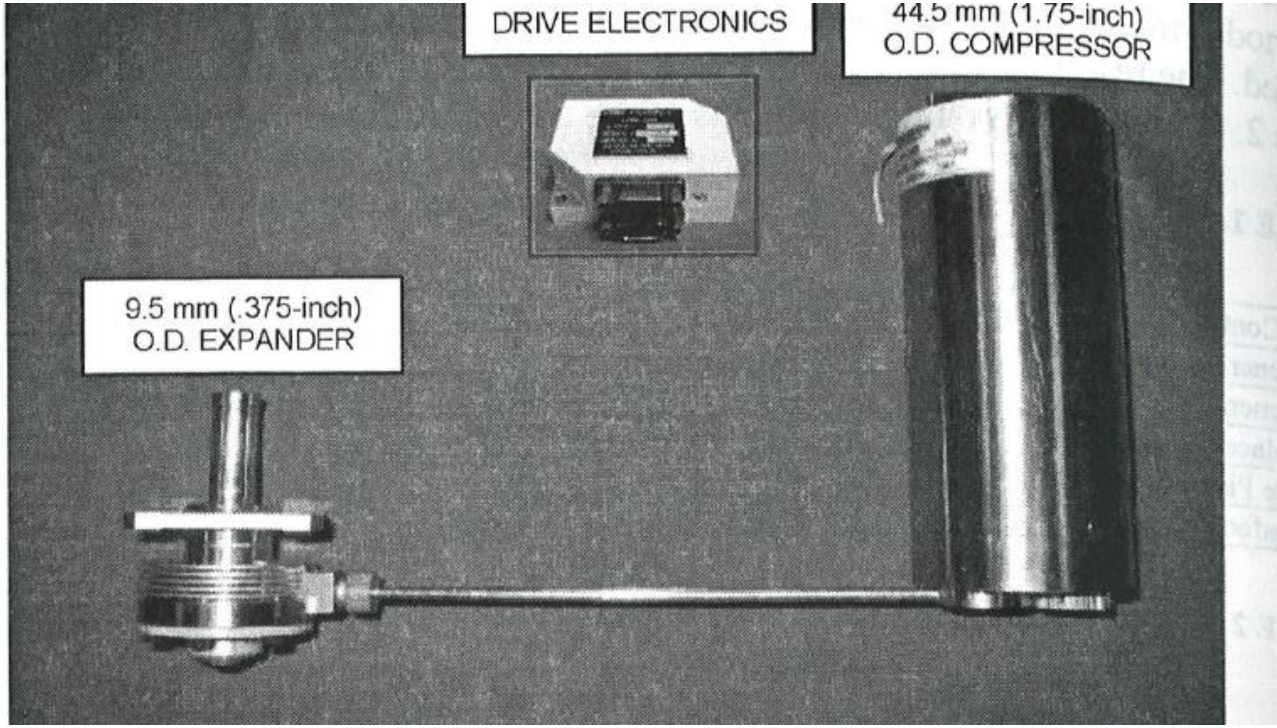
- 10 W @ 77 K
- 3 kg mass
- Nominal input power is 160 W
- Roughly 18% Carnot

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 currently provide reliquefaction of LN_2 as part of the DEAP 3600 experiment at SNOLAB

Examples of Stirling Cycle Machines



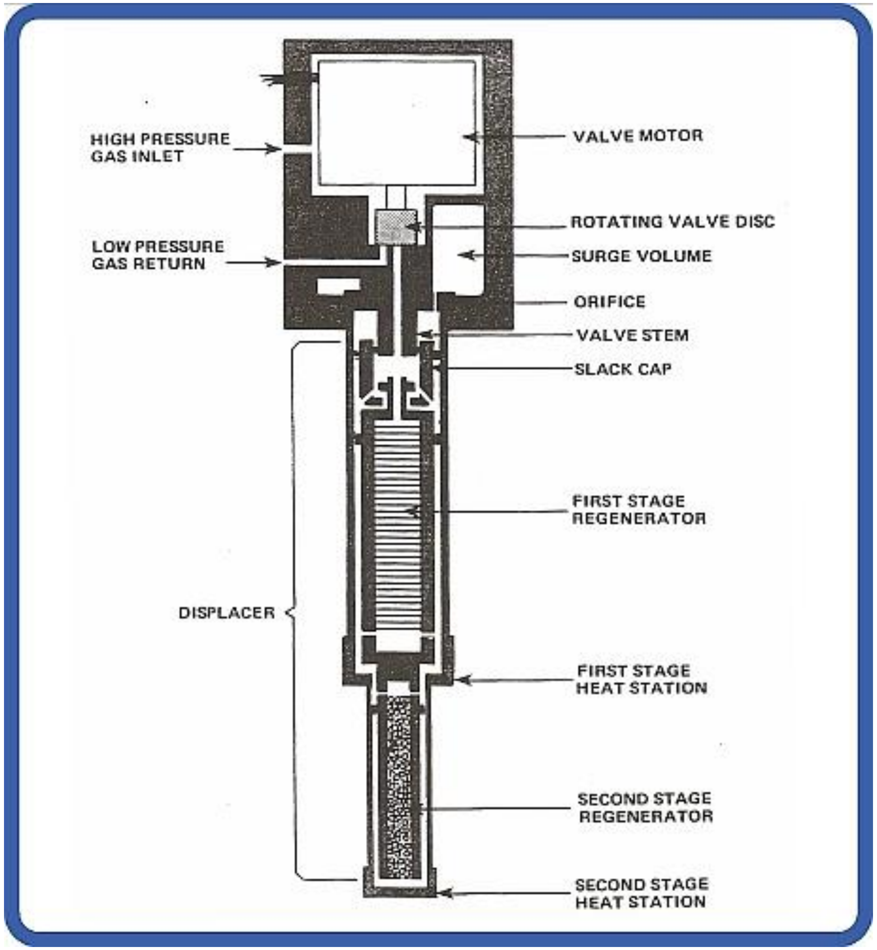
From:D.T. Kuo et al. "Performance Optimization of L-3 CE 0.6 W Linear Cryocooler" Adv. Cryo Engr. Vol 53 (2008)

- 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

Gifford-McMahon Cryocoolers

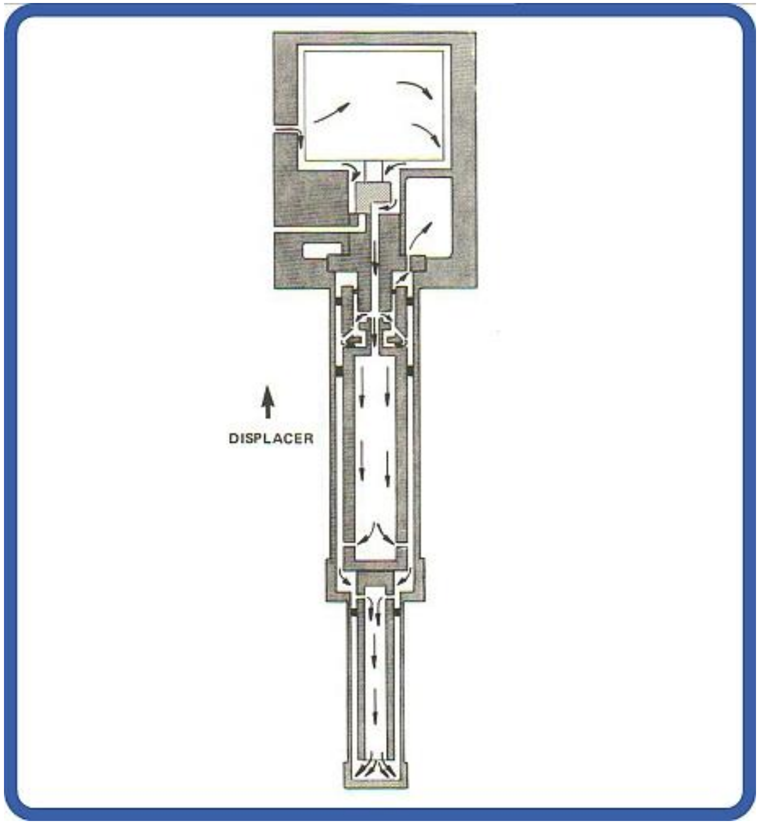
- Similar in many ways to a Stirling Cycle
- Displacer is moved not by a mechanical device but rather by differential gas pressure
- Only two moving cold parts: displacer and rotary valve
- Use of the valve allows high pressure to be generated by a commercial compressor with an oil removal system
  - Lower cost
  - More reliable
- Design of GM cryocoolers results in more robust but larger systems
- GM Cryocoolers can easily be designed with multiple cooling stages at different temperatures

Example of a GM Cryocooler (Advanced Research Systems)

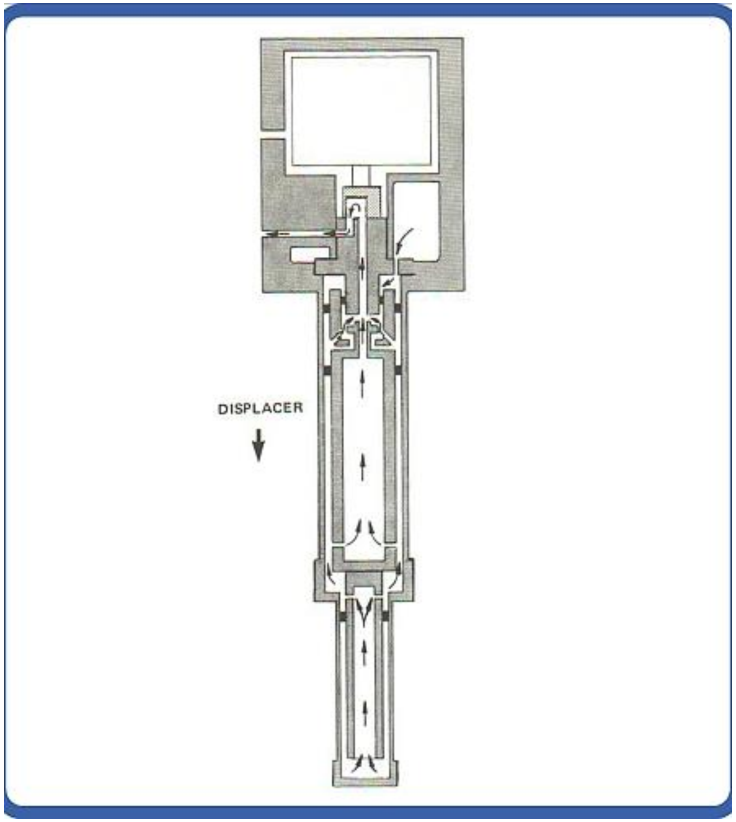


- Typical Uses
  - Cryopumping (15 K)
  - MRI Magnet Shield Cooling (~50 K)
  - MRI Magnet Reliquefiers (4 K)
  - HTS electronics (~ 60 K)

GM Cryocooler Operation



Steps 1 & 2
- High Pressure In
- Expansion



Steps 3 & 4
- Low Pressure Out
- Displacer move down

Examples of GM Cryocoolers

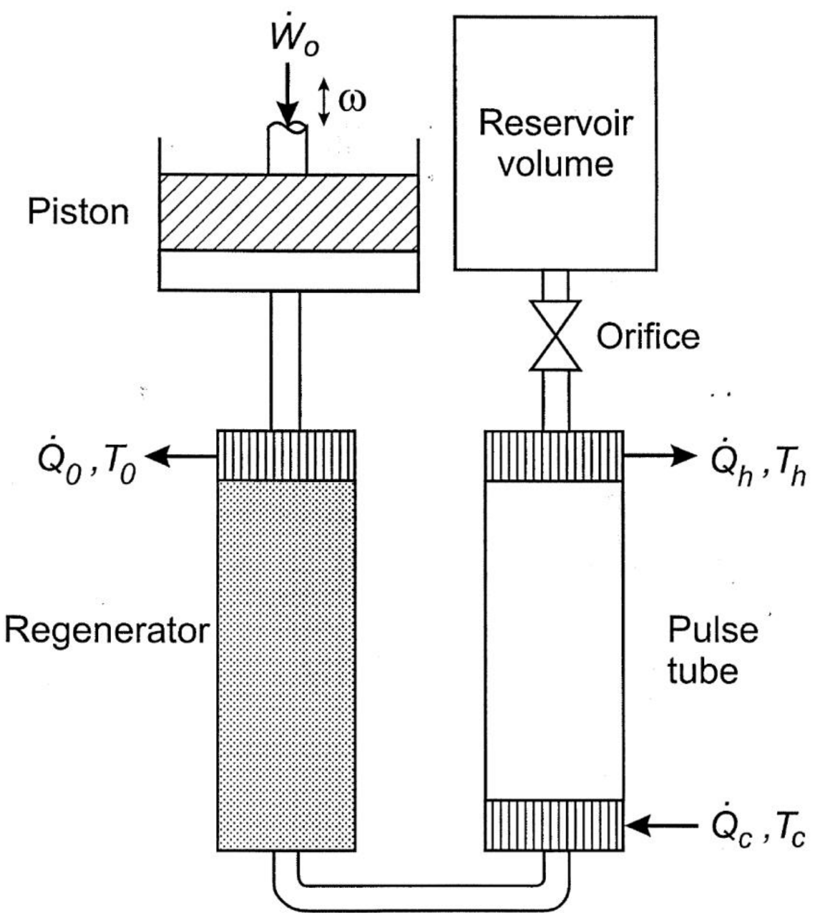
Sumitomo
35 W @ 50 K
1.5 W @ 4.2 K
18 kg

CryoMech
60 W @ 80 K

Displacers & Pulse Tube Cryocoolers

- GM and Stirling cycle cryocoolers using oscillating flows at 1 – 100 Hz
- The cold displacer plays an important role in these devices
  - Separate the heating and cooling effects of the cycle by placing the motion of the gas in proper phase with the pressure oscillations
  - Little pressure difference across the displacer but a large temperature difference
- However the cold displacer leads to a number of problems
  - Moving cold part leads to reliability problems and increased vibration at cold end
  - Axial heat conduction through the displacer leads to cycle inefficiencies
- What if we could eliminate the displacer ?

Pulse Tube Cryocoolers



- The gas in the pulse tube in effect replaces the displacer
- The pulse tube must be large enough so that the gas in cold end never reaches the warm end and gas in cold end never reaches the warm end
  - Thus gas in the middle of tube never leaves the tube and acts as an thermal insulator
  - Turbulence & mixing must be minimized
  - From this simple design there are many variations of pulse tube cryocoolers

Advantages of Pulse Tube Cryocoolers

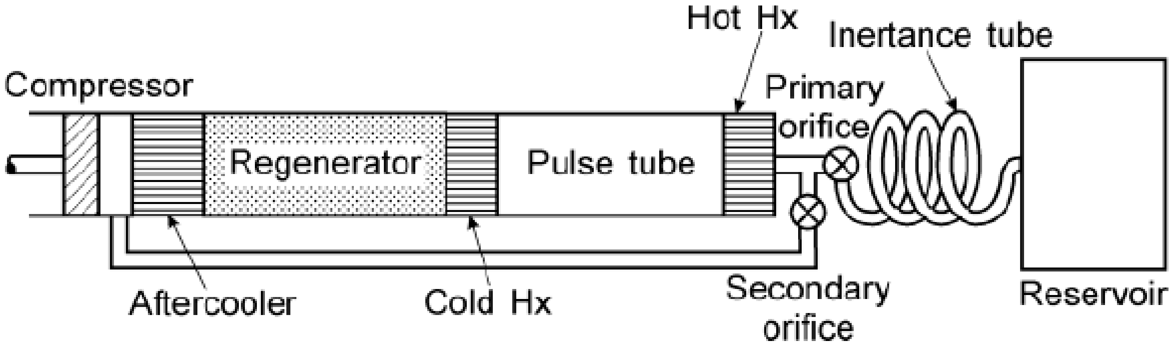
- High reliability (fewer cold moving parts)
- Lower cost
- Low vibration
- Higher efficiency
- Ability to work at all temperature levels
- Can be "space qualified"
- These advantages and the fact that there is still much to learn about pulse tubes make this a very active area of research
  - Roughly 10% of all the papers at the 2009 Cryogenic Engineering Conference dealt with pulse tube cryocoolers
- Commercial versions of pulse tube cryocoolers are available

Losses in Pulse Tube Cryocoolers

- Regenerator inefficiency (generally the largest single loss)
- Losses within the pulse tube itself
  - Heat transfer between gas and tube wall
  - Mixing of warm and cold gas segments
  - Circulation of gas within the pulse tube due to oscillating pressures (acoustic streaming)

Types of Pulse Tube Cryocoolers

- Double Inlet
  - Roughly 10% of the flow is bypassed around the regenerator and used to pressurize the reservoir
  - Reduces losses in the regenerator
  - Increases overall efficiency particularly at higher frequency operations
  - Presence of inertance tube (also used on other styles of PT cryocoolers) helps put the flow and pressure oscillations into a phase relationship that optimizes efficiency



Thermoacoustic Drivers

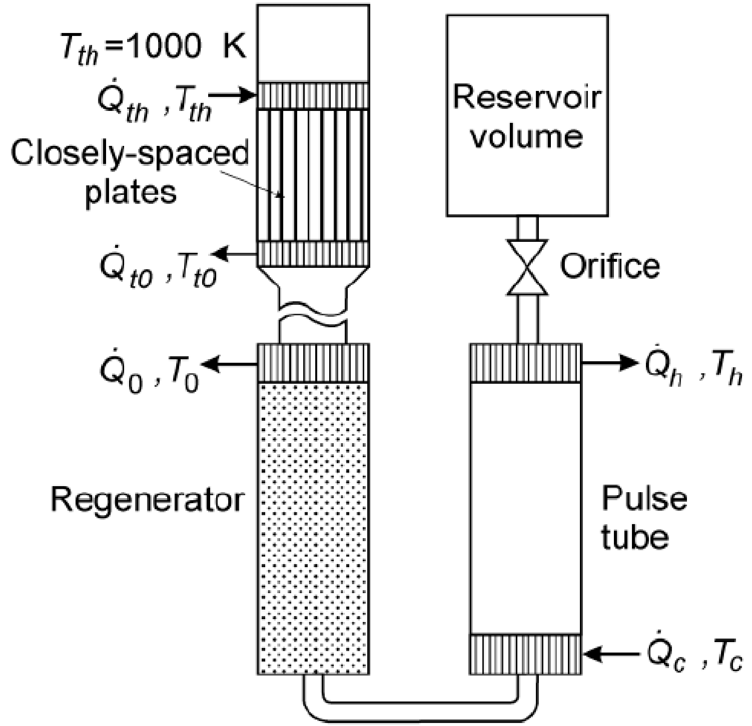
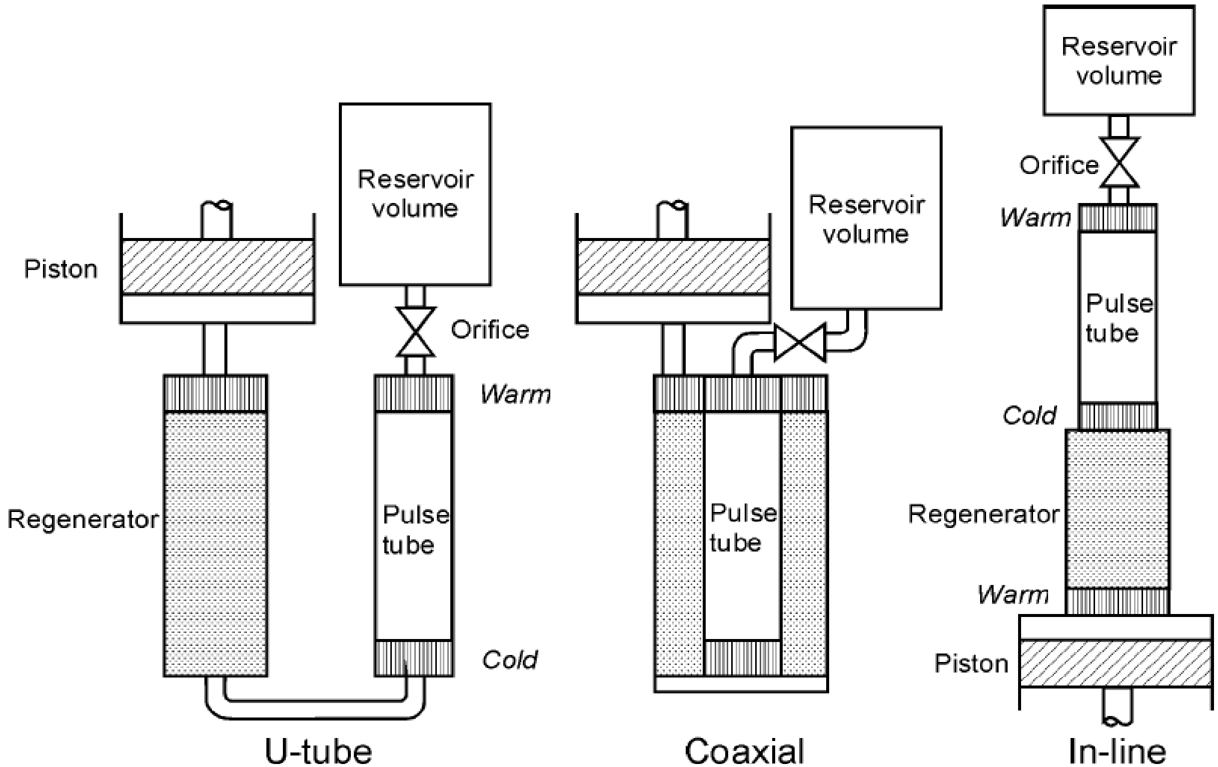


Figure 5. Schematic of ThermoAcoustically Driven Orifice Pulse Tube Refrigerator (TADOPTR)

- Can result in cryocoolers with no moving parts
- Generally only used in very large scale systems

R. Radebaugh – NIST

Different Geometries of Pulse Tube Cryocoolers



Frequently used to separate compressor vibration from the cold head

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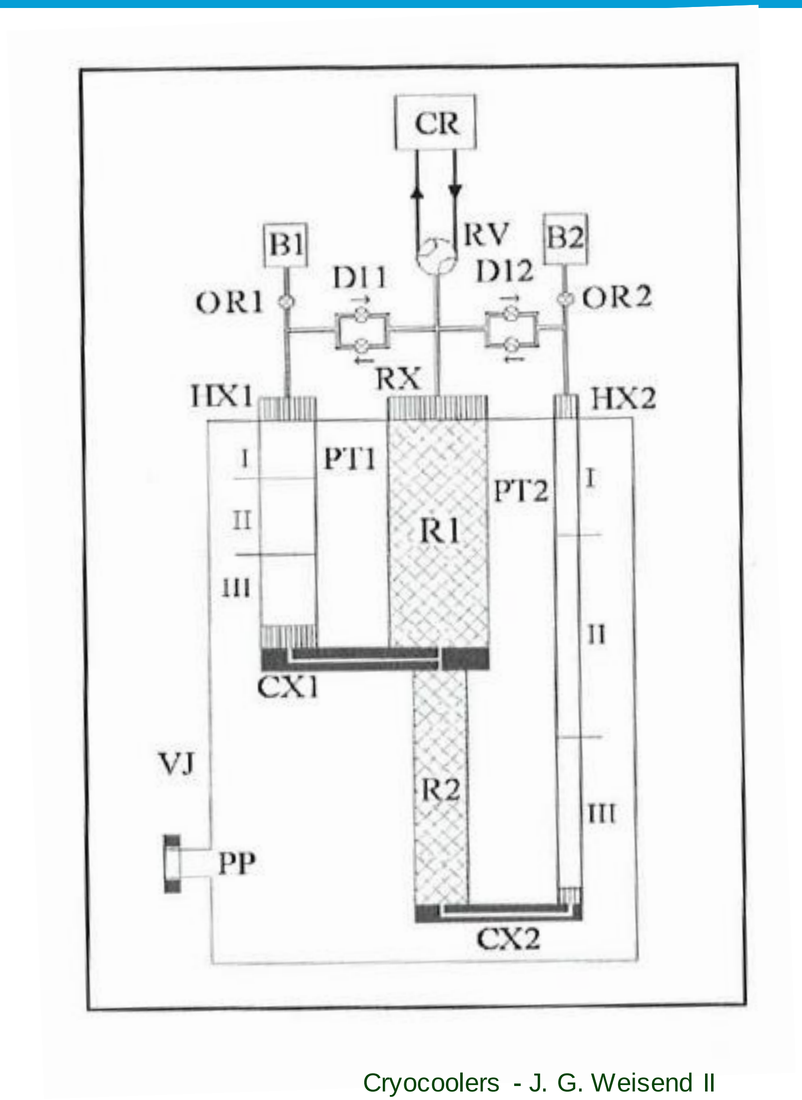
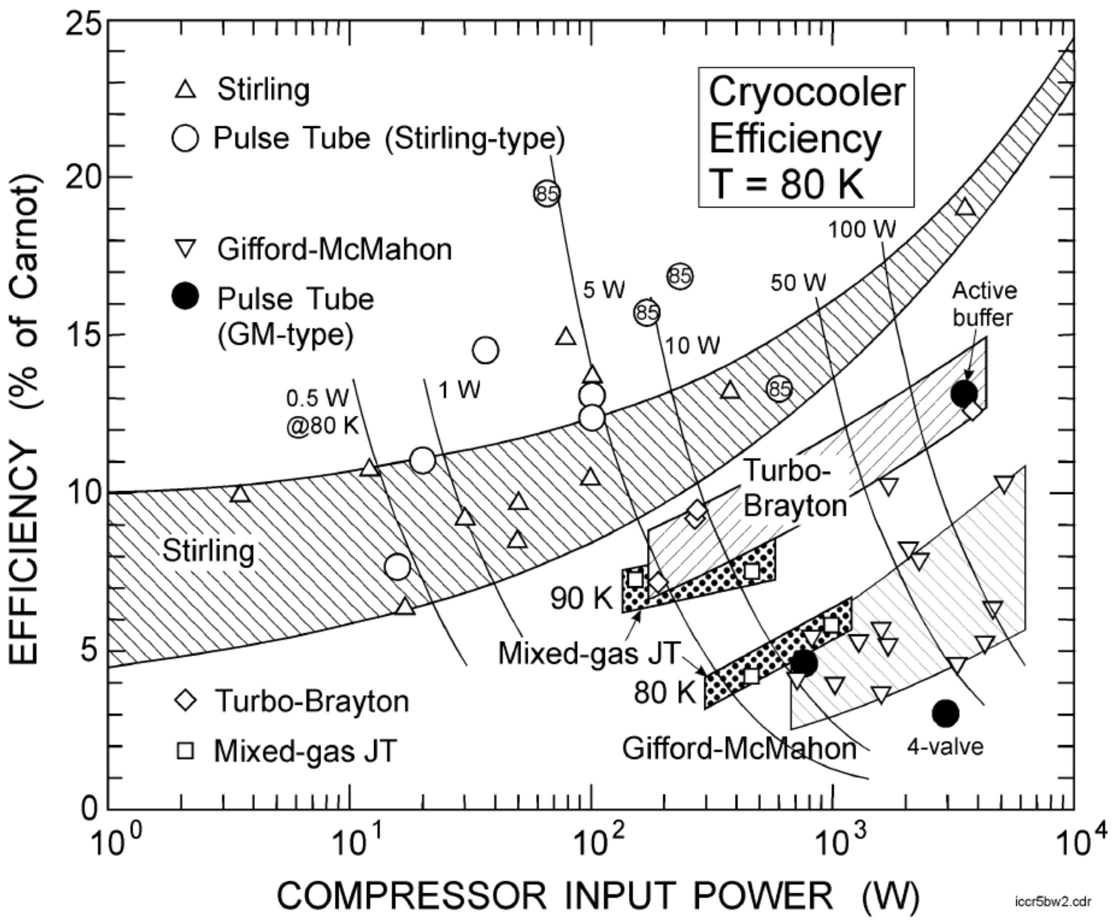
Multistage Cryocoolers Are Also Common



From Kasthurirengen et al Proc. ICEC 22 (2009)

Pulse Tube and other Cryocooler % Carnot at 80 K



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Pulse Tube Cryocoolers
Commercially Available Examples

- CryoMech PT810
  - 14 W @ 20 K
  - 80 W @ 80 K

- CryoMech PT415
  - 40 W @ 45 K
  - 1.5 W @4.2 K

Pulse Tube Cryocoolers Commercially Available Examples

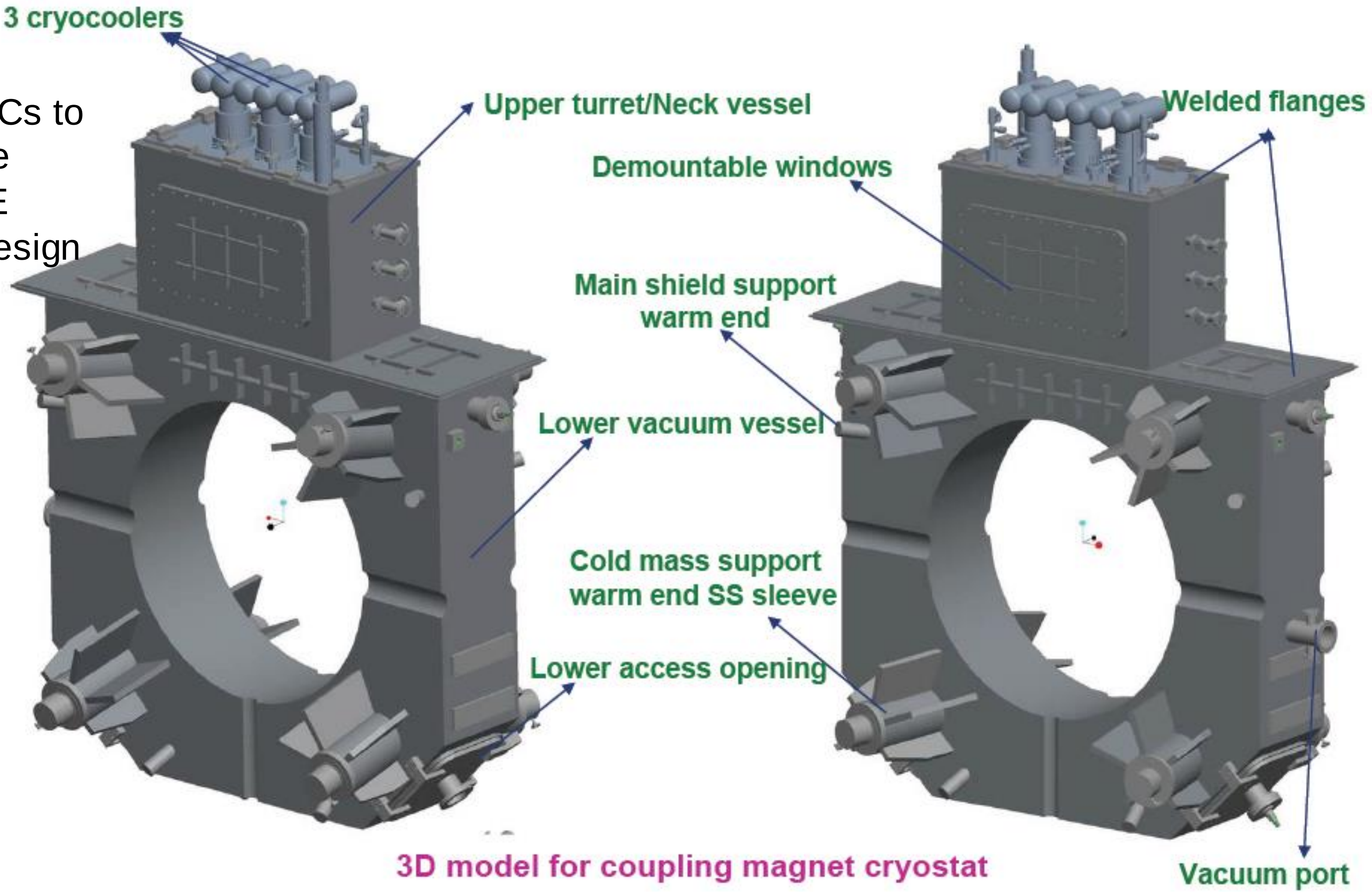
- SHI Cryogenics SRP-062B
  - 30 W @ 65 K
  - 0.5 W @ 4.2 K
  - 6.5 kW power input

- Sierra Lobo
  - 4 W @ 65 K
  - 4 W @ 20 K
  - Can be used for Zero Boil Off Propellant Storage

Example of Pulse Tube Cryocoolers in Accelerators (MICE experiment)

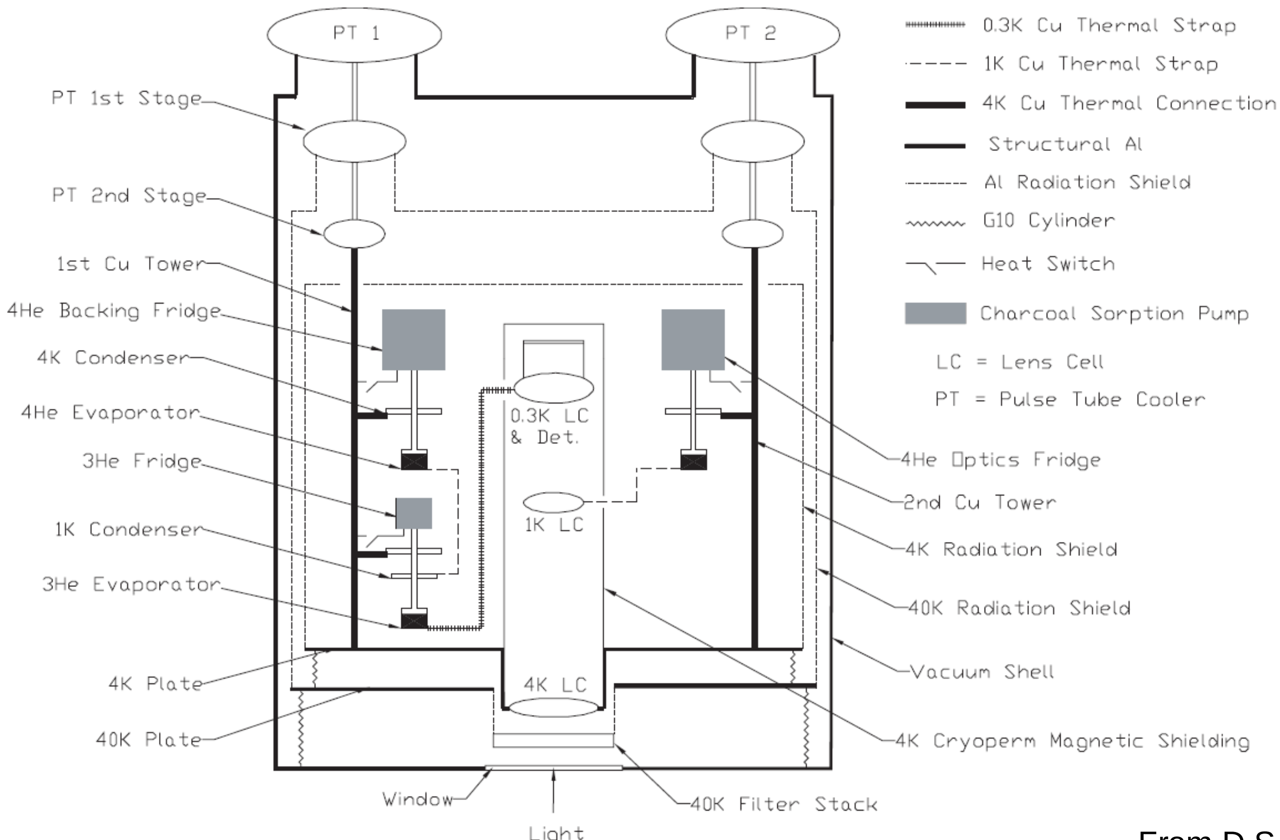
3 x 1.5 W PT CCs to reliquify He in the MICE Coupling coil design

7 T Solenoid Field



3D model for coupling magnet cryostat

Example of PT Use
Atacama Cosmology Telescope



Remote site
Liquid cryogens a problem
Uses 2 PT from Cryomech
40 W @ 45 K
1 W @ 4.5 K

From D.S. Swetz Atacama Cosmology Telescope PhD dissertation U. Penn 2009

Example of PT use
LNG production using a TADOPTR

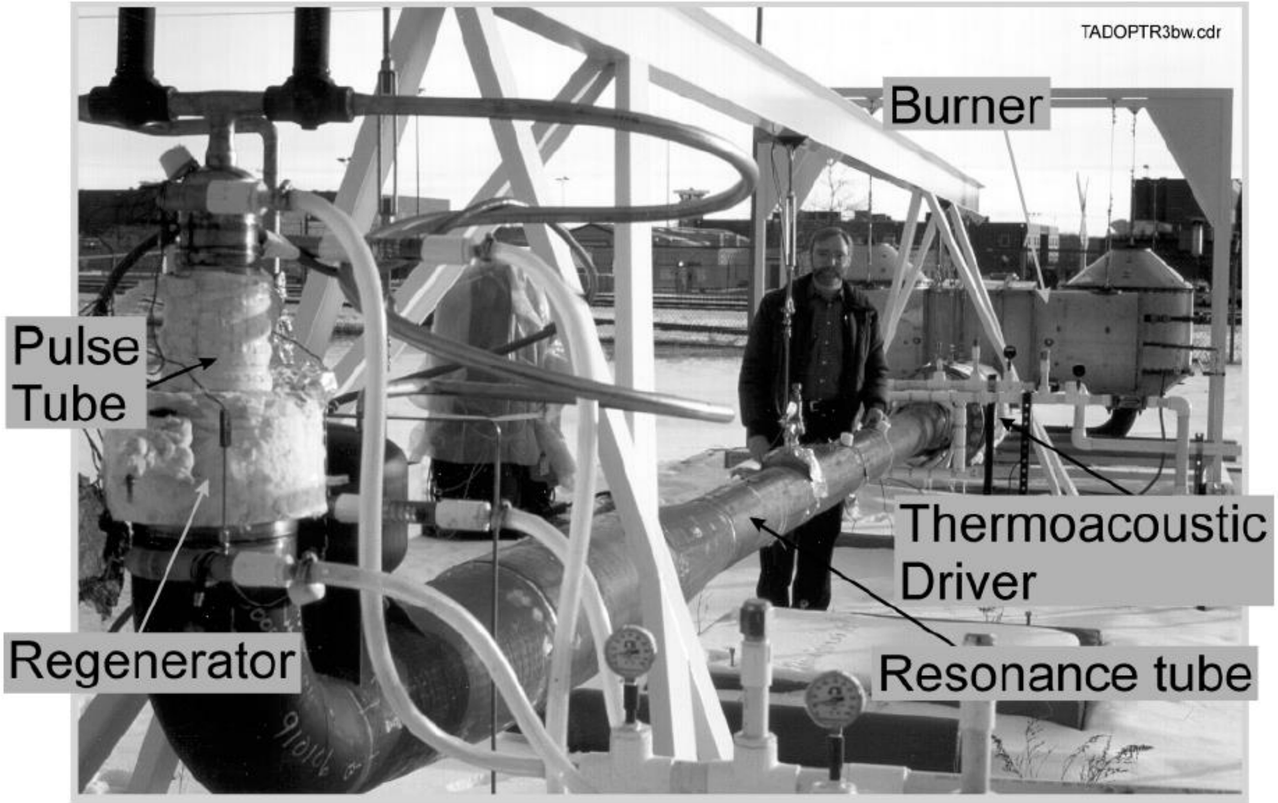


Figure 12. TADOPTR natural gas liquefier (600 L/day, 2.0 kW at 120 K)

No moving parts
burns 1/3 of natural gas stream
to liquefy the rest

From
R. Radebaugh
NIST

Space Applications

19 W @ 90 K
222 W input power

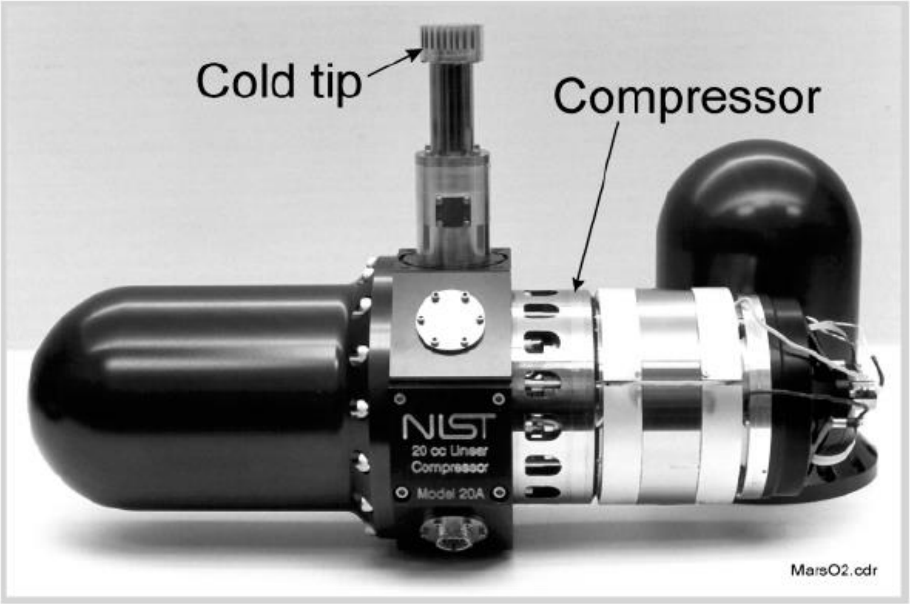


Figure 10. Pulse tube refrigerator for studies of liquefying oxygen on Mars (580 mm total length)

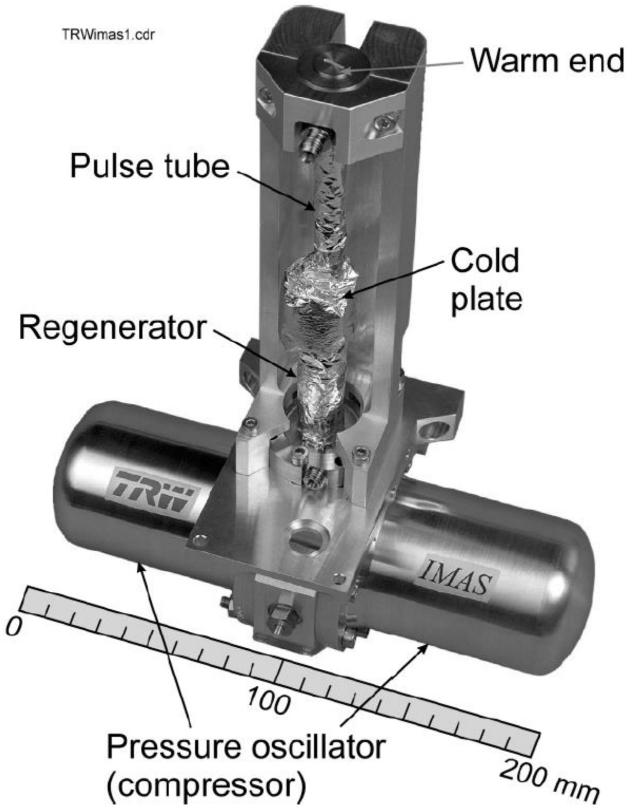
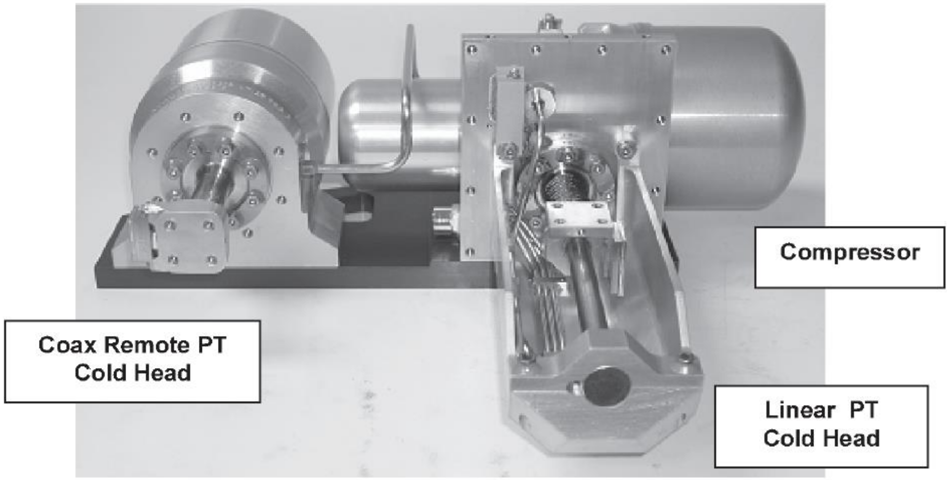


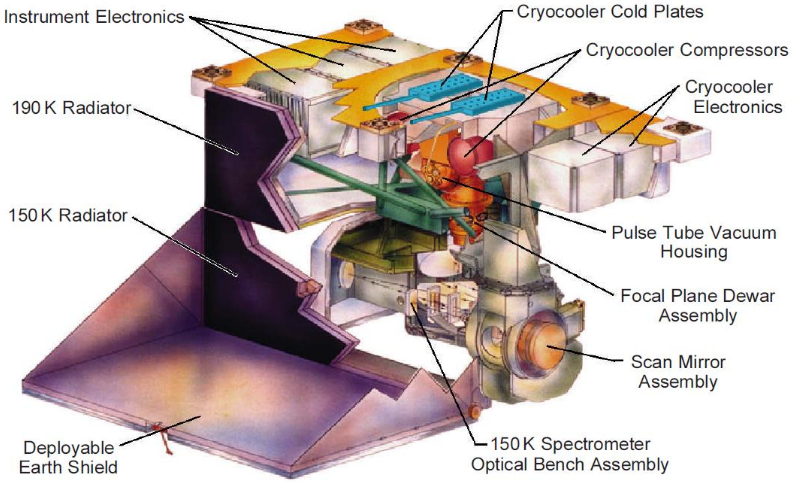
Figure 11. Pulse tube refrigerator for Integrated Multispectral Atmospheric Sounder (space appl.)

0.5 W @ 55 K

Both figures From R. Radebaugh Proc. Instit. of Refrig.

Space Applications





2.3 W @ 53 K and 8 W @ 183 K
Designed for sensor cooling on NASA GOES-R Satellite

Colbert et al.
Cryocoolers 15 (2009)

0.5 W @ 58 K
Atmospheric Infrared Sounder
On orbit for the last 8 years

Ross et al.
Cryocoolers 15 (2009)

Summary

- Cryocoolers are becoming more and more common in physics and accelerator applications.
- 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
- A significant industrial base exists for these devices
- Pulse tube cryocoolers, in particular, are a very active area of cryogenic research
- Their potential for low vibration and high reliability make them particularly attractive to space applications
- They are a Some additional online resources for pulse tubes and other types of cryocoolers are:

http://www.cryocooler.org/ Contains online proceedings of the International Cryocooler Conferences

http://www.elsevier.com/wps/find/journaldescription.cws_home/30407/description#description Online link to the journal *Cryogenics* which includes proceedings of the Space cryogenics Workshops