SNS COLLEGE OF TECHNOLOGY
(An Autonomous Institution)
COIMBATORE–35

DEPARTMENT OF AEROSPACE ENGINEERING

SPACE PROPULSION – Unit III
CRYOGENIC ENGINEERING

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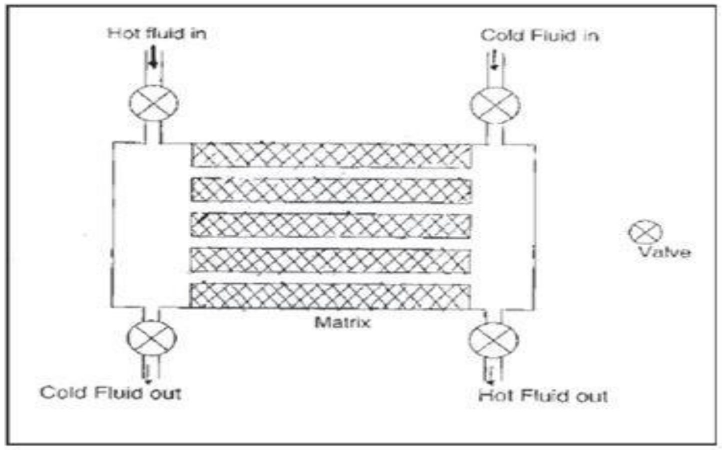
Effect of compressor and expander efficiencies on the performance of claude system/refrigerator?

- The compressor efficiency has no effect on the liquid yield,as long as enough energy is available to provide the required pressure levels for the cycle.
- However compressor work requirements are affected by the compressor efficiency.
- In fact actual work requirements are inversely proportional to the overall compressor efficiency.
- On the other hand,the efficiency of the expander affects both the liquid yield and the work requirements,if the expander work is utilized to help compress the gas.
- Also the adiabatic efficiency of the expander affects the enthalpy drop across the expander.

NOTE:This topic is beyond the scope of our syllabus..but it was asked once,so i am including a summary.To get full picture refer page 139-140 Barron.

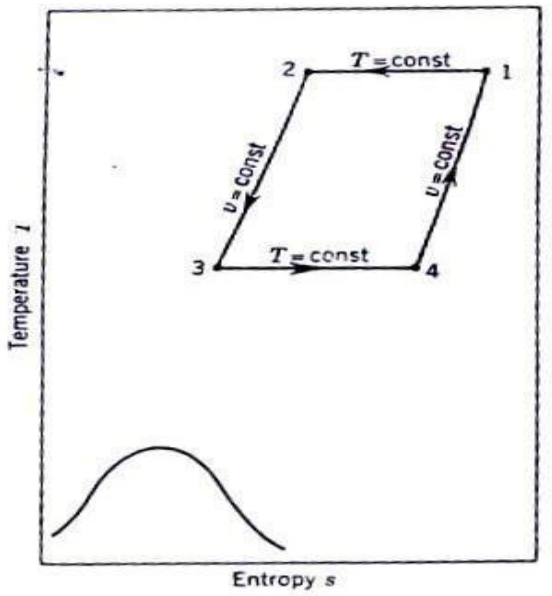
Regenerative heat exchanger-Regenerator

- A regenerative heat exchanger, or more commonly a regenerator, is a type of heat exchanger where heat from the hot fluid is intermittently stored in a thermal storage medium before it is transferred to the cold fluid.
- To accomplish this the hot fluid is brought into contact with the heat storage medium, then the fluid is displaced with the cold fluid, which absorbs the heat.
- In regenerative heat exchangers, the fluid on either side of the heat exchanger can be the same fluid.
- The fluid may go through an external processing step, and then it is flowed back through the heat exchanger in the opposite direction for further processing.
- Usually the application will use this process cyclically or repetitively.



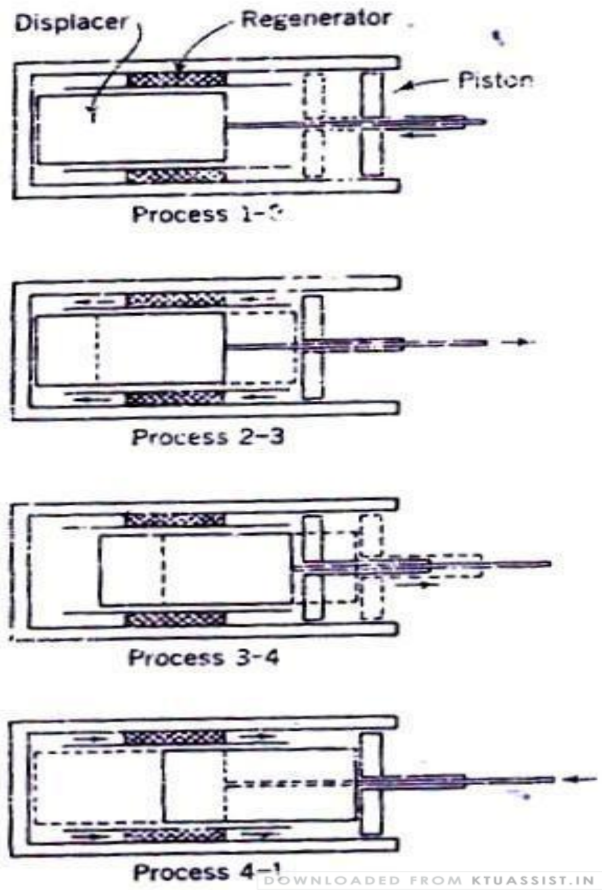
PHILIPS REFRIGERATOR(Stirling Cryocooler)

- The Philips refrigerator operates on the Stirling cycle, which was invented in 1816 by a Scottish minister, Robert Stirling, for use in a hot-air engine.
- The first Stirling cycle refrigerator was constructed by Alexander Kirk (Kirk 1874) around 1864.
- The Philips refrigerator consists of a cylinder enclosing a piston, a displacer, and a regenerator.
- The piston compresses the gas, while the displacer simply moves the gas from one chamber to another without changing the gas volume, in the ideal case.
- The heat exchange during the constant-volume process is carried out in the regenerator.



The sequence of operations for the system is as follows.

- **Process 1-2.** The gas is compressed isothermally while rejecting heat to the high-temperature sink (surroundings).**(Heat rejection)**
- **Process 2-3.** The gas is forced through the regenerator by the motion of the displacer. The gas is cooled at constant volume during this process. The energy removed from the gas is not transferred to the surroundings but is stored in the regenerator matrix.
- **Process 3-4.** The gas is expanded isothermally while absorbing heat from the low-temperature source. **(Refrigeration effect)**
- **Process 4-1**. The cold gas is forced through the regenerator by the motion of the displacer; the gas is heated during this process. **The energy stored during process 2-3 is transferred back to the gas. In the ideal case (no heat leaks), heat is transferred to the refrigerator only during process 3-4, and heat is rejected from the refrigerator only during process 1-2.**



Derivation of COP-Phillips Refrigerator (proven same as CARNOT)

- If we assume that the heat transfers to and from the refrigerator are reversible, the heat transferred may be determined by the Second Law of Thermodynamics.
- Heat rejected = $Q_r = mT_1(S_2 - S_1)$
- Heat absorbed = $Q_a = mT_3\,(S_4 - S_3)$
- where m is the mass of gas it' the refrigerator cylinder.
- By the First Law, Wnet = $Q_r + Q_a$ for a cycle, so the coefficient of performance of the ideal Philips refrigerator is

$$COP = \frac{-Q_a}{W_{net}} = \frac{T_3}{T_1(s_1 - s_2)/(s_4 - s_3) - T_3}$$

- If the working fluid behaves as an ideal gas. we may write

$$s_1 - s_2 = c_v \ln(T_1/T_2) + R\ln(\upsilon_1/\upsilon_2) = R\ln(\upsilon_1/\upsilon_2) = R\ln(\upsilon_4/\upsilon_3)$$

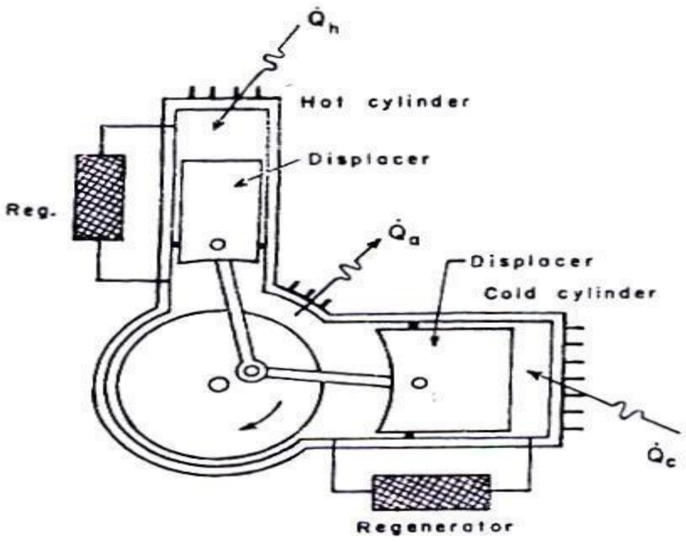
$= s_4 - s_3$

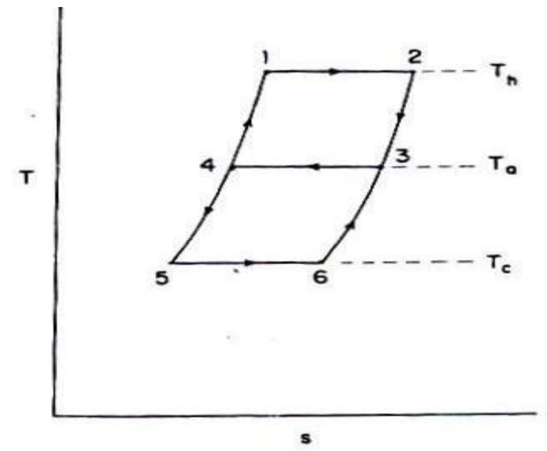
- The coefficient of performance of an ideal Philips refrigerator with an ideal gas as the refrigerant is

$$COP = \frac{T_3}{T_1 - T_3}$$

- **This is the same expression as that for the COP, of a Carnot refrigerator; therefore. the ideal Philips refrigerator would have a figure of merit of unity.**

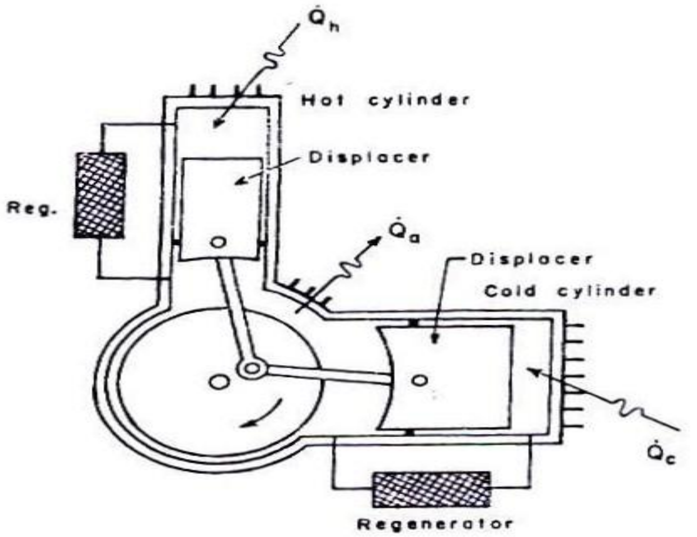
Vuilleumier refrigerator

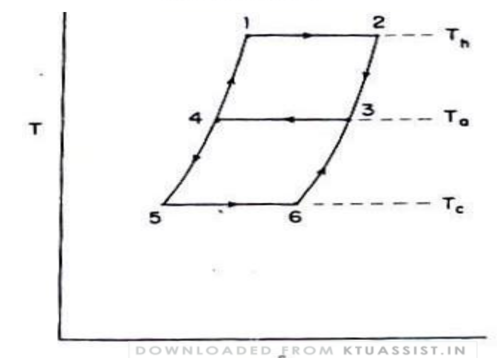




Vuilleumier refrigerator

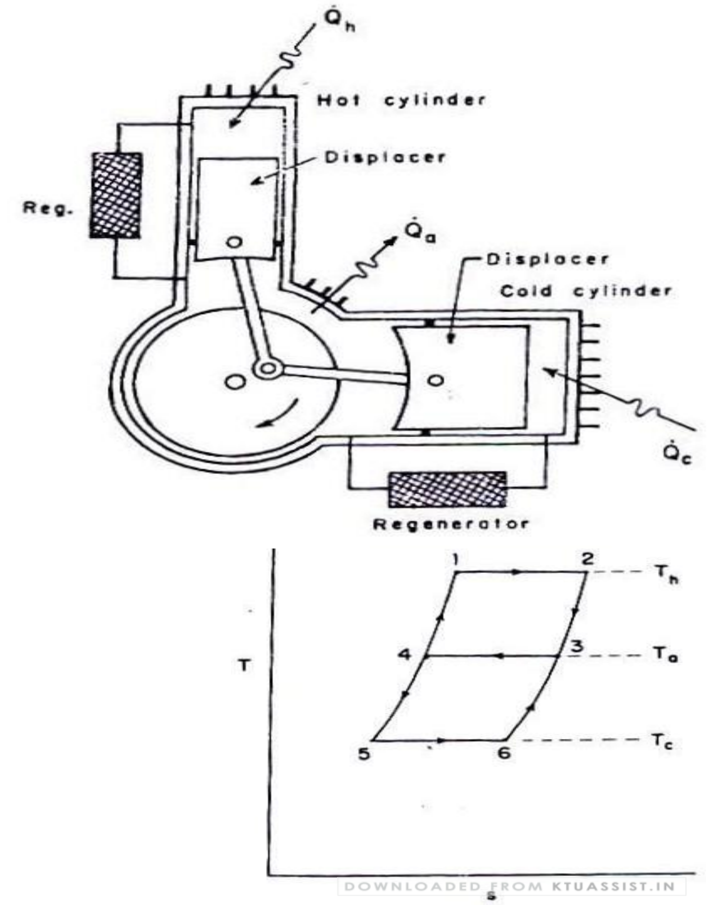
- The Vuilleumier refrigerator, first patented by Rudolph Vuilleumier in 1918, is similar to the Stirling refrigerator, except the VM refrigerator uses a "thermal" compressor instead of a mechanical compressor.
- In the ideal VM cycle, heat is added from a high-temperature source to the gas in the "hot" cylinder, and the displacer moves downward to maintain the temperature of the gas constant at T_h (process 1-2).
- At the same time, near-ambient temperature gas flows from the intermediate volume through the regenerator to the hot volume (process 4-1).
- The displacer then moves upward and gas is displaced from the hot volume to the intermediate volume (process 2-3).



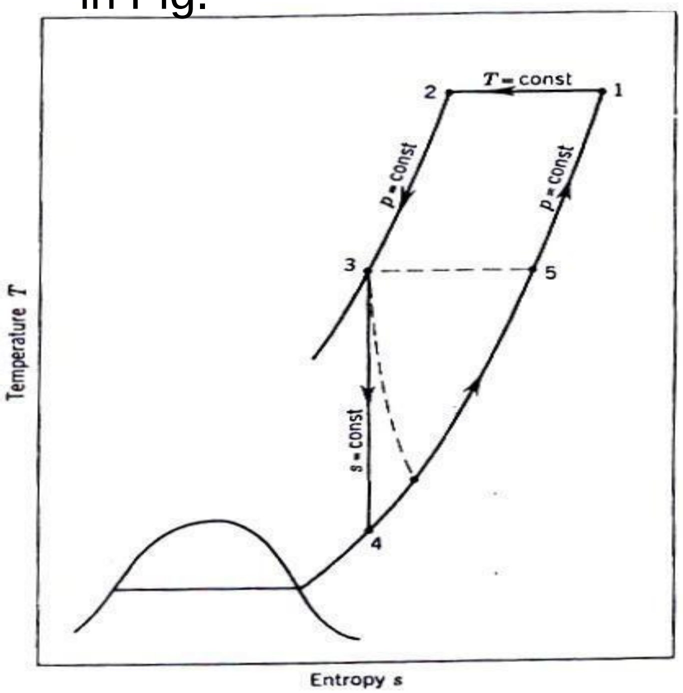


Vuilleumier refrigerator

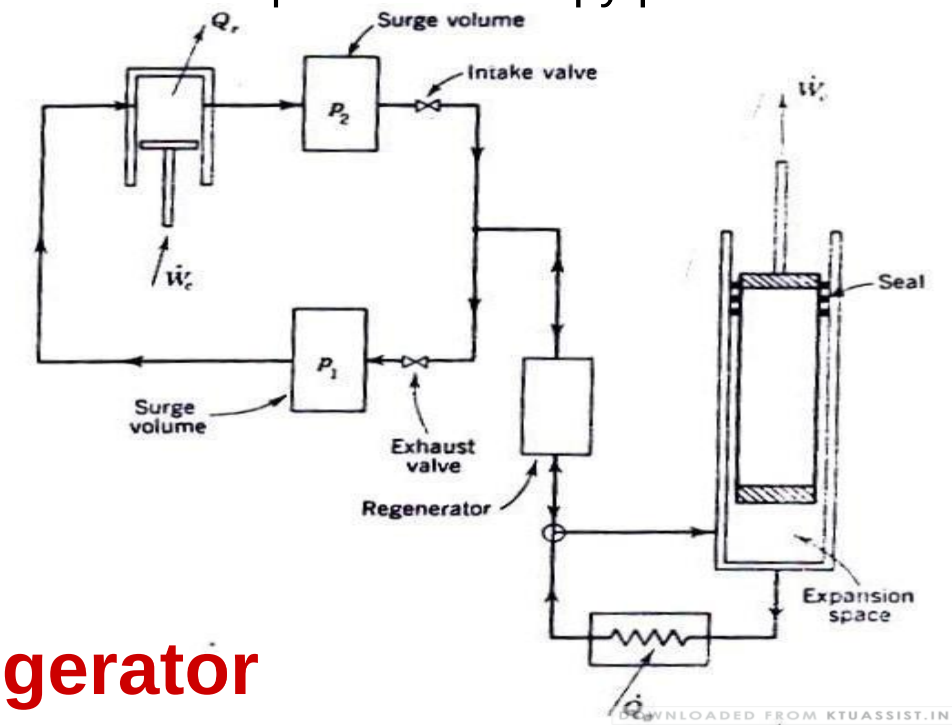
- Heat is rejected from the intermediate volume to maintain the temperature of the gas in the volume constant at T. (process 3-4).
- As the cold displacer is moved to the left, heat is absorbed by the gas in the cold volume from the low-temperature source to maintain the gas temperature constant at T, (process 5-6).
- At the same time, gas from the intermediate volume flows through the cold regenerator to the cold volume (process 4-5).
- The cold displacer then moves back to the right, and gas is displaced from the cold volume through the cold regenerator to the intermediate volume (process 6-3).



- The Solvay refrigerator was invented in Germany about 1887
- The Solvay refrigerator is shown schematically in Fig.If we were to consider a unit mass of gas as it flows through the system, if would trace out the path on the temperature-entropy plane as shown in Fig.

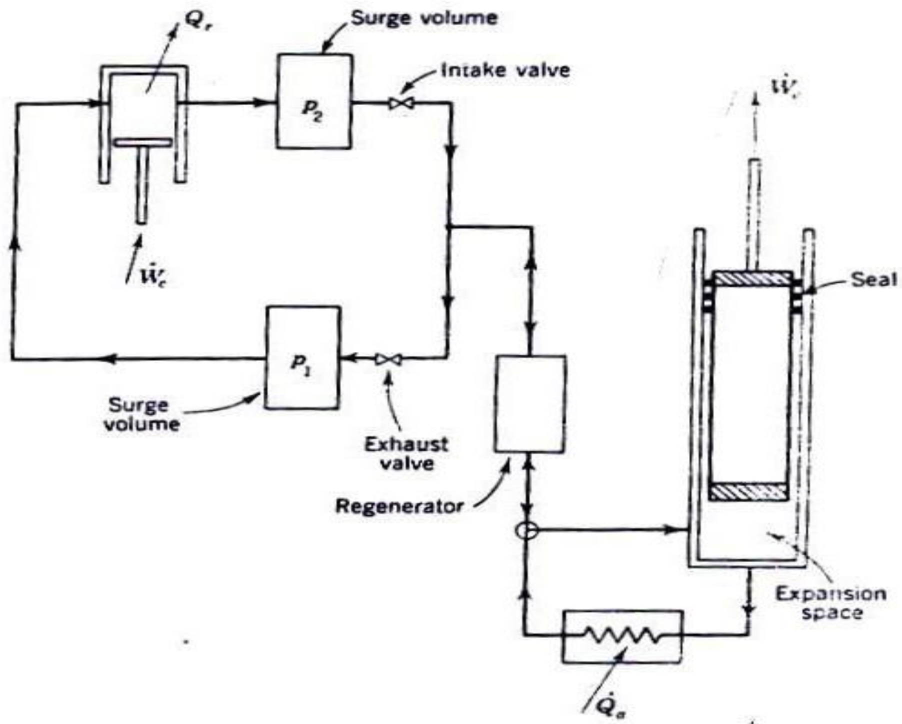


Solvay refrigerator



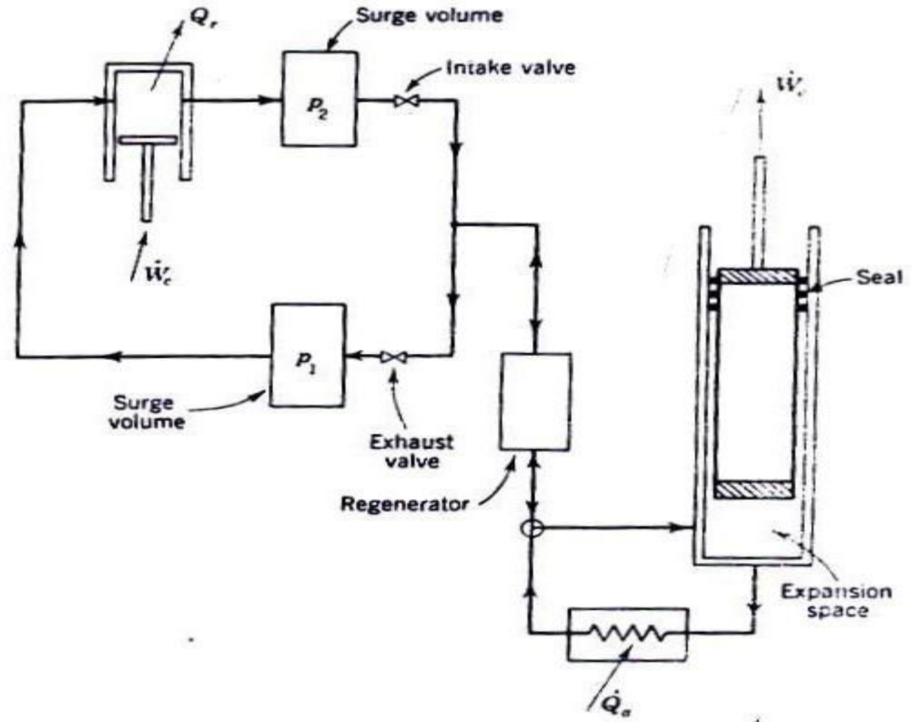
Solvay refrigerator

- **Process 1-2**. With the piston at the bottom of its stroke, the inlet valve is opened. The high-pressure gas flows into the regenerator,and the system pressure is increased from a low pressure P_1 to a higher pressure P_2
- **Process 2-3.** With the inlet valve still open, the piston is raised to draw a volume of gas into the cylinder. The gas has been cooled during its flow through the regenerator.
- **Process 3-4.** The inlet valve is closed, and the gas within the cylinder is expanded (isentropically in the ideal case) to the initial pressure P_1. As the gas expands, it does work on the piston, and energy is removed from the gas as work. The temperature of the gas therefore decreases.

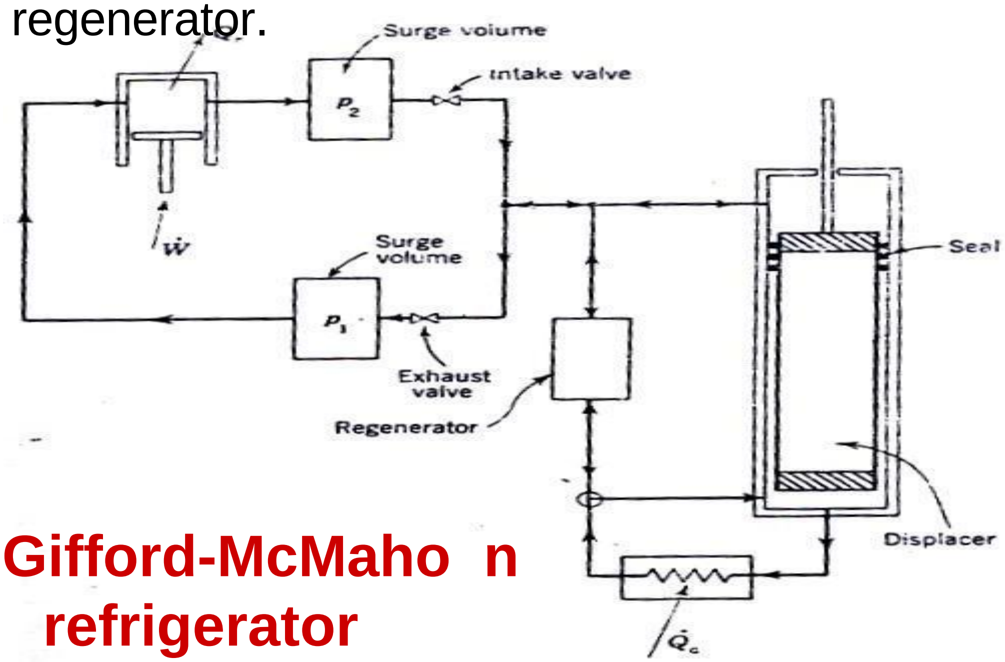


Solvay refrigerator

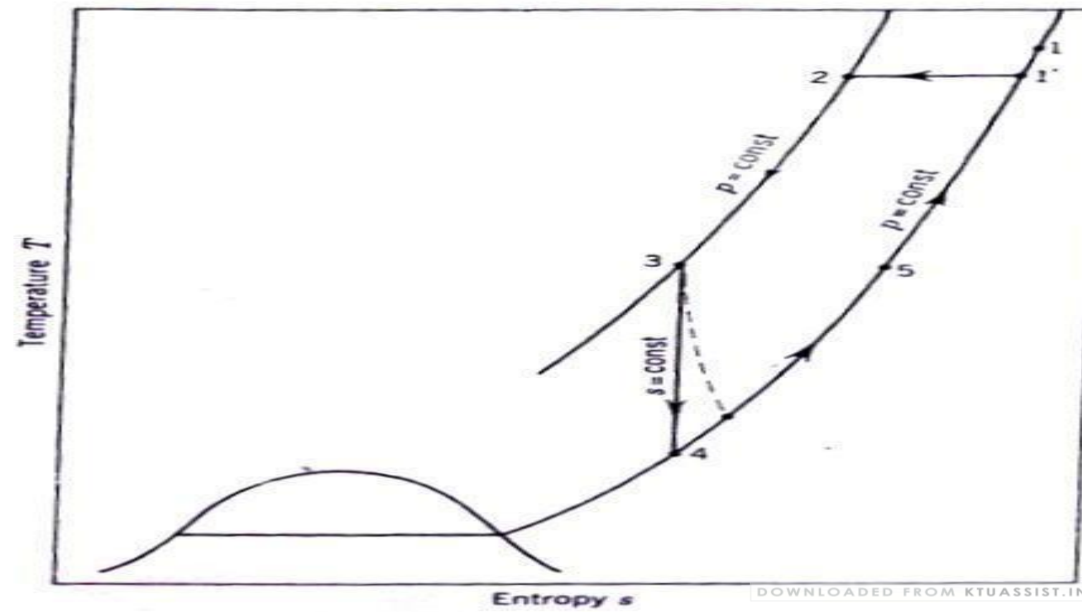
- **Process 4-5**. The exhaust valve is opened, and the piston is lowered to force the cold gas out of the cylinder. During this process, the cold gas passes through a heat exchanger to remove heat from the cooled space.
- **Process 5-1**. The gas finally passes out through the regenerator, in which the cold gas is warmed back to room temperature.



his system consists of a compressor, a cylinder closed at both ends, a displacer within the cylinder, and regenerator. **This system differs from the Solvay refrigerator in that no work is transferred from he system during the expansion process.** The displacer serves the purpose of moving the gas from ne expansion space to another and would do zero net work in the ideal case of zero pressure drop in he regenerator.



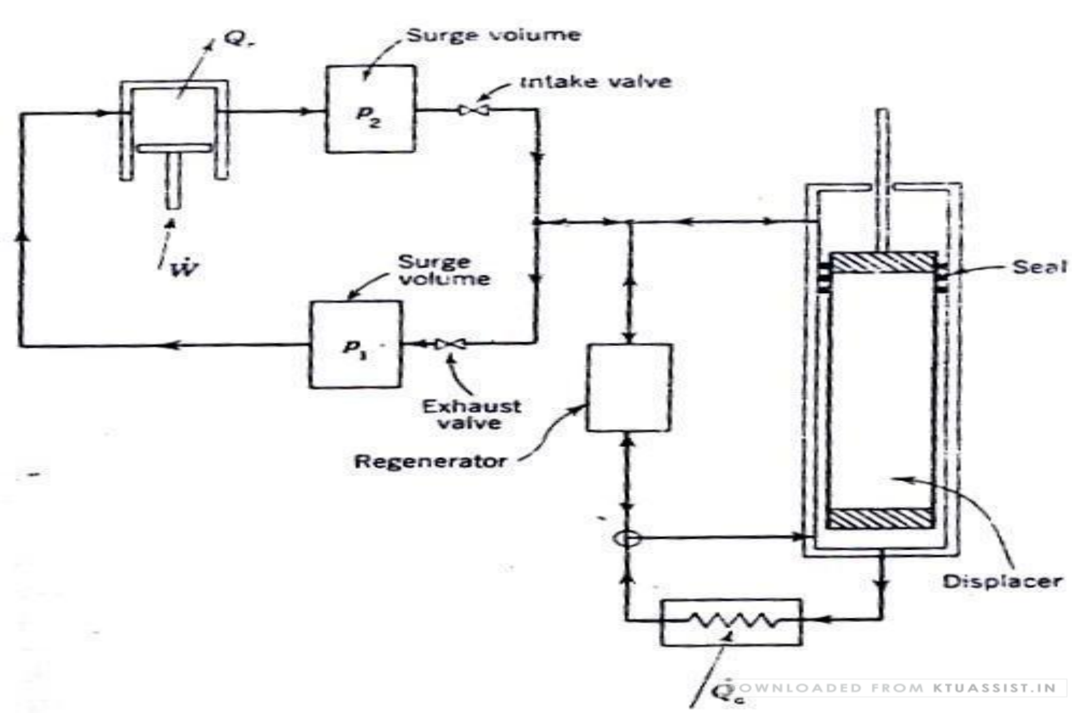
Gifford-McMaho n refrigerator



Gifford-McMahon refrigerator

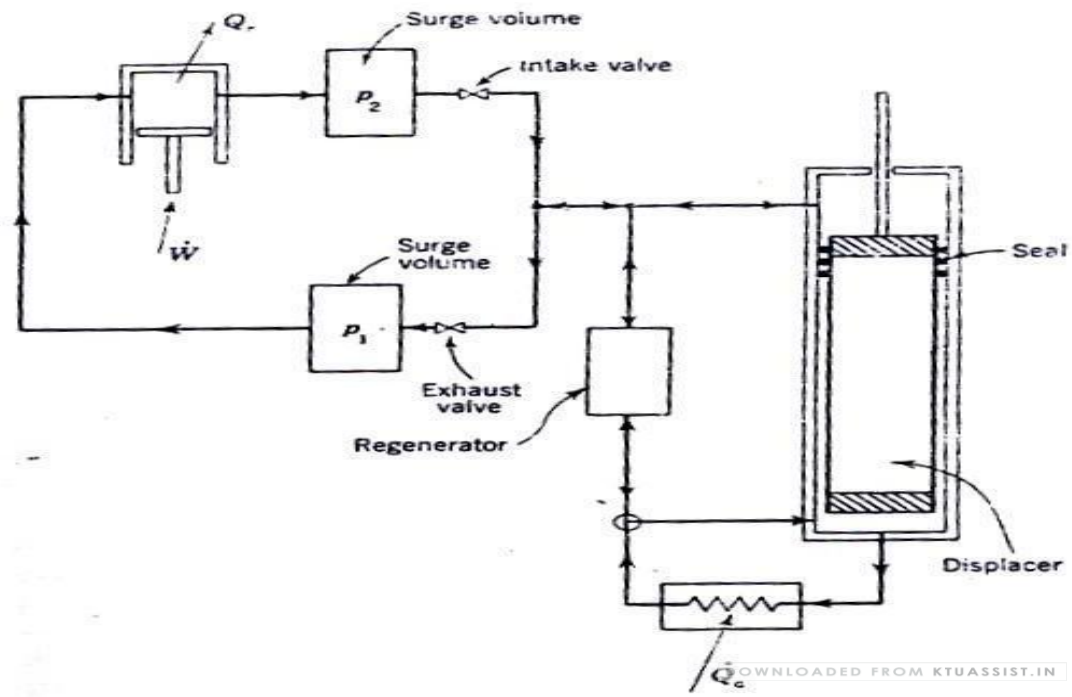
Process 1-2. With the displacer at the bottom of the cylinder, the inlet valve is opened and the pressure within the upper expansion space is increased from a low pressure P1 to a higher pressure p2. The volume of the lower expansion space is practically zero during this process because the displacer is at its lowest position.

Position 2-3:With the inlet valve still open and the exhaust valve closed, the displacer is moved to the top of the cylinder. This action moves the gas that was originally in the upper expansion space down through the regenerator to the lower expansion space. Because the gas is cooled as it passes through the regenerator, it will decrease in volume so that gas will be drawn in through the inlet valve during this process to maintain a constant pressure within the system.



Gifford-McMahon refrigerator

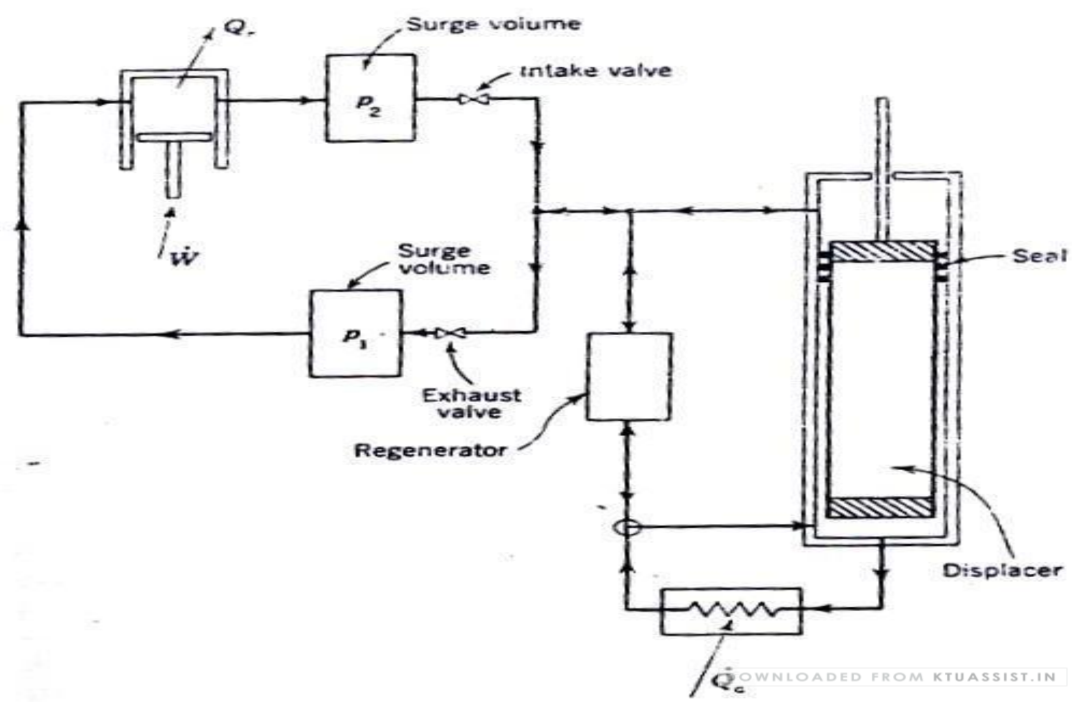
Process 3-4. With the displacer at the top of the cylinder, the inlet valve is closed and the exhaust valve is opened, thus allowing the gas within the lower expansion space to expand to the initial pressure P1 The gas that is finally within the lower expansion space does work to push out the gas that leaves during this process; therefore, energy is removed as work from the gas finally left in the lower expansion space. This causes the gas in the lower expansion space to drop to a low temperature. This process is similar to the expansion process in the Simon liquefier (see Sec. 3.20).



Gifford-McMahon refrigerator

Process 4-5. The low-temperature gas is forced out of the lower expansion space by moving the displacer downward to the bottom of the cylinder. This cold gas flows through a heat exchanger in which heat is transferred to the gas from the low-temperature source.

Process 5-1. The gas flows from the heat exchanger through the regenerator, in which the gas is warmed back to near ambient temperature.



DILUTION REFRIGERATOR

- A He-3/He-4 dilution refrigerator is a cryogenic device that provides continuous cooling to temperatures as low as 2 mK, with no moving parts in the very-low-temperature region.
- The cooling power is provided by the heat of mixing of the Helium-3 and Helium-4 isotopes.
- The idea that cooling could be achieved by means of dilution of He-3 by superfluid He-4 (dilution refrigerator) was first proposed by Heinz London in the early 1950s, and was experimentally realized in 1964 in the Kamerlingh Onnes Laboratorium at Leiden University.

DILUTION REFRIGERATOR

- A schematic of He^3-He^4 dilution refrigerator is shown
- The gas (pure He-3)is compressed in a vacuum pump from 4 Pa to 4kPa.
- It is then cooled in a heat exchanger.
- It is then passed through a liquid helium bath and thus cooled to 4.2K.
- It is then passed through a bath in which liquid heli boiling at 1.2K,hence the gas(pure He^3) is now condens liquid helium and its temperature reduced to 1.2K
- It is now passed through a capillary tube(hence c further) into a "still" which is maintained at 0.6K.
- Now the liquid He is at 0.6K.

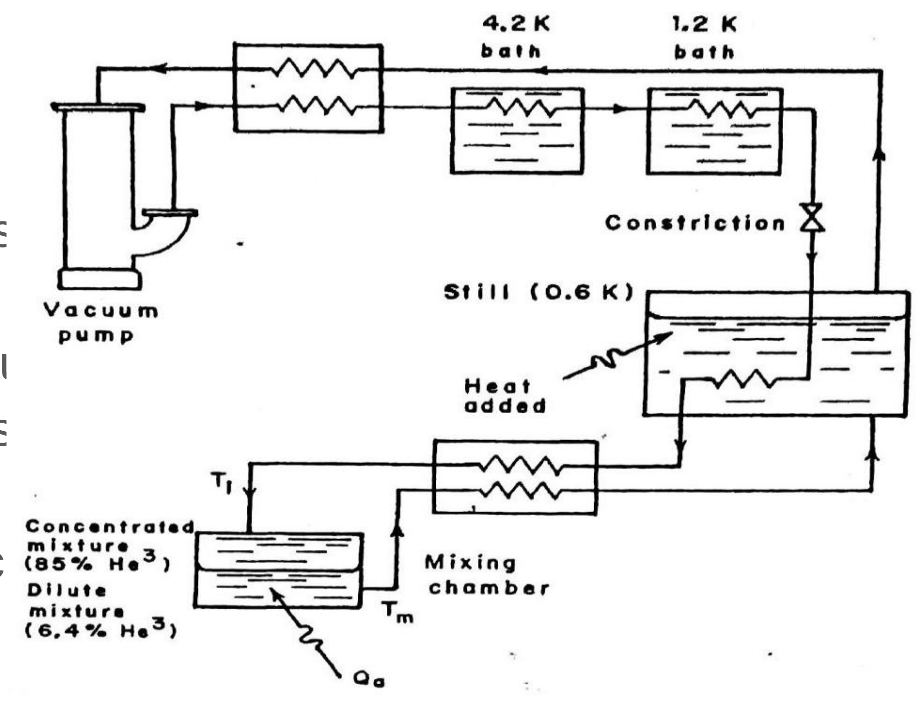


Fig. 5.31. He^3-He^4 dilution refrigerator schematic.

DILUTION REFRIGERATOR

- The liquid helium is now passed through a heat exchanger where it is further cooled.
- The liquid helium then enters the mixing chamber,where the He-3 is mixed with He-4 at temperatures between 0.005K and 0.050K.
- In the mixing chamber,the liquid separates into two phases:
    - One phase we'll call the He-3 rich phase, because it contains mostly He-3
    - The second phase we'll call the He-3 dilute phase OR He-4 rich phase, because it is mostly He-4, it will, however, always be composed of at least 6% He-3, no matter what temperature.
- The two phases are maintained in liquid-vapor form. Since there is a boundary between both phases, extra energy is required for particles to go from one phase to another.

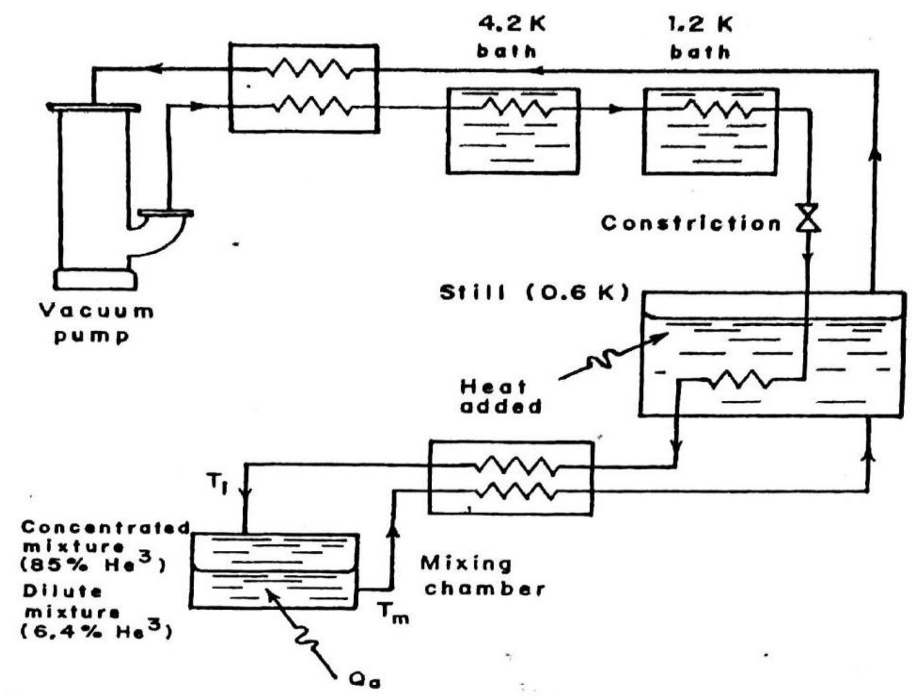


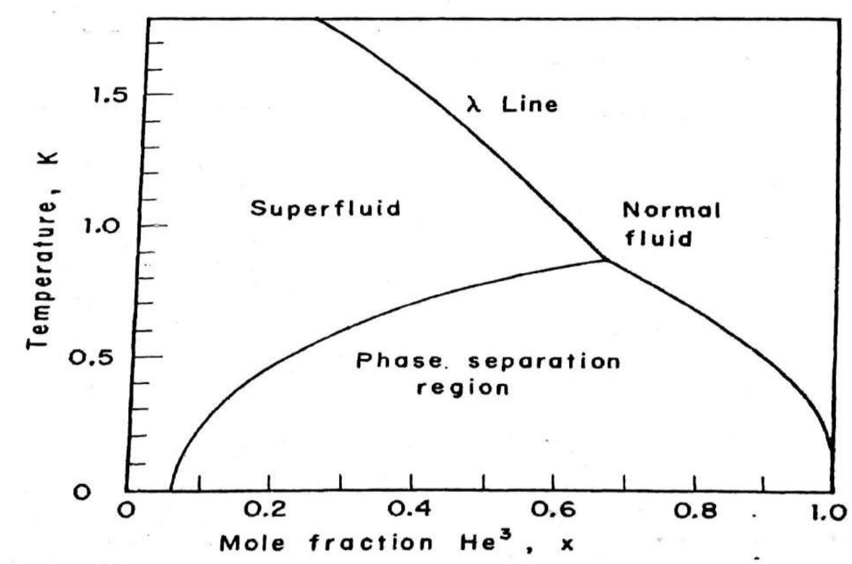
Fig. 5.31. He^3-He^4 dilution refrigerator schematic.

DILUTION REFRIGERATOR

- Inside the chamber, the He-3 is diluted as it flows from the concentrated phase through the phase boundary into the dilute phase.
- However, it needs energy to get past the boundary.
- The energy is in the form of heat, from the walls of the mixing chamber; the walls are in thermal contact with whatever you're trying to cool down.
- The heat necessary for the dilution is the useful cooling power of the refrigerator, as the process of moving the He-3 through the

  phase boundary is endothermic and removes heat from the mixing chamber environment.(space to be refrigerated)

Fig. 5.32. Phase diagram for He^3-He^4 mixtures.



DILUTION REFRIGERATOR

- **Another way of thinking** about this process is in terms of expansion.
- He-4 is inert, in that it does not react with other molecules and thermodynamically can be thought of as a vacuum in some situations.
- Thus when the He-3 moves from the 3He rich phase to the He-4 rich phase, it expands into an almost vacuum.
- This expansion takes heat out of the walls of the mixing chamber, reducing the temperature of whatever you're trying to cool.
- The dilute mixture returns through the heat exchanger to the sill where heat is added to evaporate the He-3 from the mixture,which goes to the vacuum pump and the cycle continues

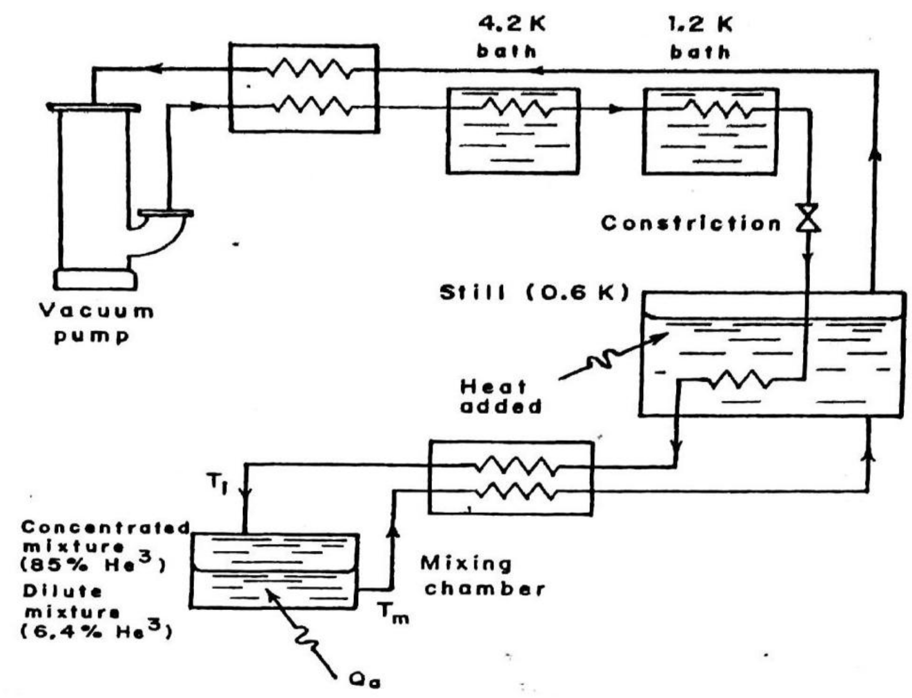


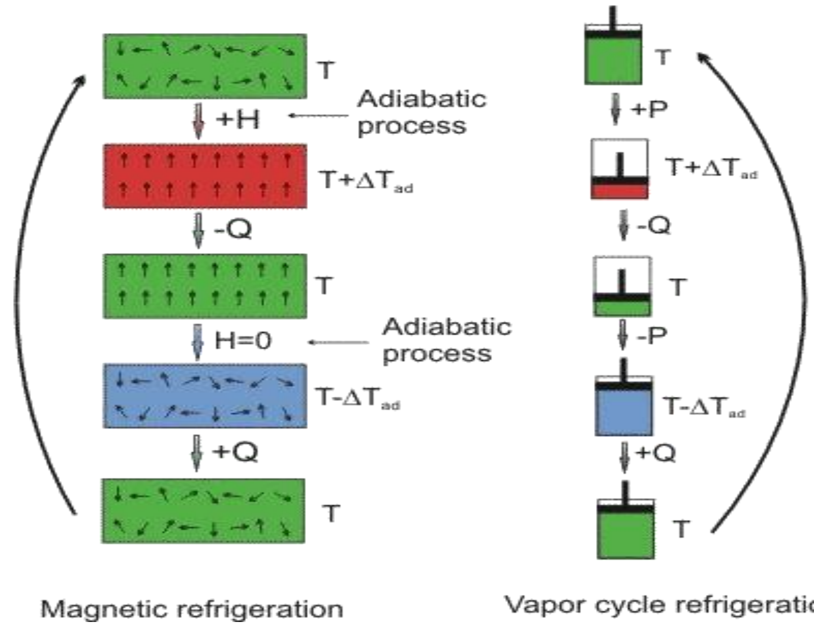
Fig. 5.31. He^3-He^4 dilution refrigerator schematic.

Refrigeration using Solids as Working Medium Magnetic Cooling(Adiabatic Demagnetization)

- In all the systems discussed previously,either a liquid or a gas was used as the working substance.For these systems,the lowest temperature that we can achieve is 0.6K (using helium).
- Giauque and Debye independently suggested a way to break this “temperature barrier” to achieve absolute zero temperature.
- They pointed out that a paramagnetic substance could be used instead of a gas or liquid and that a magnetic field could be used instead of the expansion of the fluid to attain the lower temperature.

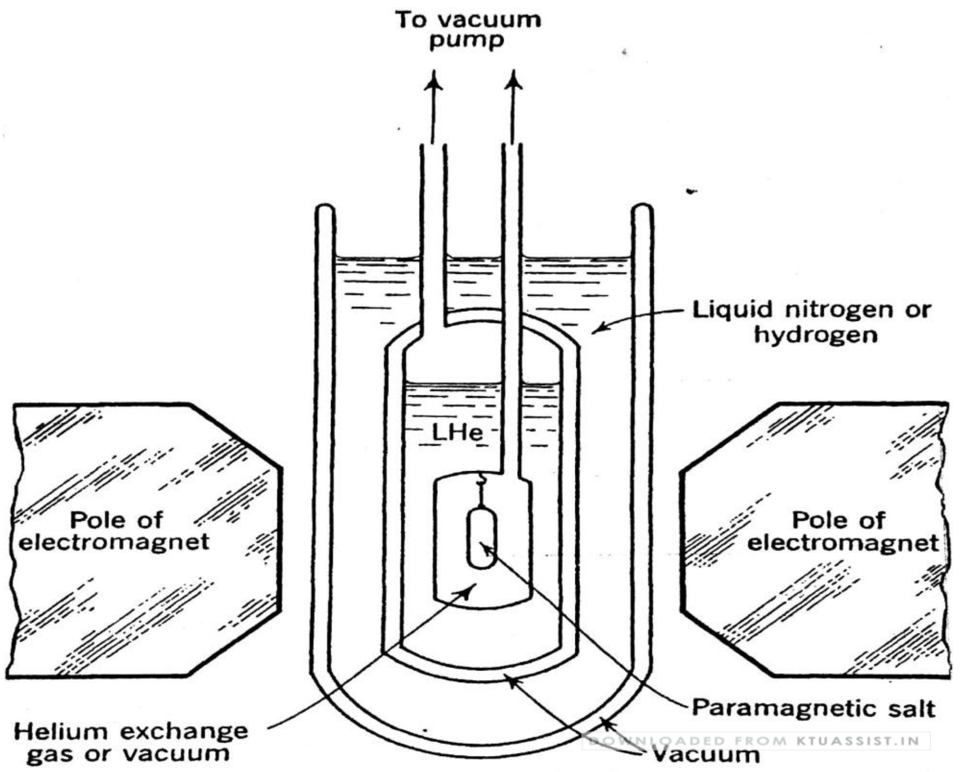
Adiabatic Demagnetization:How it works?

- In the **absence of an external magnetic field,** the dipoles of the paramagnetic material are more or less **randomly arranged(high entropy),** even at low temperatures.
- If we **apply a magnetic field at constant temperature(analogous to compressing a gas isothermally)**,we shall tend to align the magnetic moments of the atoms of the paramagnetic material,**thereby introducing order or decreasing the entropy** of the material.
- Now,if the **magnetic field is removed reversibly and adiabatically ie isentropically(corresponding to a reversible adiabatic expansion of the gas)**,the alignment of the **dipole moments is now disordered**,**but the entropy should remain contant.(isentropic)**.
- **To maintain entropy constant.even after alignment is disordered.the temperature of the paramagnetic material must decrease**
- This process is called **adiabatic demagnetisation.**and it is this process **that allows us to enter the temperature region below 0.6K**

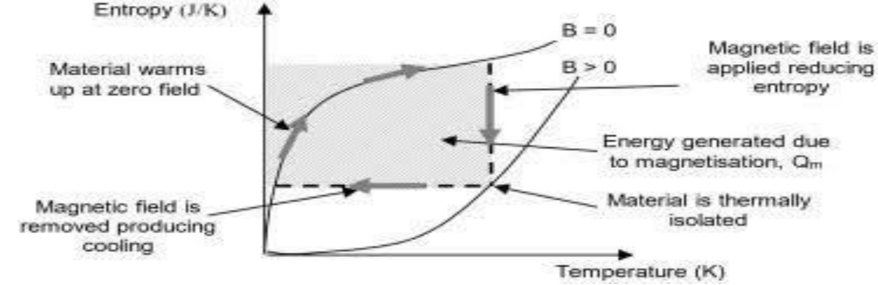


Adiabatic Demagnetization:Apparatus

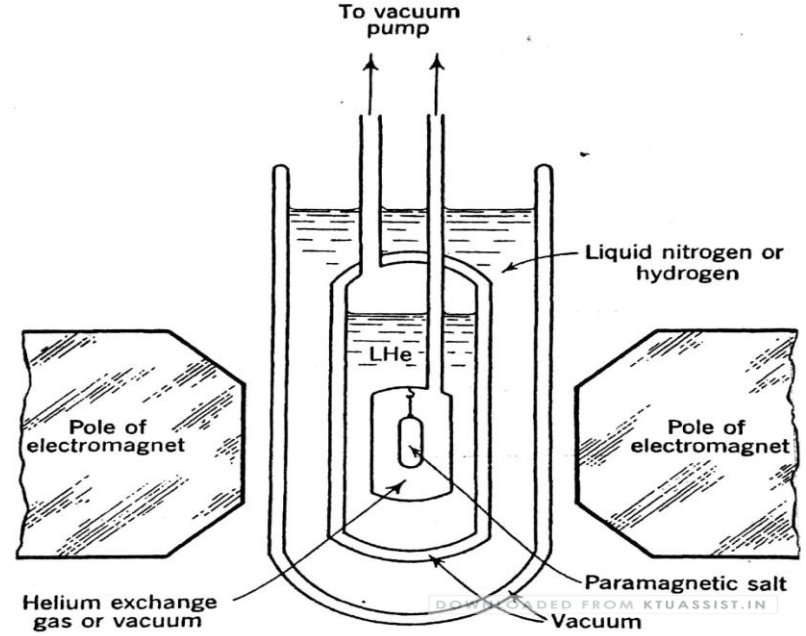
- A schematic of an apparatus to carry out the adiabatic demagnetization process is shown in figure.
- A paramagnetic salt pellet is suspended in a chamber by silk or nylon threads.
- This chamber is initially filled with gaseous helium,and the chamber is then immersed in a liquid helium bath.
- The liquid helium is boiling under reduced pressure,so its temperature and the temperature of the paramagnetic salt are about 1K.
- The helium bath is surrounded by a liquid nitrogen/hydrogen shield to reduce the heat transfer from ambient to the helium bath.
- This entire assembly is placed between the poles of a powerful electromagnet,which is shaped so that the field of the magnet is concentrated around the salt pellet.



- The magnetic field is turned on and maintained for about an hour to allow the heat of magnetization(similar to the heat developed during compression of a gas) to be conducted to the helium bath by the gaseous helium in in the small chamber,thereby maintaining the salt at its original temperature.
- When thermal equilibrium is attained,the gaseous helium(which is called an exchange gas) is to pumped away thermally isolate the paramagnetic salt.
- The magnetic field is then removed, and the temperature of the salt drops to a very low value.
- Temperatures as low as 0.0014K have been obtained by by this method.

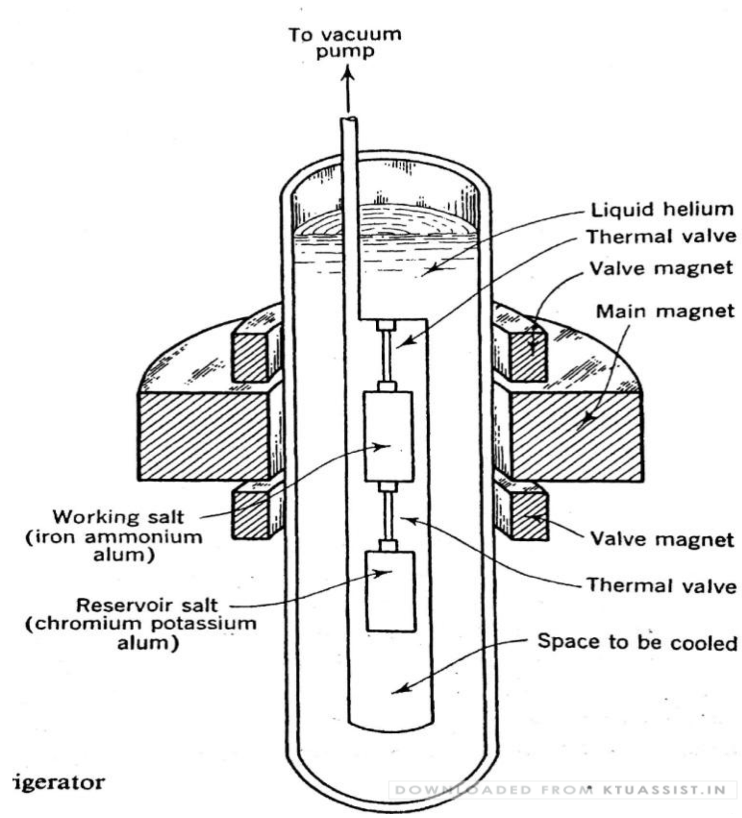


Adiabatic Demagnetization:Apparatus



Magnetic Refrigerator

- Figure shows the **schematic of a magnetic refrigerator** working on the principle of adiabatic demagnetisation.
- **Process1-2:**The magnetic field is applied to the working salt while the upper **thermal valve(valve for enabling and disabling heat conduction)** is open and lower thermal valve is closed.
- When the upper thermal valve is open,heat may be transferred from the working salt to the liquid helium bath,thereby maintaining the salt temperature fairly constant,
- The thermal valve between the working salt and the reservoir salt is closed so that the heat will not flow back into the low temperature reservoir during the process.
- **Process 2-3**:Both thermal valves are closed,and the magnetic field around the working salt is reduced adiabatically to some intermediate valve.During the process,the temperature of the working salt decreases.



- Figure shows the schematic of a magnetic refrigerator working on the principle of adiabatic demagnetisation.
- **Process 3-4:** The thermal valve between the working salt and the reservoir salt is opened and the field around the working salt is reduced to zero while heat is absorbed isothermally by the working salt from the reservoir salt.
- **Process 4-1**: Both thermal valves are closed, and the magnetic field around the working salt is adiabatically increased to its original value.

Magnetic Refrigerator