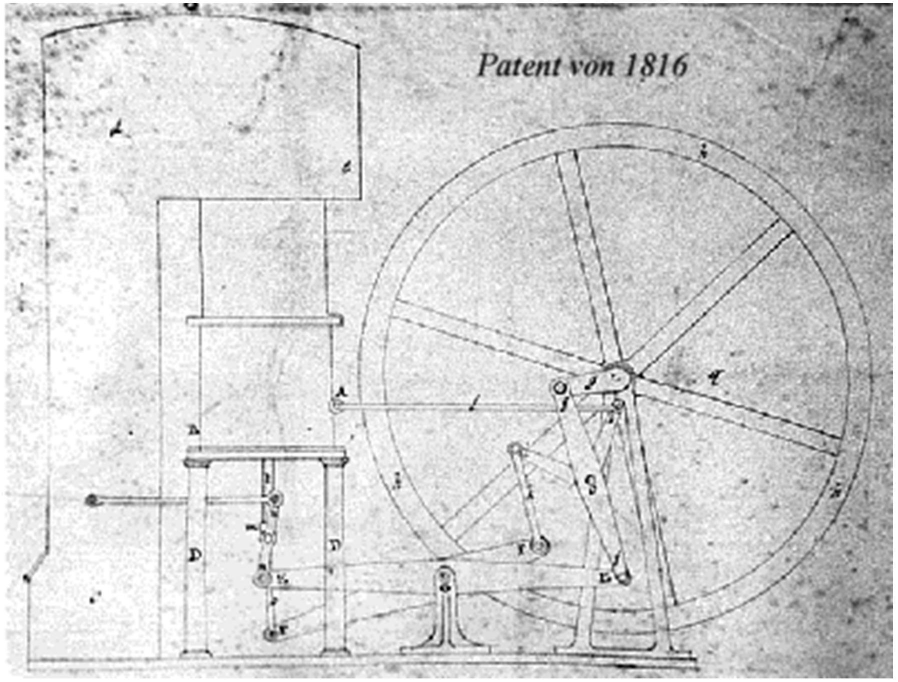
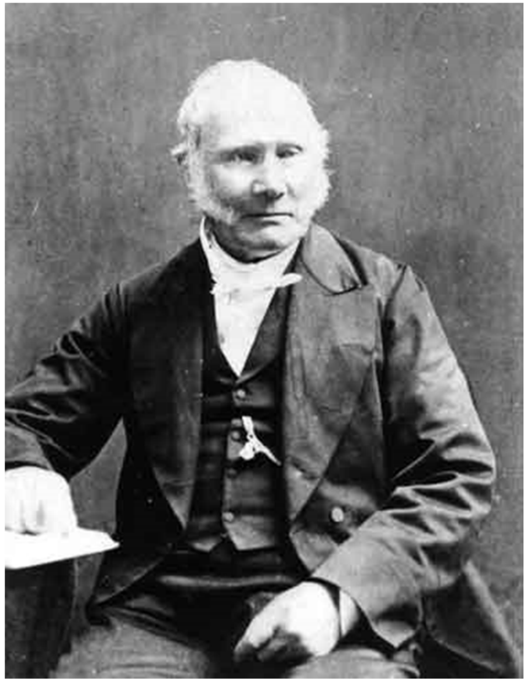
Stirling Machine Basics

Dr. Sergey Riabzev

50 RICOR
CRYOGENIC & VACUUM SYSTEMS
COOL YEARS

Stirling Engine Patent





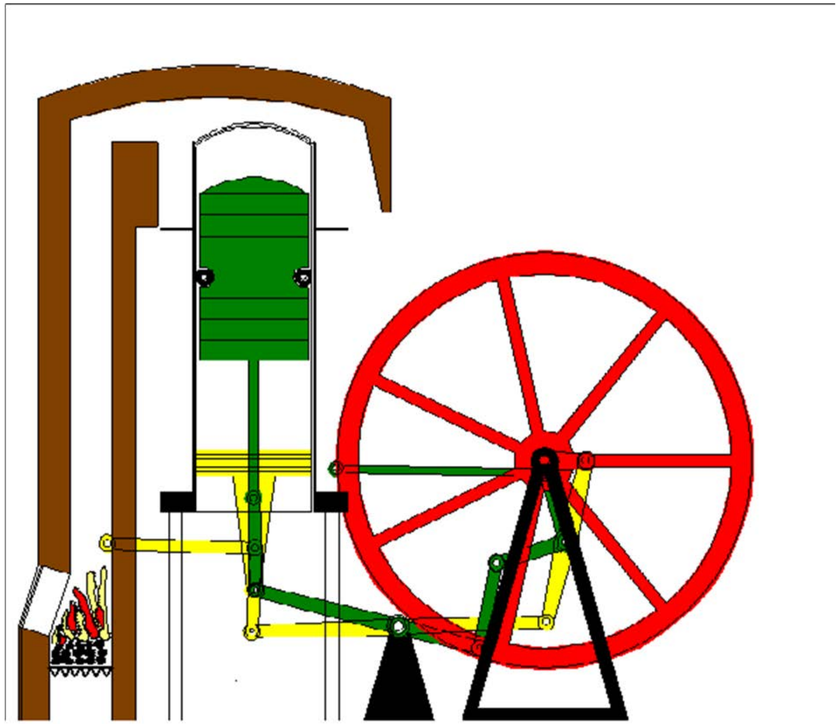
In 1816 The **Heat Economizer** (also known as **The Regenerator**) was patented by Scottish reverend, Dr. Robert Stirling (1790-1878) . This was a motive power engine which worked on **low fuel consumption** in contrast to the current technology of steam. The engine was also safer than steam engines which were in their early days susceptible to explosions.

Stirling Engine Patent

The patent described the process of what became known as the **Stirling Engine Cycle**. The **external combustion** engine was characterized by a **power piston**, a **displacer** to move the enclosed air between the **hot and cold ends** and a **regenerator** that was placed between the hot and cold ends of the displacer cylinder.

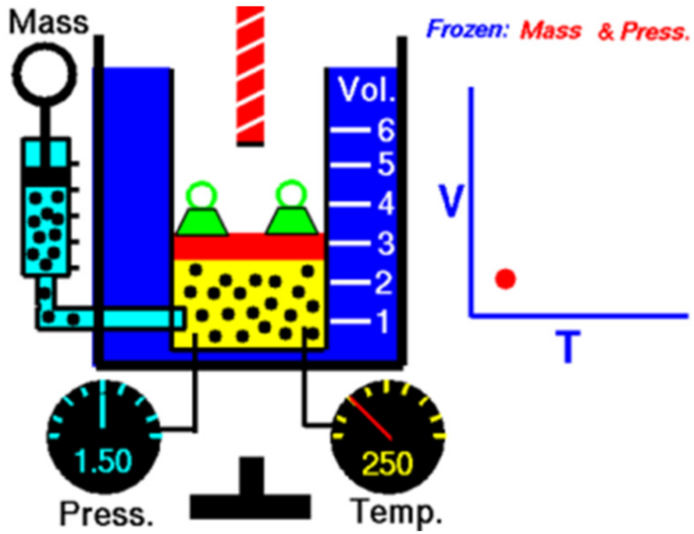
The end result was **more efficient operation** of the engine that **reduced the amount of energy needed** to heat up the working air.

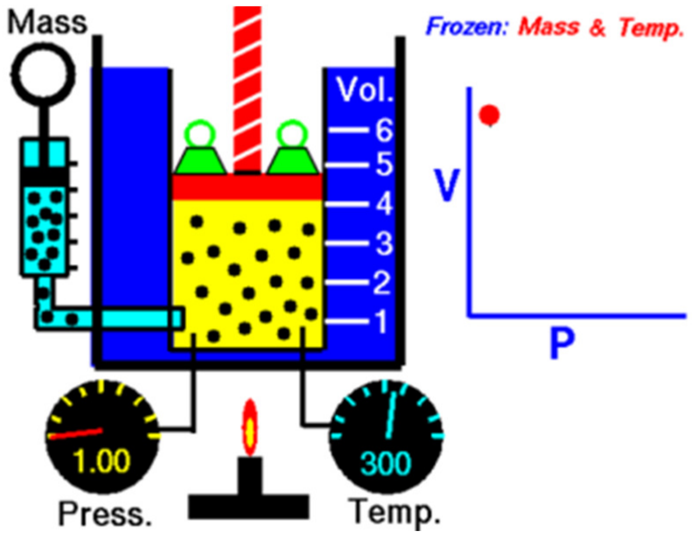
In 1818 Stirling built the first practical version of his engine, with the application of pumping water from a quarry.



For almost 200 years, the basic concept of the Stirling engine remains unchanged, although the advances in regenerator materials, clearance seal technology, flexure bearing designs etc., have made the **Stirling engine a very efficient, reliable and robust machine**.

Stirling Engine. A bit of theory





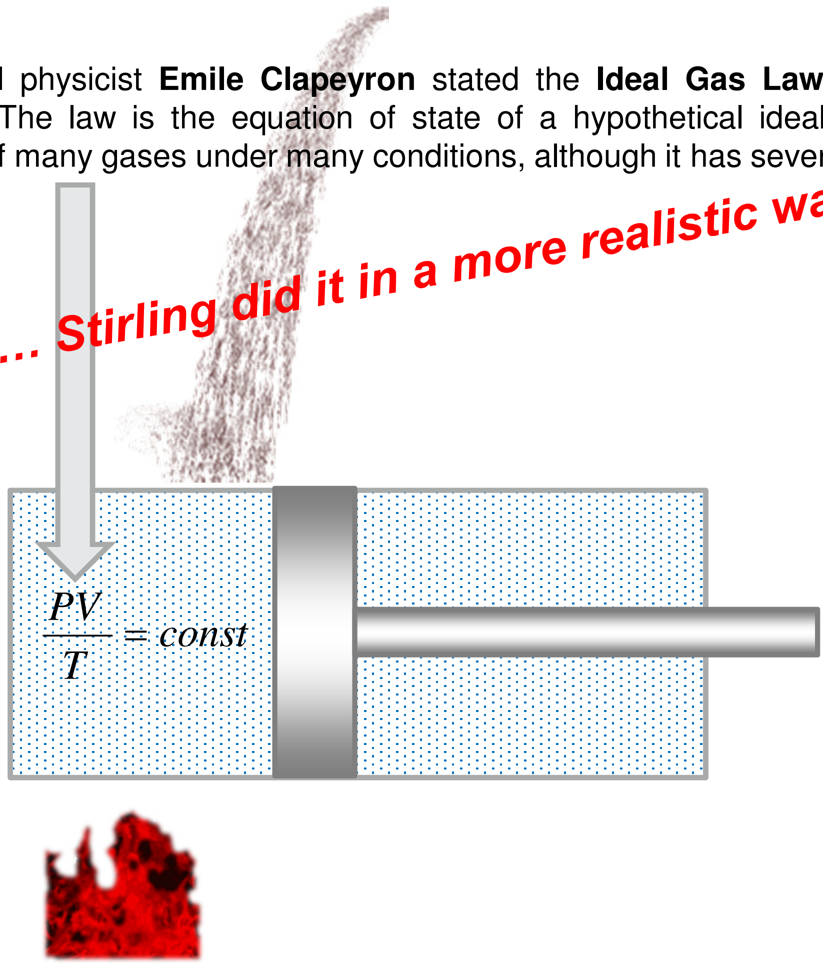
Charles's law (also known as the **law of volumes**) is an experimental gas law which describes how gases tend to expand when heated. It was first published by French natural philosopher **Joseph Louis Gay-Lussac** in **1802**, although he credited the discovery to unpublished work from the **1780** by French scientist **Jacques Charles**.

Boyle's law (sometimes referred to as the **Boyle-Mariotte law**) describes the inversely proportional relationship between the absolute pressure and volume of a gas, if the temperature is kept constant within a closed system. The law was named after Irish chemist and physicist **Robert Boyle**, who published the original law in **1662**.

Stirling Engine. How stuff works?

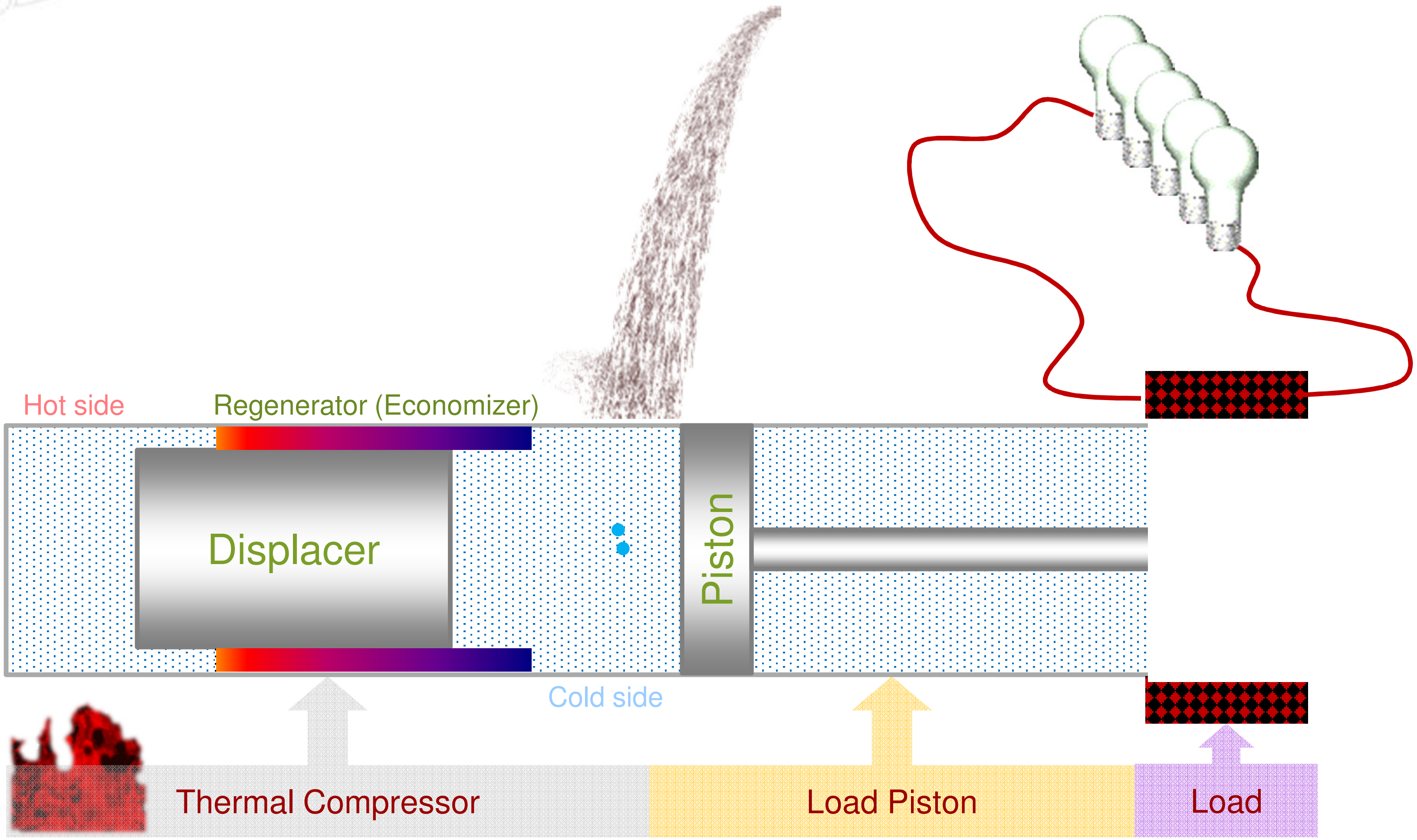
In **1834** French engineer and physicist **Emile Clapeyron** stated the **Ideal Gas Law** as a combination of Boyle's and Charles's law. The law is the equation of state of a hypothetical ideal gas. It is a good approximation to the behavior of many gases under many conditions, although it has several limitations.

Well… Stirling did it in a more realistic way…



$$\frac{PV}{T} = const$$

Stirling Engine. How stuff works?



Stirling Engine. Advantages

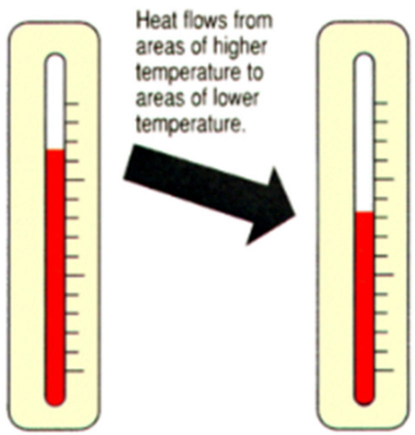
- Highly efficient
- Highly reliable and long-life
- Acoustically silent
- No maintenance required
- Mechanism is simpler than other reciprocating engine types. No valves, no bearings, the burner system can be relatively simple. Crude Stirling engines can be made using common household materials
- Can be used with a variety of heat sources (e.g. gas, oil, sun, wood, organic waste, heat waste…). And even ice!!!

Stirling Engine. Disadvantages

- Due to very high temperature, the materials must resist the corrosive effects of the heat source, and have low creep (deformation). Typically these material requirements substantially increase the cost of the engine. The materials and assembly costs for a high temperature heat exchanger typically accounts for 40% of the total engine cost.
- Can not start instantly; it literally needs to "warm up".
- Power output tends to be constant, its adjustment can require careful design and additional mechanisms. This property is less of a drawback where constant power output is actually desirable

What is Chilling?

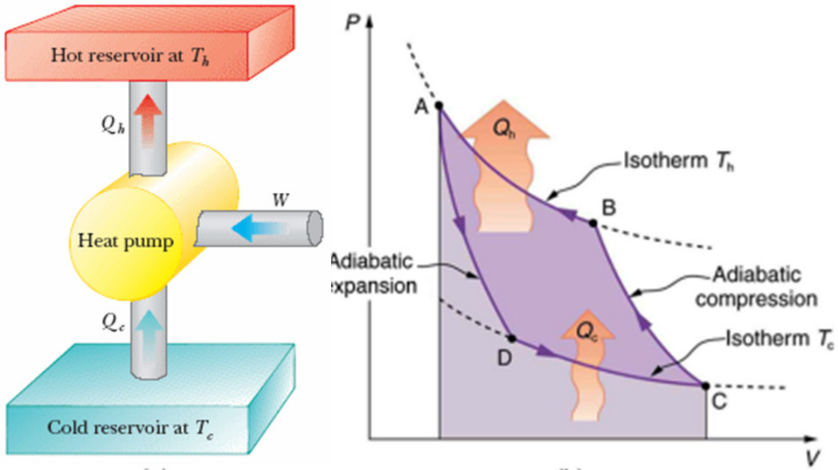
•Process of ***heat dissipation*** from an object into available ***natural chilling agents*** - air &water.



•**No thermodynamic work** should be done on the chilling agent

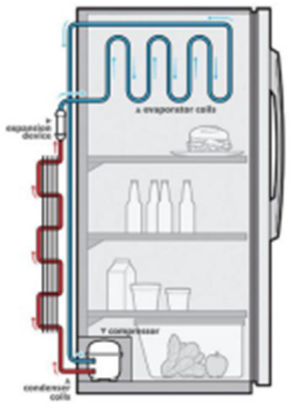
What is Refrigeration?

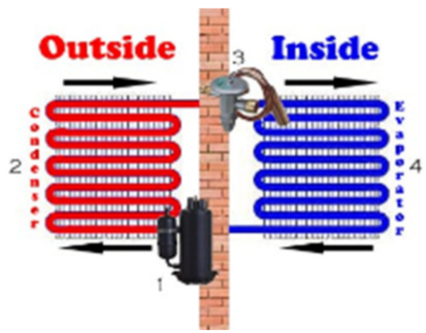
According to the second law of thermodynamics heat cannot spontaneously flow from a colder location to a hotter area; work is required to achieve this. The work of heat transport is traditionally driven by mechanical work, but can also be driven by magnetism, laser or other means



(a) (b)

An air conditioner requires work to cool a living space, moving heat from the cooler interior (the cold reservoir) to the warmer outdoors (the hot reservoir). Similarly, a house refrigerator moves heat from inside the cold icebox (the cold reservoir) to the warmer room-temperature air of the kitchen (the hot reservoir)





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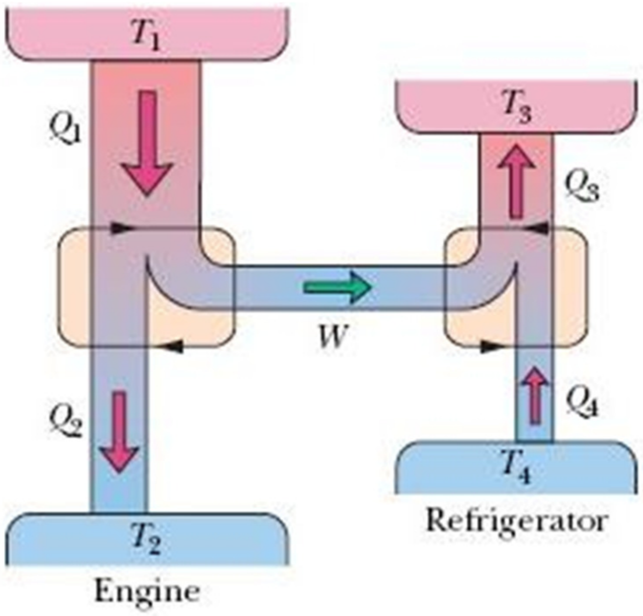
Stirling Refrigerator

The Stirling engine can be driven in reverse, using a mechanical energy input to drive heat transfer in a reversed direction (i.e. **a heat pump, or refrigerator**).



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Stirling Refrigerator. History

- In 1834, noted British astronomer **John Herschel** applied the **Stirling cycle for cooling**. This was the first known case of using the Stirling machine for refrigeration purposes.
- Later, Scottish born **John Gorrie** may have been the first to apply the **Stirling machine for making ice**. From descriptions published in 1876 by Alexander Carnegie Kirk, it seems that by then Stirling cycle cooling was well known in technical circles.
- Over time, advancements in Stirling cycle machines become less frequent and almost disappeared by 1900 until they were rediscovered in the 1940s by researchers at Philips Co. in the Netherlands. **Philips used pressurization to significantly improve power density**.
- Beginning in 1946, **Philips applied the Stirling cycle for deep temperature use in the generation of liquefied gases** (US Patent 2,907,175, March 14, 1955). These machines are still in production by Stirling Cryogenics and Refrigeration BV.

Cryogenics. What's that?

Cryogenics is the **science of producing low-temperature conditions, and studying materials properties under these conditions**.

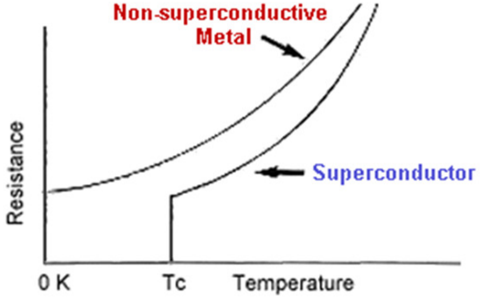
The word **cryogenics** comes from the Greek word ***cryos*** , meaning "cold," combined with a shortened form of the English verb "to **gen**erate.“

It has come to mean the generation of temperatures well below those of normal human experience.

First use of the word "Cryogenics"

December 1894

by Prof H. Kamerlingh Onnes, Dutch physicist, when established first "Cryogenic Laboratory" in University of Leiden, Netherlands

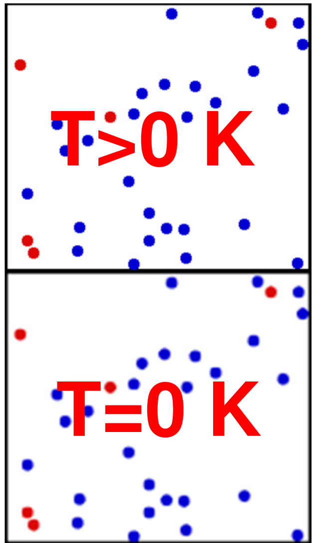


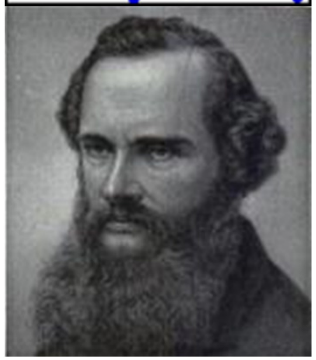
In this laboratory, the effect of Superconductivity was discovered in 1911.

What is Temperature?

The temperature of any material—solid, liquid, or gas—is a **measure of the energy it contains**. That energy is due to various forms of motion among the atoms or molecules of which the material is made. A gas that consists of very rapidly moving molecules, for example, has a higher temperature than one with molecules that are moving more slowly.

In 1848, English physicist William Thomson (later known as Lord Kelvin; 1824–1907) pointed out the possibility of having a material in which **particles had ceased all forms of motion**. The absence of all forms of motion would result in a complete absence of heat and temperature. Thomson defined that condition as **absolute zero**.





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Where Cryogenic range begins?

Definition of National Institute of Standards and Technology (NIST)
at Boulder, Colorado

below -150°C (123 K…

due to the normal boiling points of th… ***permanent gases**** (He, H_2, Ne, N, O… …low -150°C

Hey, it looks like the HOT detectors (~150K) are beyond the Cryogenics Science…

* **Permanent gas** - a gas tha… by compression alone at normal temperature. The term was first coined by Michae…) when he failed to liquefy hydrogen and oxygen even up to few thousand times th… …ure.

Lowest temperature in Nature

~1K

cooler than the cosmic
microwave background radiation

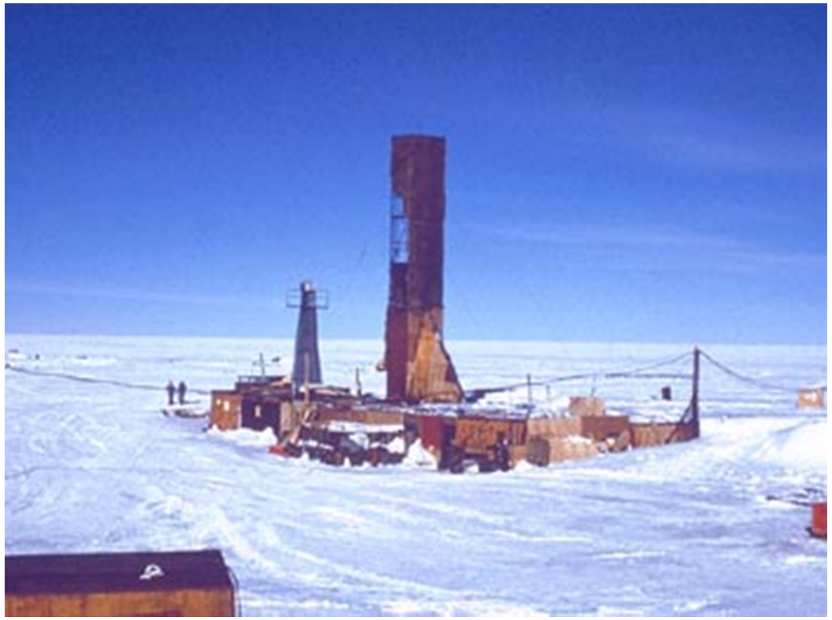
“Boomerang” Nebula*,
“Centaurus” Constellation

* The “Boomerang” Nebula is formed from the outflow of gas from a star at its core. The gas is moving outwards at a speed of about 600,000 km/h and expanding rapidly as it moves out into space. This expansion is the cause of the nebula's very low temperature.

Lowest temperature on Earth

–89.4 °C
(183.8K)

Russian “VOSTOK” station in Antarctica,
Recorded in 1983



Lowest temperature achieved by scientists

- In 2003, researchers at Massachusetts Institute of Technology (MIT) achieved

500 pico Kelvin

(0.0000000005 K)

Tom Pasquini (left) and Aaron Leanhardt (right) in front of the machine where they and collaborators cooled a sodium gas to 500 pico Kelvin.

- For reaching the record-low temperatures, the MIT researchers invented a novel way of confining atoms, which they call a "gravito-magnetic trap." As the name indicates, the magnetic fields act together with gravitational forces to keep the atoms trapped.

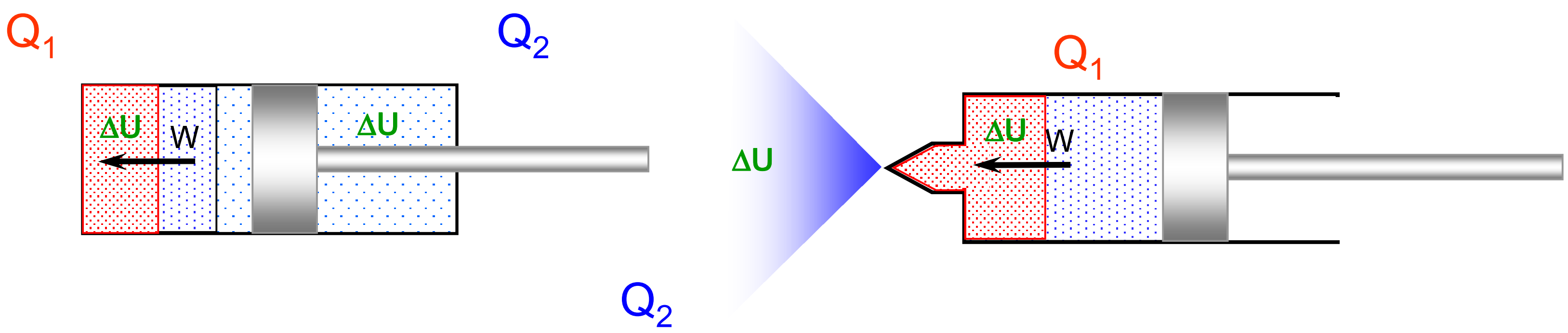
Basic physical phenomenon utilized in refrigeration

Bike hand pump

Why we sense a pump heating through pumping a bike's tire?

Basic physical phenomenon utilized in refrigeration

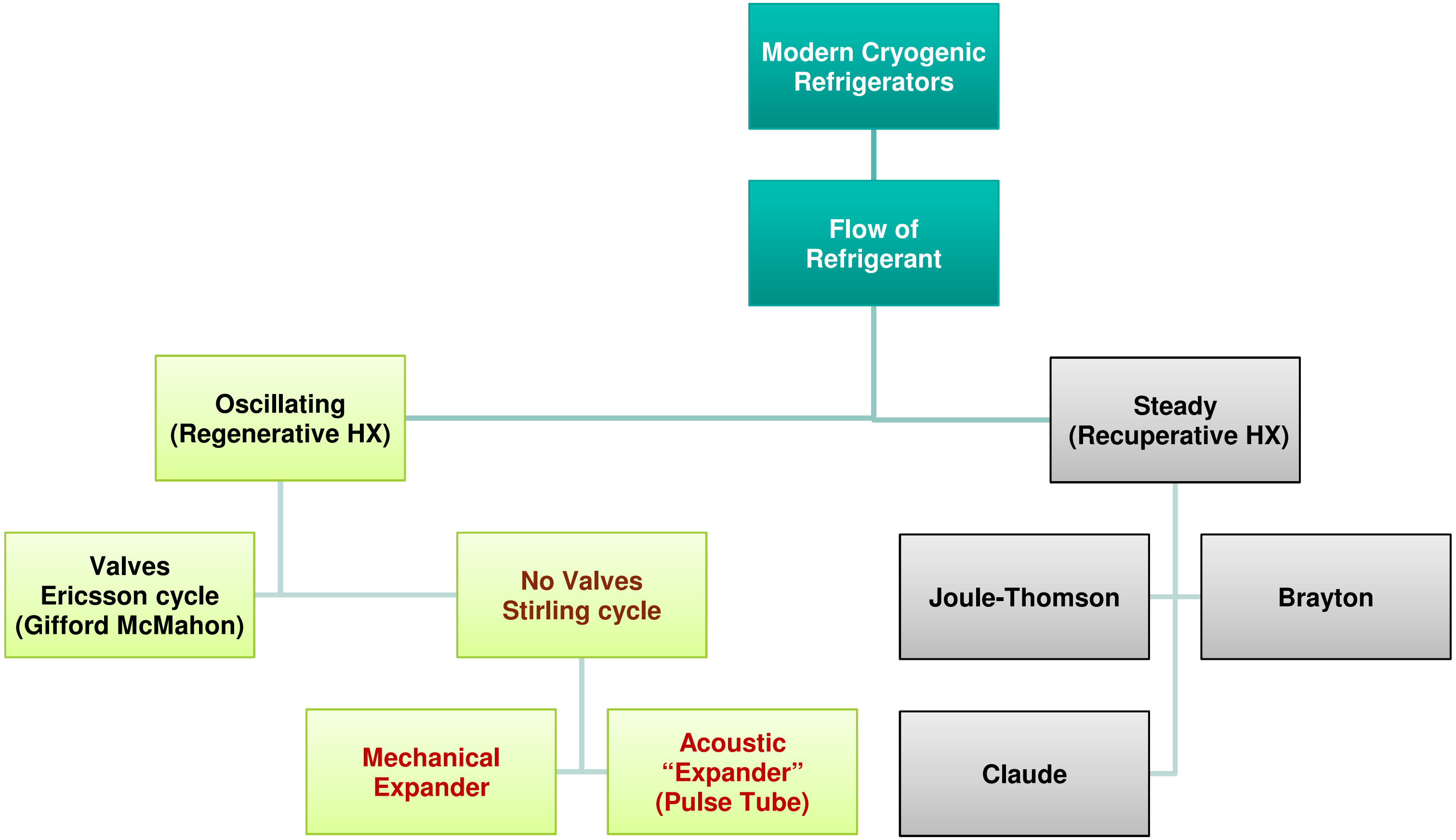
W – Work applied to a gas
ΔU – Change in Internal Energy of a gas
Q – Heat emitted from / absorbed by a gas



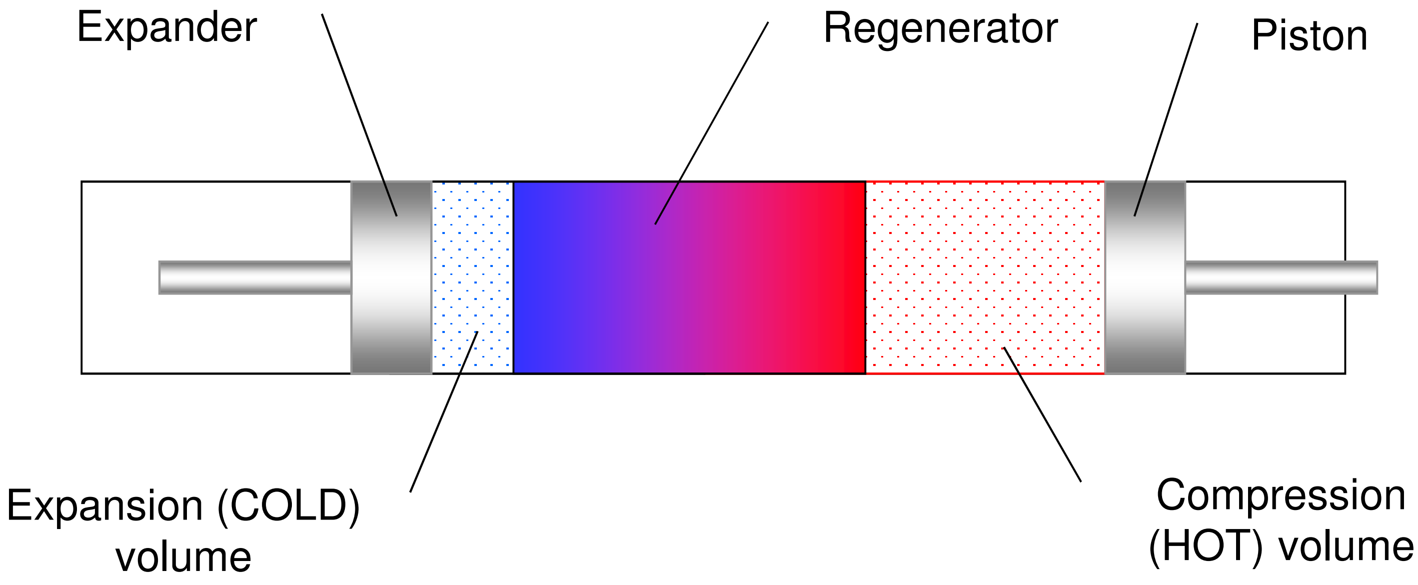
$$\Delta U = \Delta Q - \Delta W$$

(First Law of Thermodynamics)

Classification of cryogenic refrigerators

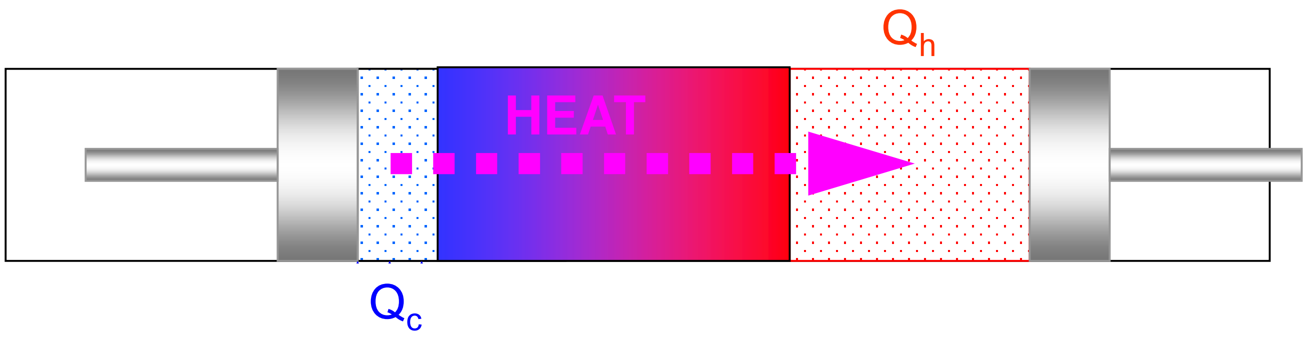


Basic structure of Stirling Machine



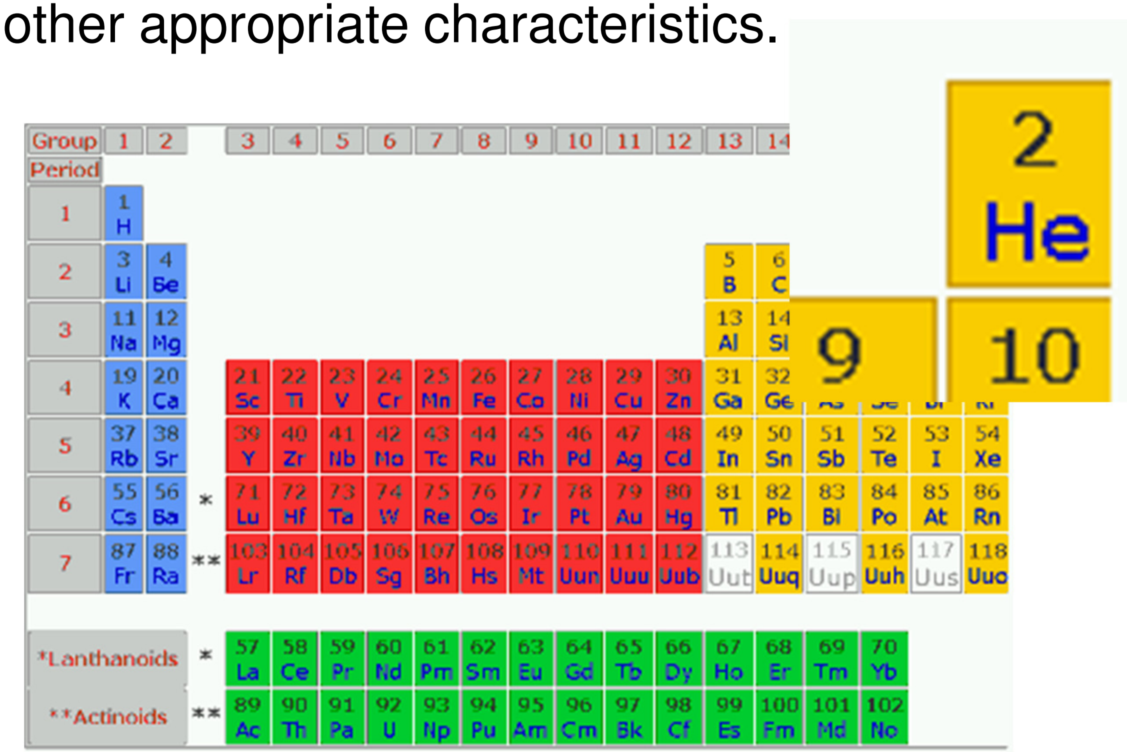
Basic structure of Stirling Machine

Proper timing of the Piston &Expander enables the heat pumping process

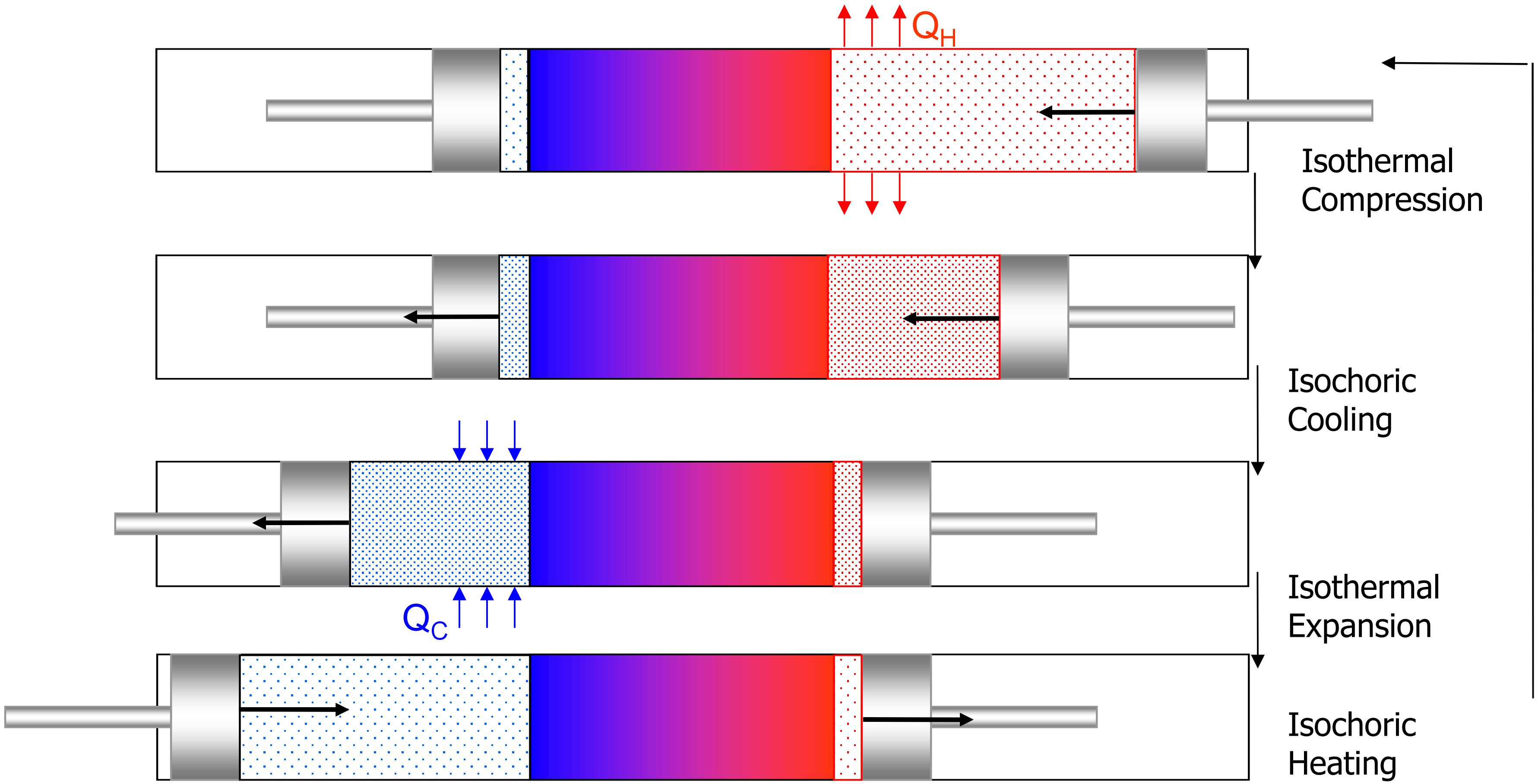


Refrigerant

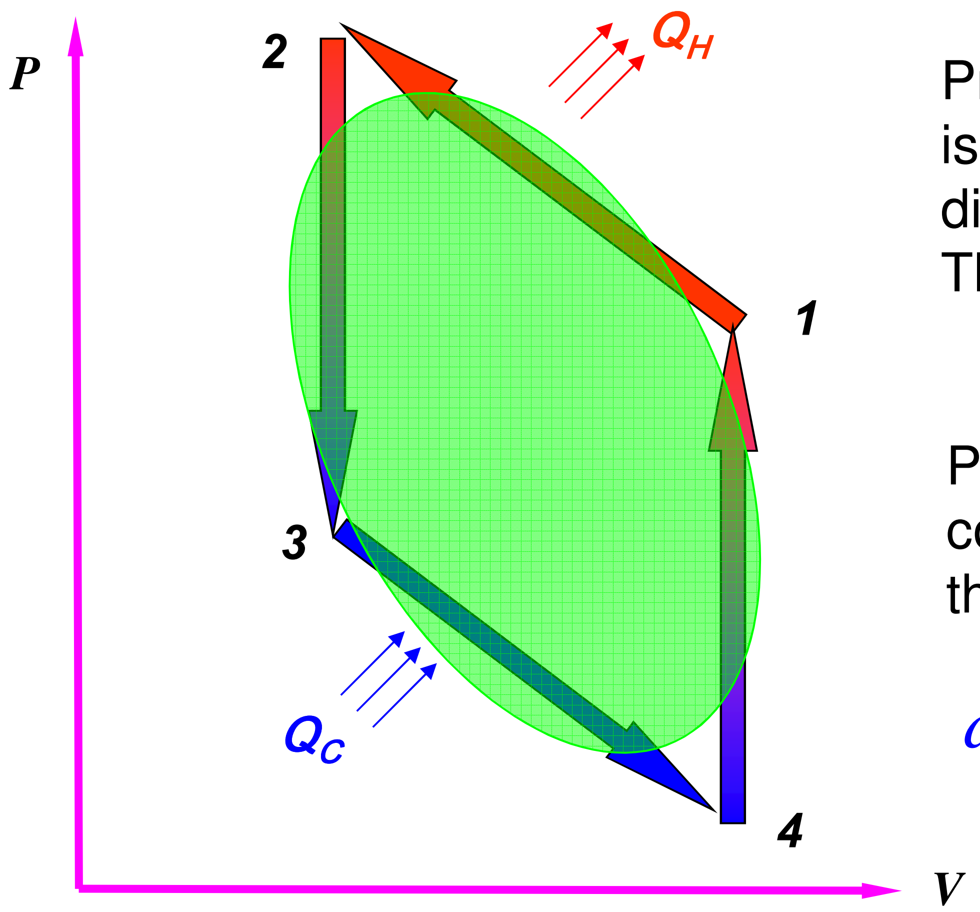
Pure Helium (He) is the typical refrigerant used in Stirling machines, thanks to low liquefaction temperature (4.2°K) and other appropriate characteristics.



4 stages of Stirling cycle



PV-Diagram



Pressure-Volume (P-V) diagram is one of the fundamental diagrams in the Stirling Cycle Theory

PV-diagram's area indicates a cooling work ***W*** done through the cycle

$$dW = \int PdV$$

Theoretical Coefficient Of Performance (COP) of Stirling cycle

As the Stirling engine is a perfectly reversible machine, its COP is given by the famous relation, which is also called the Carnot COP:

$$\eta_{heating} = T_H / (T_H - T_C) \times 100\%$$

$$\eta_{refrigeration} = T_C / (T_H - T_C) \times 100\%$$

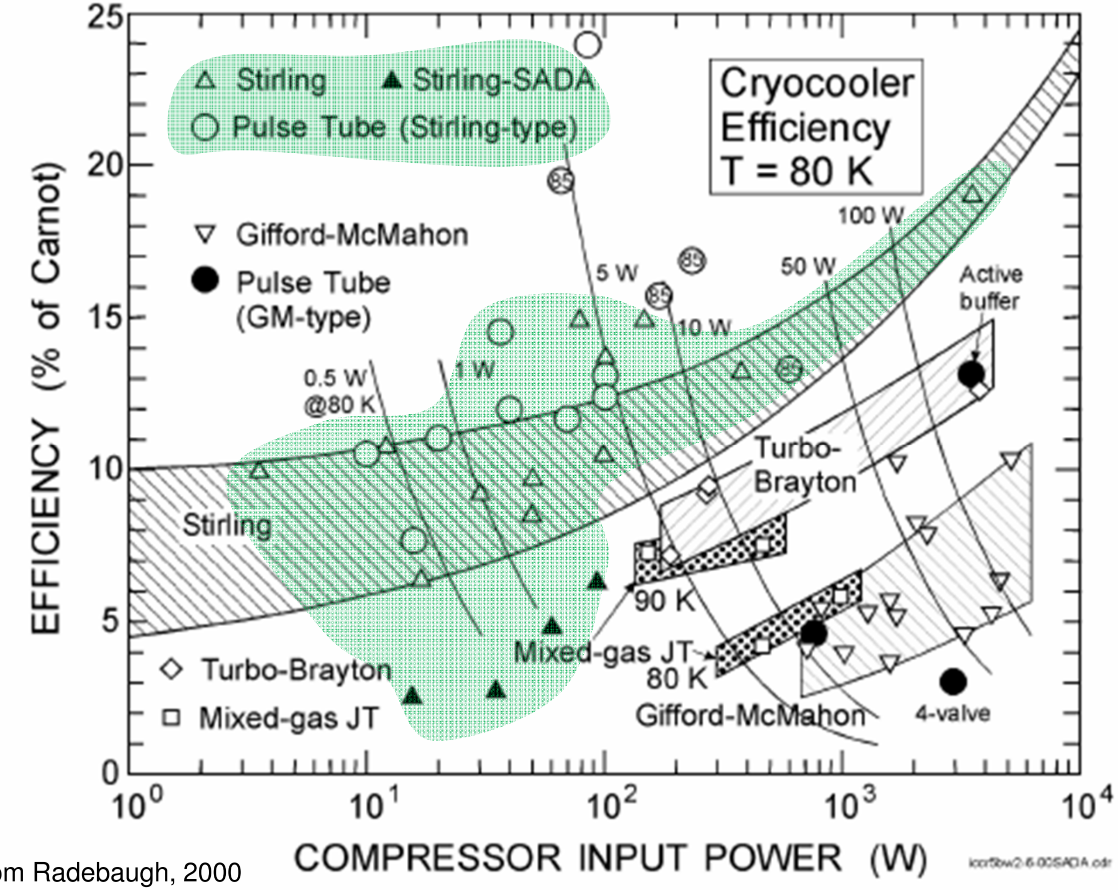
Examples for refrigeration COP:

T_H=300K, T_C=80K, η_{300-80} = 80/(300-80) x 100% = **67%**

T_H=300K, T_C=150K, $\eta_{300-150}$ = 150/(300-150) x 100% = **100%**

The reason for not using the term 'efficiency' is that the COP (Coefficient Of Performance) can often be greater than 100%. Since these devices are moving heat, not creating it, the amount of heat they move can be greater than the input work. Therefore, heat pumps can be a more efficient way of heating than simply converting the input work into heat, as in an electric heater or furnace.

Practical COP of Stirling cycle (% of Carnot)



from Radebaugh, 2000

Practical COP is much lower than Carnot COP, as a number of losses related to heat-exchange, gas flow, pressure, friction, etc., take place in a real machine.

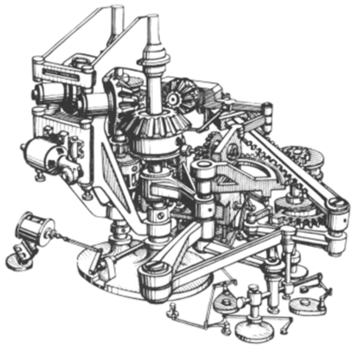
$$\eta_{pract}=Q_{lift} / W_{pv} * 100\%$$

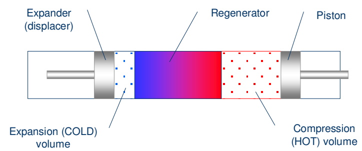
Normalized to temperatures Efficiency of a real refrigerator is typically assessed as % of Carnot

$$\eta=\eta_{pract}/\eta_{refrigeration} * 100\%$$

Efficiency of a real Stirling machine

Overall electro-mechanical COP of Stirling Machine is a product of partial efficiencies of all subsystems involved:





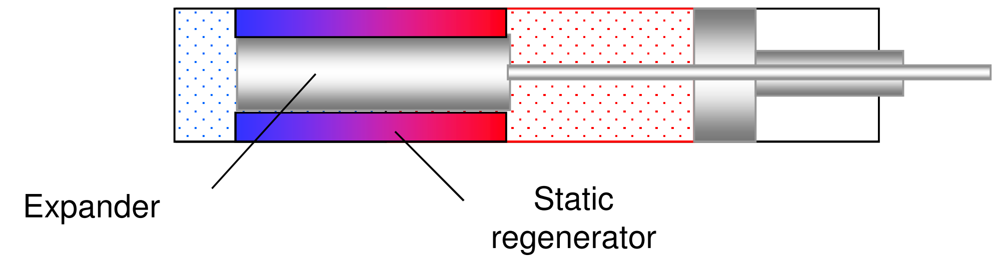
Electrical efficiency of Controller x **Electro-mechanical efficiency of Motor** x **Mechanical efficiency of apparatus** x **Practical COP of Stirling cycle**

$\eta_{pract} = Q_{lift} / W_{pv}$

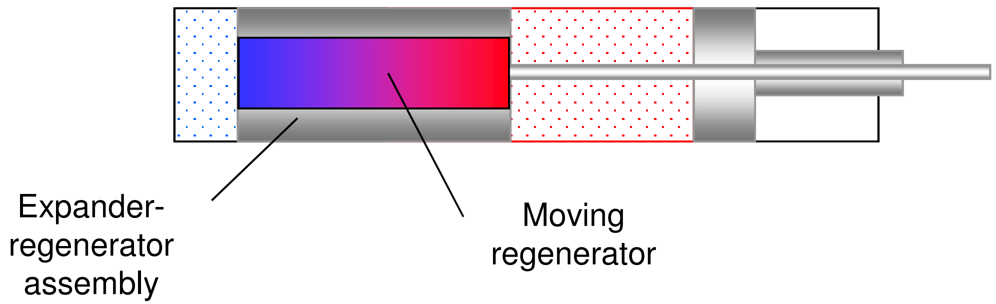
Efficiency of a real Stirling machine is a ratio between actually lifted heat $\boldsymbol{Q_{lift}}$ and actually consumed electric power $\boldsymbol{W_{el}}$

$$\eta_{real} = Q_{lift} / W_{elec} \times 100\% < 10\% \text{ (300-80K)}$$

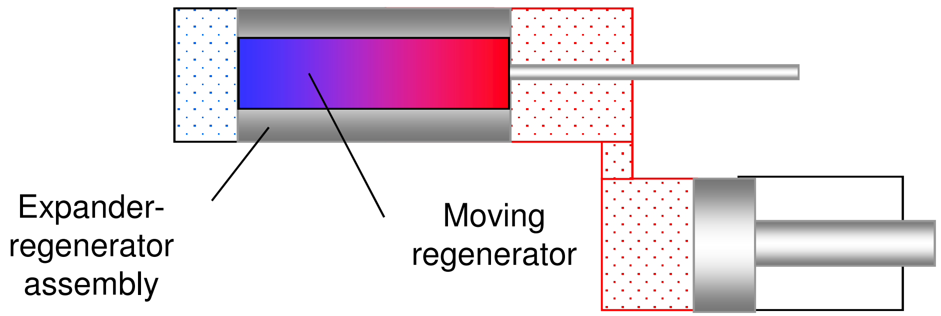
Typical design of regenerator



Beta design with static regenerator



Beta design with moving regenerator



Gamma design with moving regenerator

Typical Designs of Stirling Refrigerators

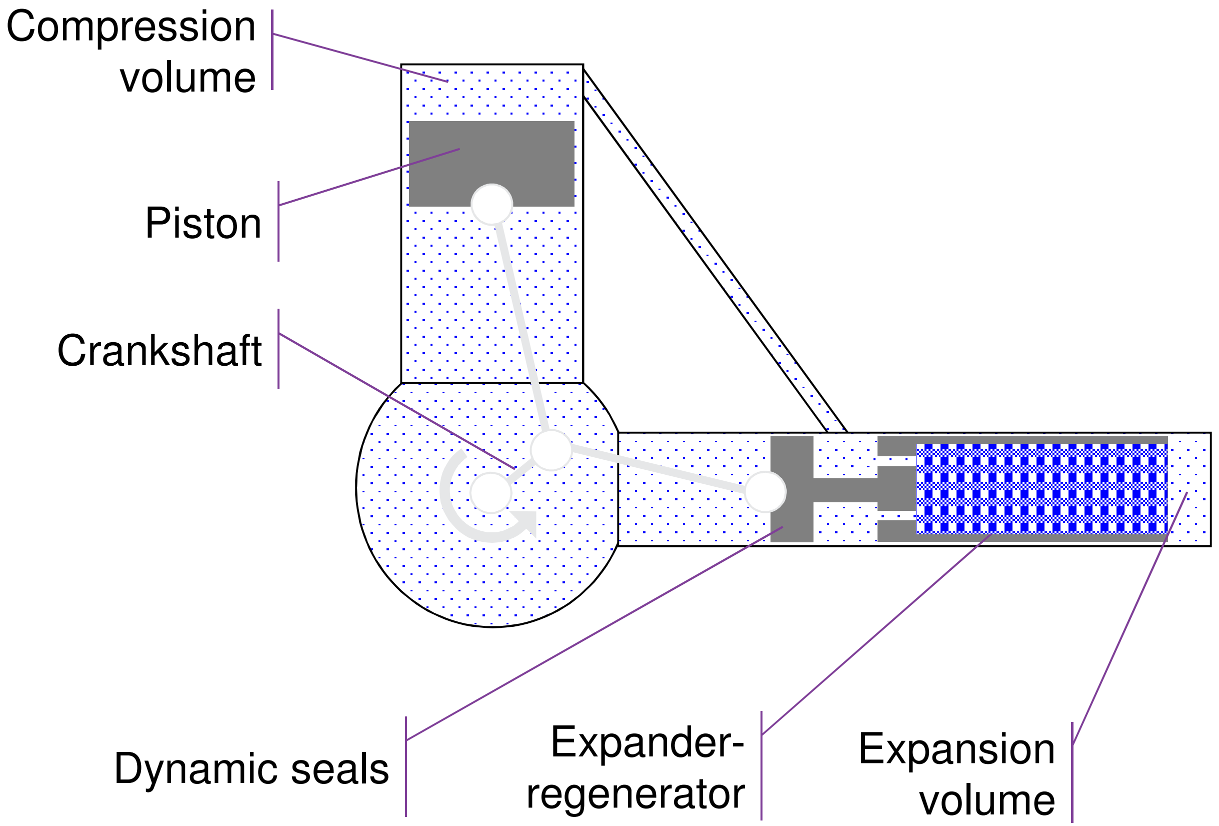
Rotary Compressor + mechanically driven Expander

Rotary Compressor + pneumatically driven Expander

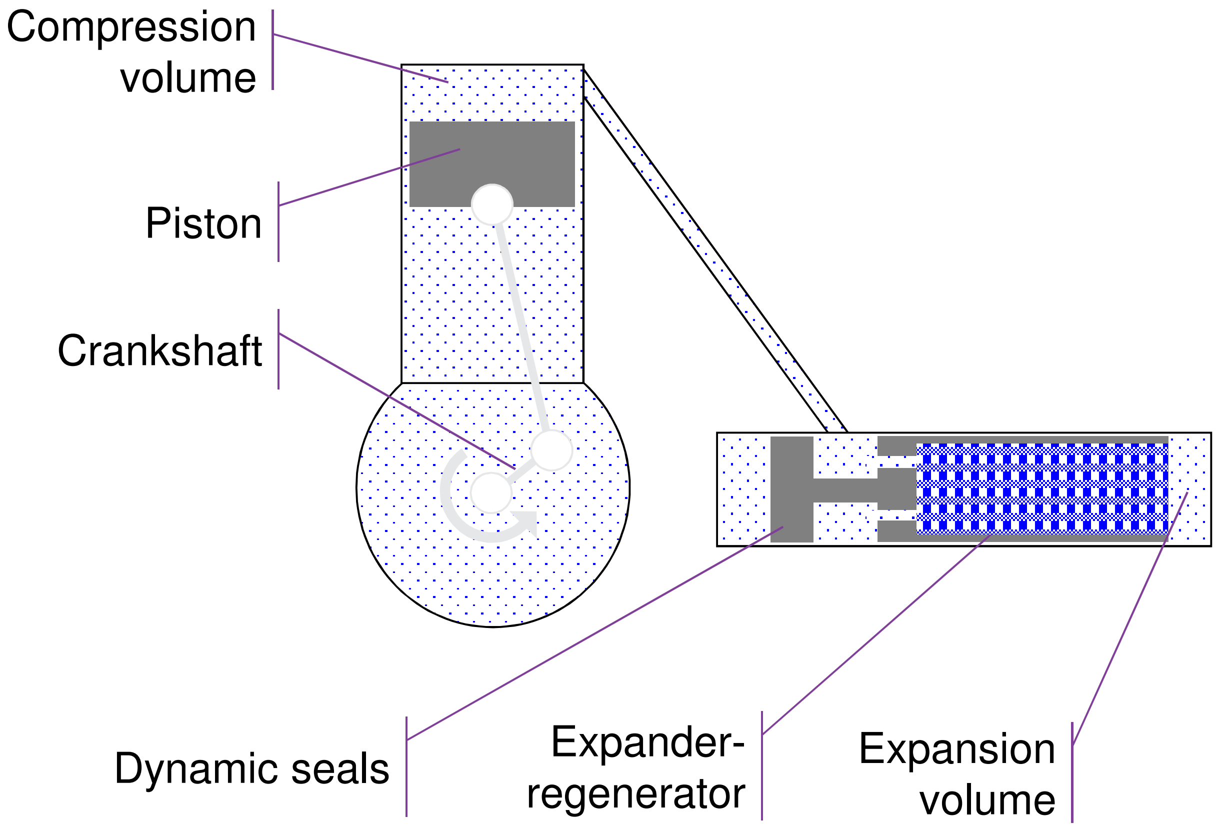
Linear Compressor + pneumatically driven Expander

Linear Compressor + electro-mechanically driven Expander

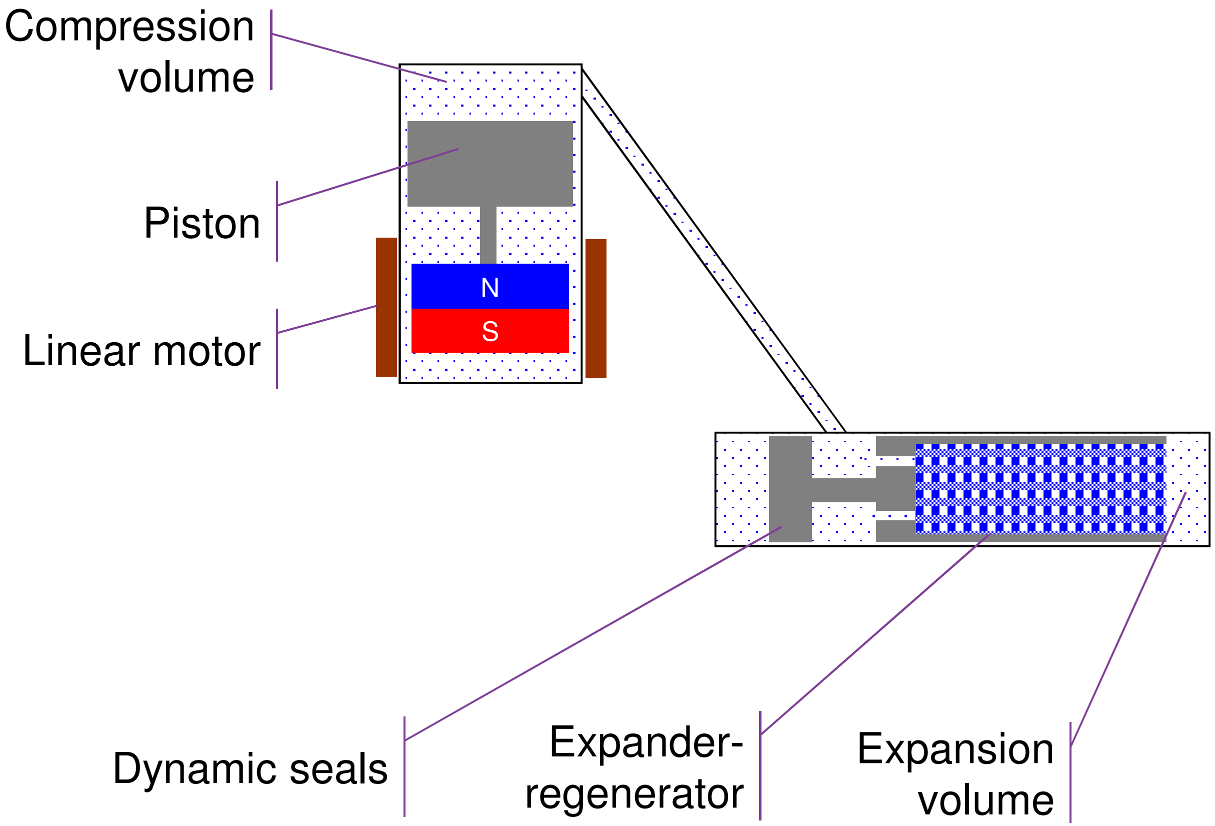
Rotary Compressor + Mechanically driven Expander



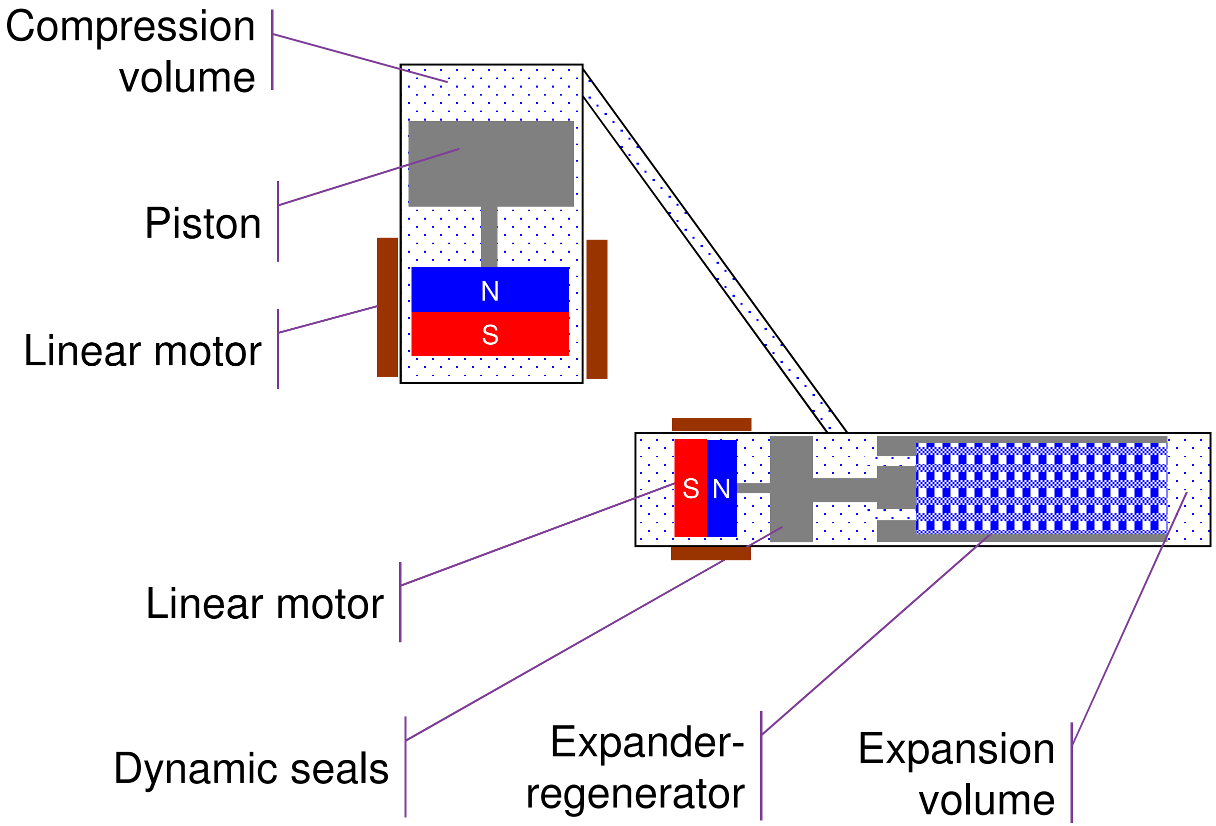
Rotary Compressor + Pneumatically driven Expander



Linear Compressor + Pneumatically driven Expander

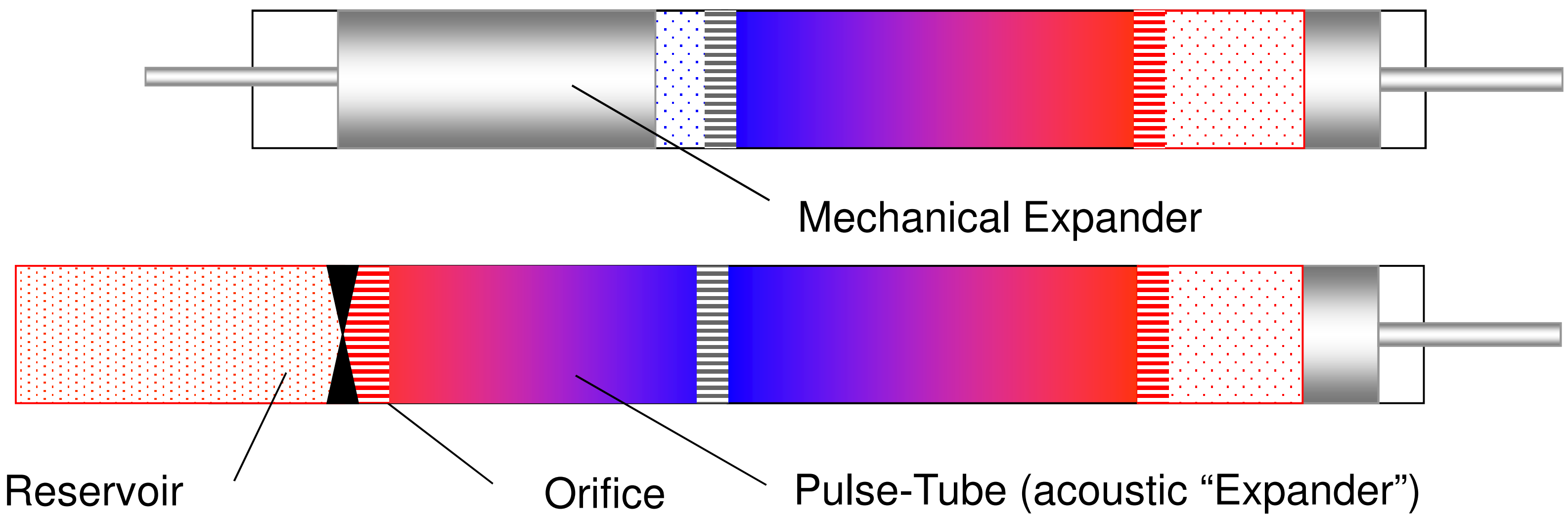


Linear Compressor + Electromechanically driven Expander

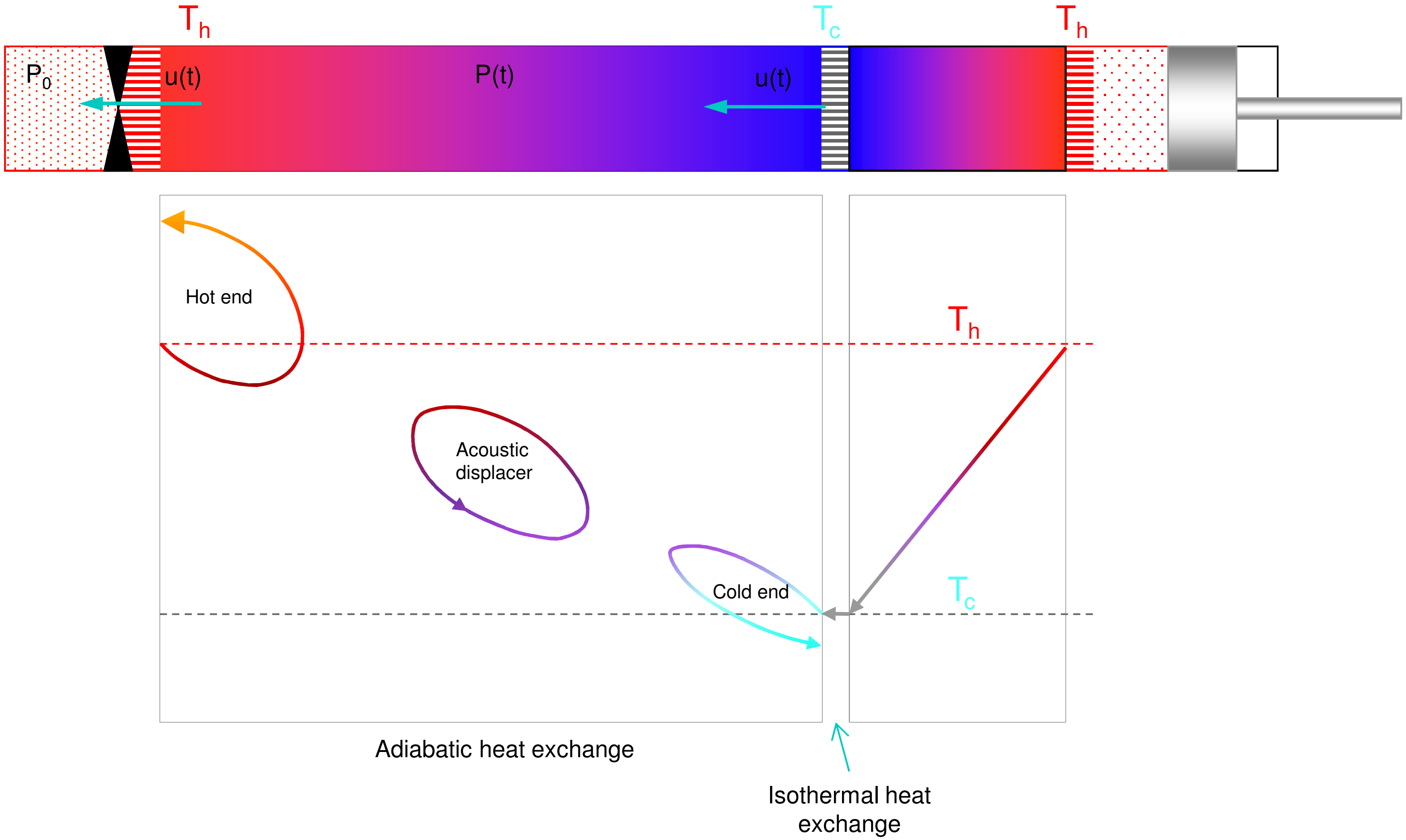


Pulse Tube basics

The theory behind Pulse Tube refrigerators is virtually similar to that of the Stirling machines, with the volume displacement mechanism of the Expander replaced by the Orifice (Inertance tube) & Reservoir configuration.



Pulse Tube basics



Theoretical Coefficient Of Performance (COP) of Pulse Tube Machine

Pulse Tube refrigerator is not perfectly reversible due to presence of flow resistance element (Orifice, Inertance). Therefore equation of Carnot COP does not hold. Instead, the COP of an ideal PTR is given by:

$$\eta_{PT} = T_C / T_H \times 100\%$$

Examples of PT COP:

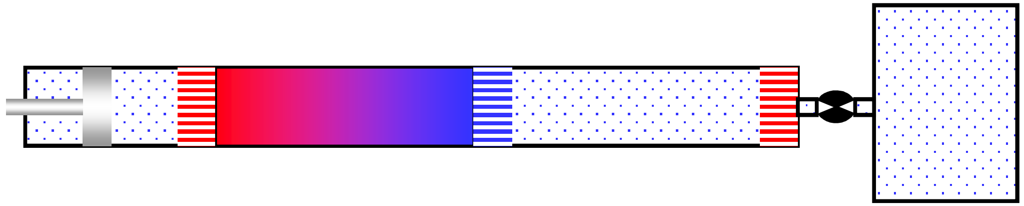
T_H=300K, T_C=80K, $\eta_{300\text{–}80}$ = *80/300 x 100% =* ***27%*** *(67% for regular Stirling)*

T_H=300K, T_C=4K, $\eta_{300\text{–}4}$ = *4/300 x 100% =* ***1.33%*** *(1.36% for regular Stirling)*

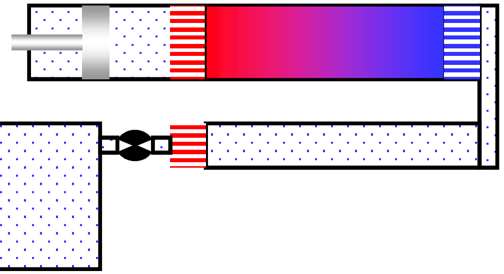
The COP of PT refrigerators at room temperature is low. However, below about 80 K the COP is comparable with other coolers and in the low-temperature region the advantages get the upper hand

Configurations of Pulse Tube Machines

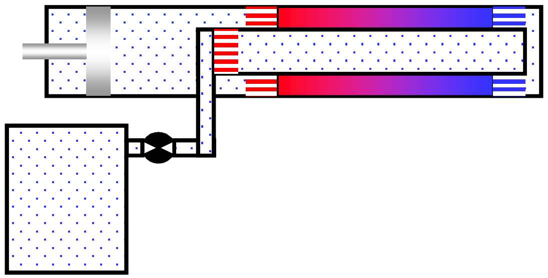
- In-line PT



- U-shape PT



- Coaxial PT



Ricor Propriety

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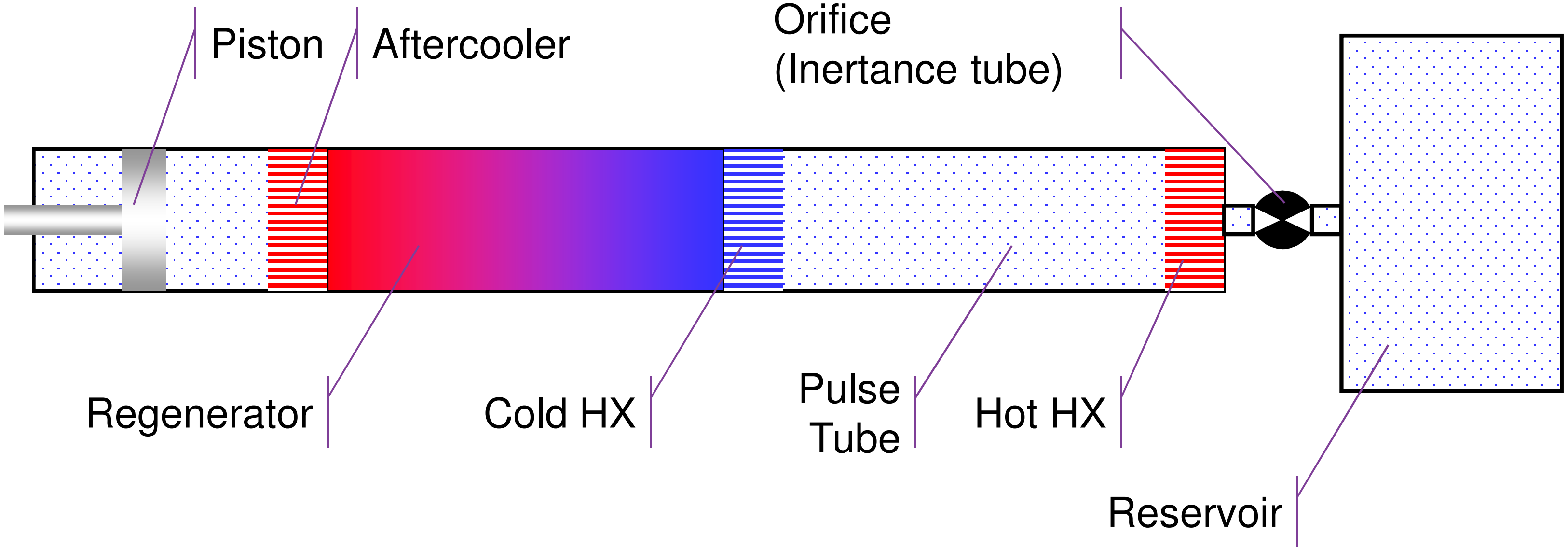
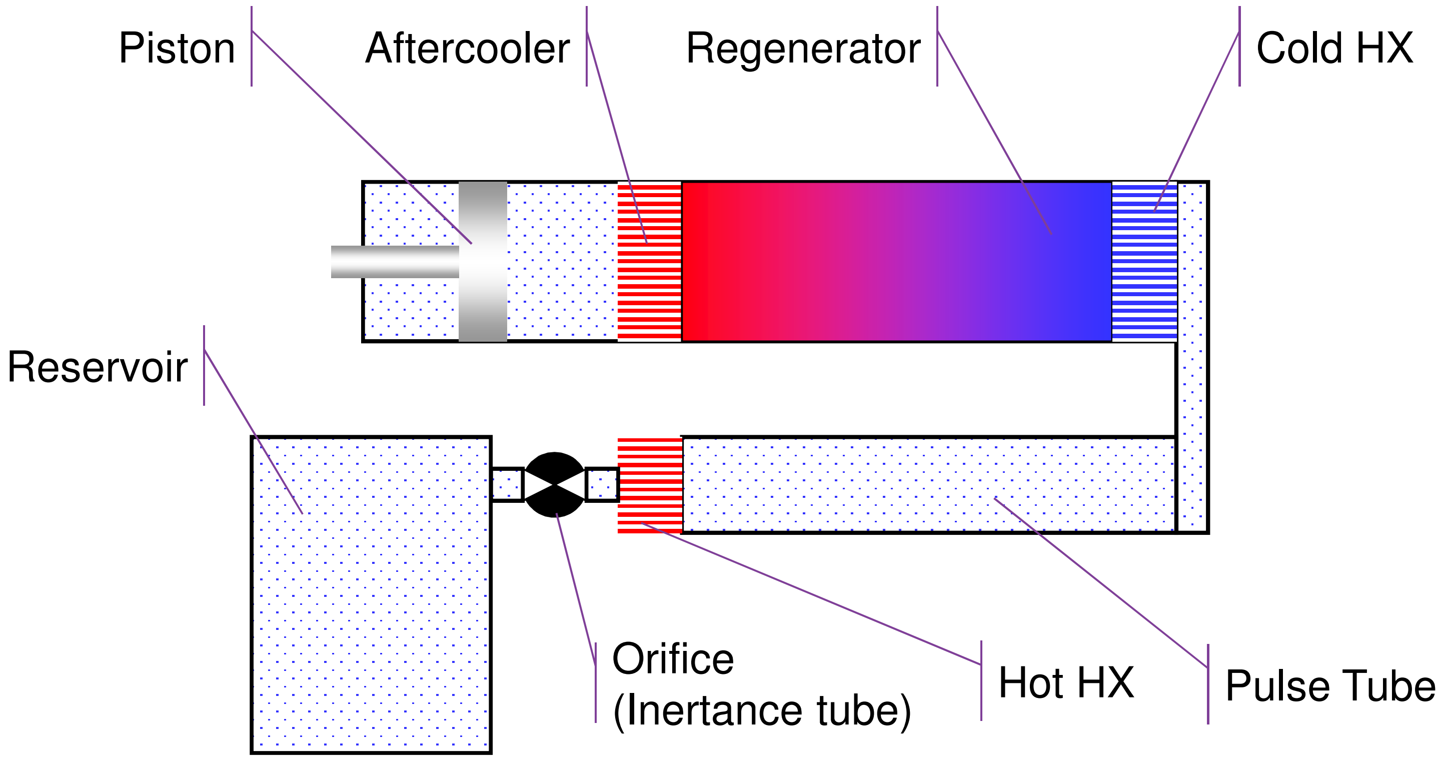
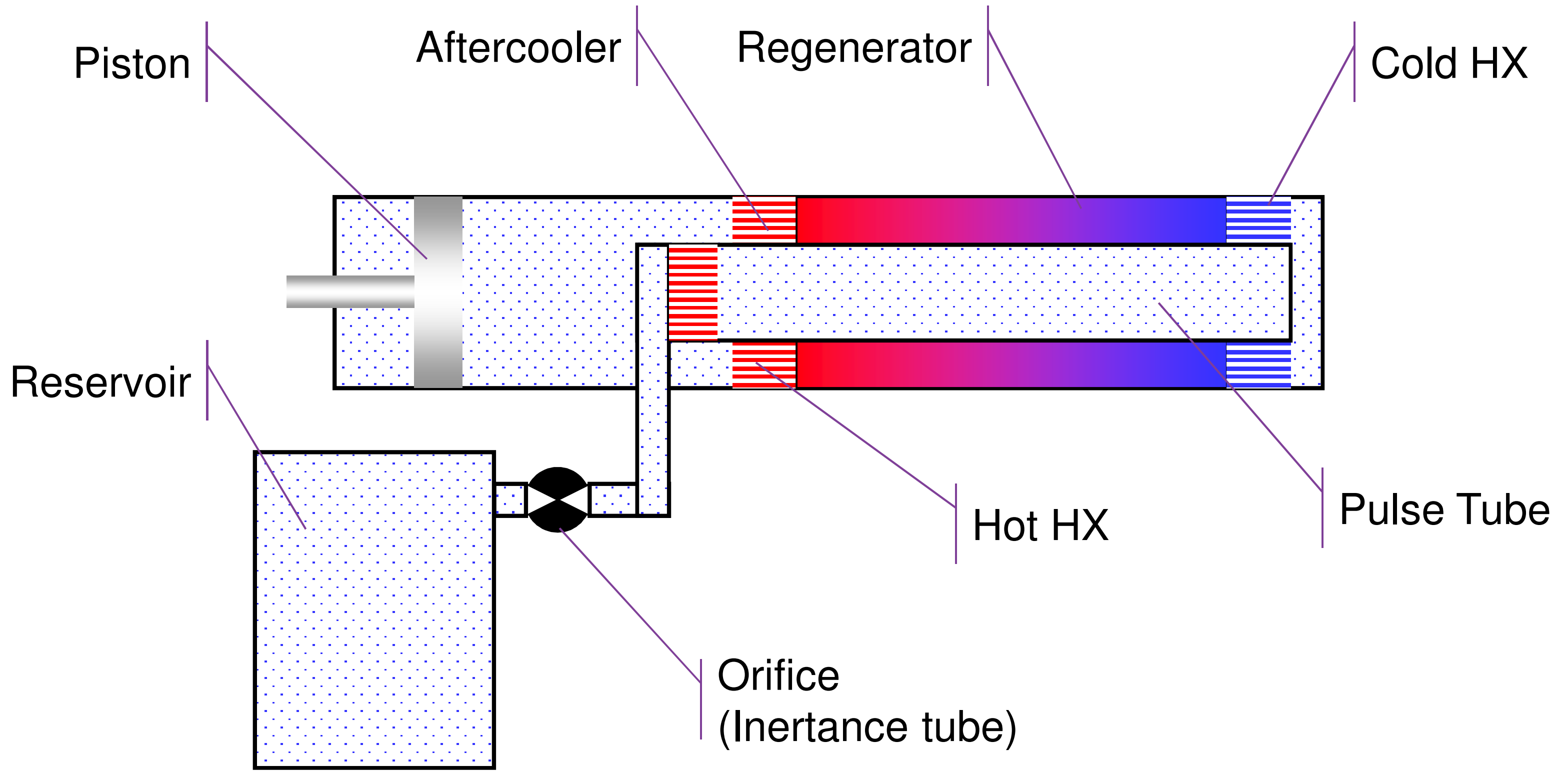
Inline PT configuration



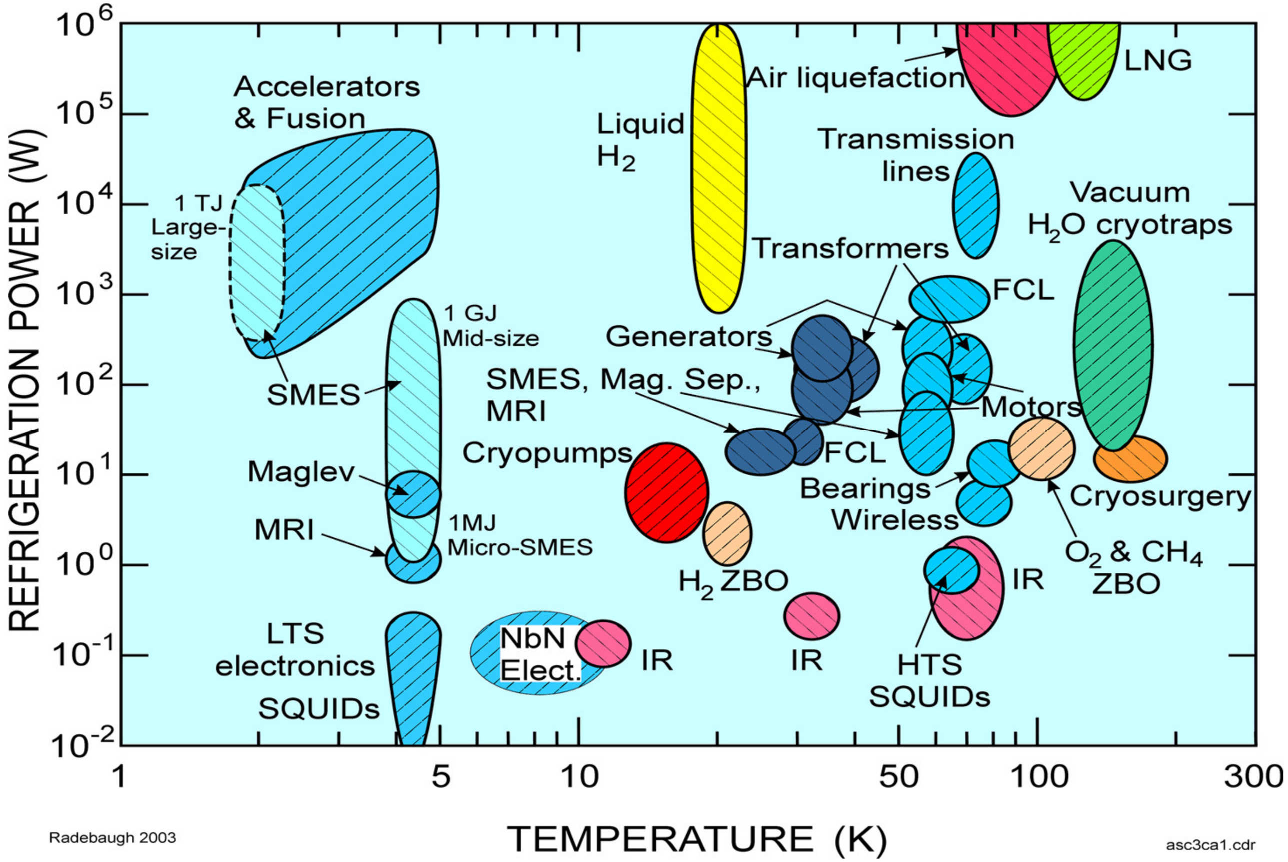
U-shape PT configuration



Coaxial PT configuration



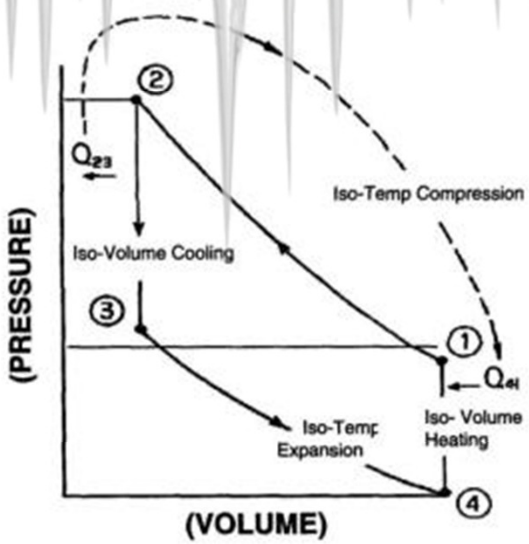
Typical Cryogenic Applications



Typical Cryogenic Applications

- IR – Infra Red imagers
- Vacuum applications
  - H_2O Vapor Cryotraps
  - Cryopumps
- HTSC (High Temperature Super Conductor) applications
  - RF-filters – Wireless communication
  - FCL (Fault Current Limiters) - Electricity
  - SQUID's - Superconducting QUantum Interference Device
  - Motors, Generators, Transformers
  - Magnetic Bearings
  - Magnetic Separators
- Air liquefaction
- Cryosurgery
- ZBO - zero boil-off storages
- MRI – magnetic resonance imaging
- etc

The End



Thanks for your attention