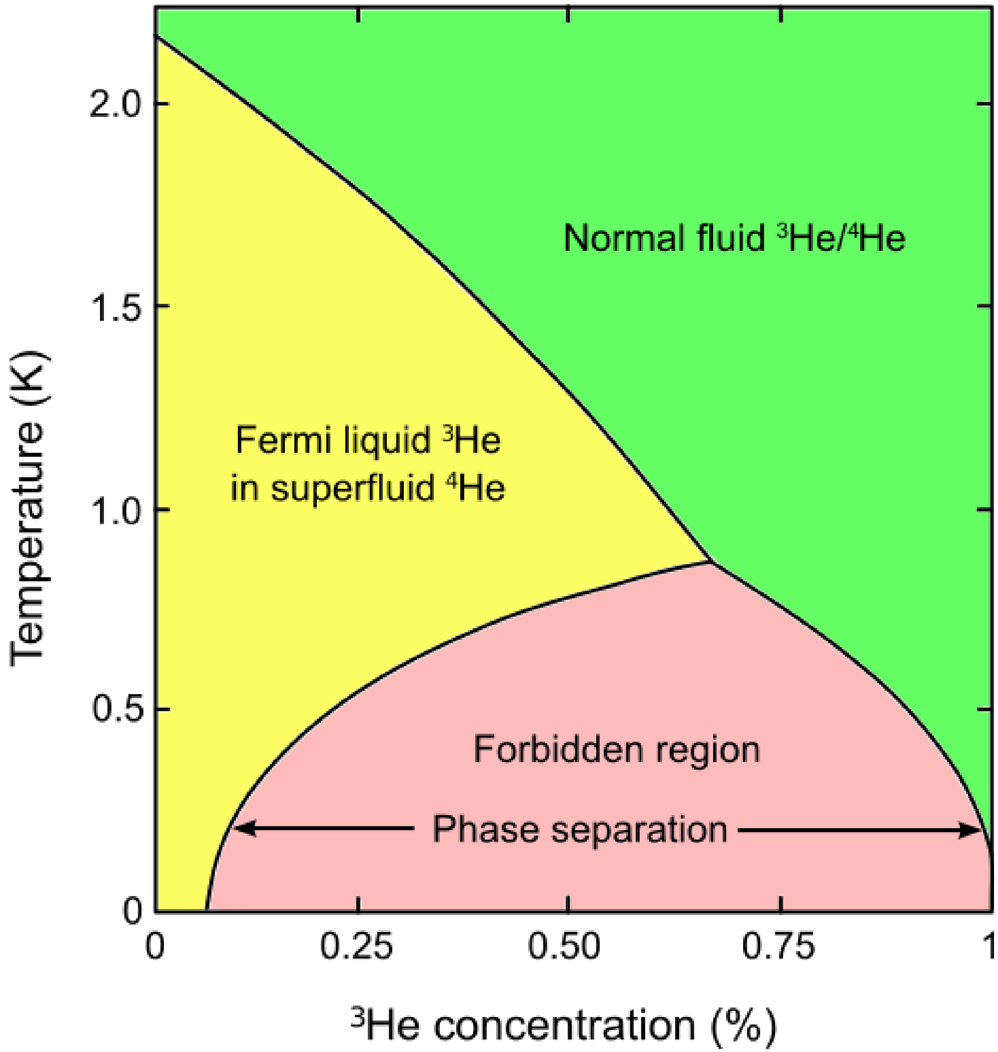
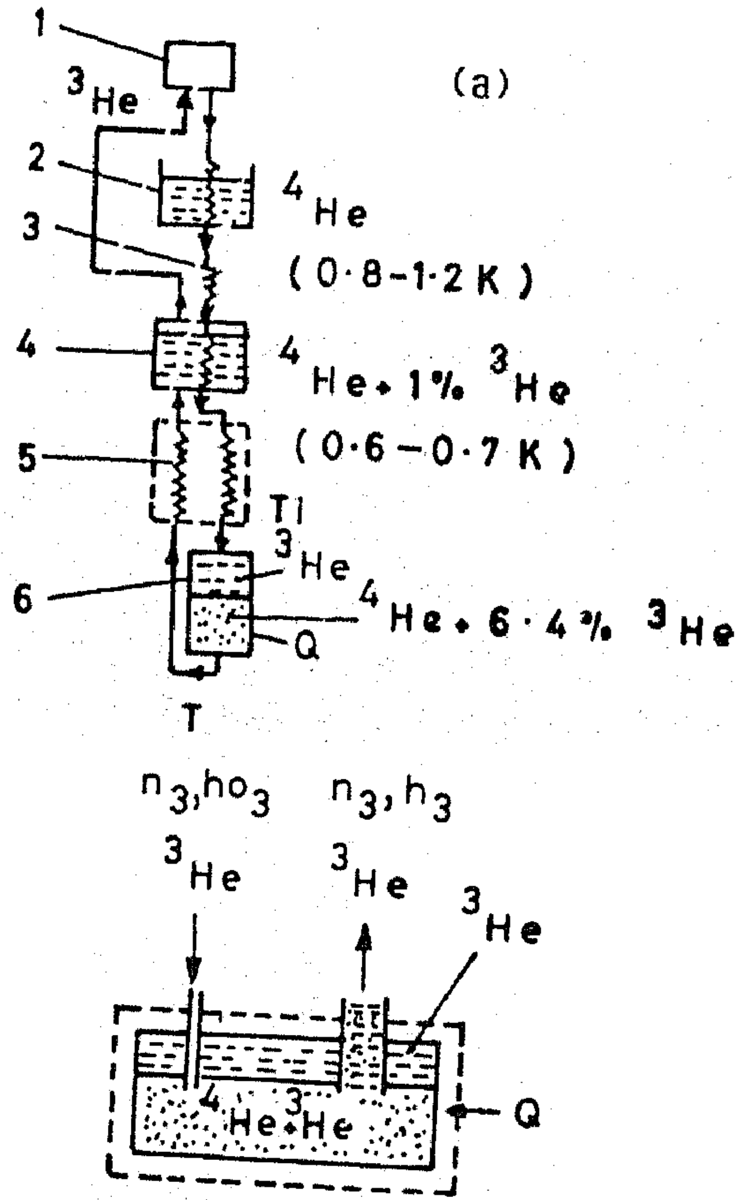
He^3 dilution refrigerator

A **helium-3 refrigerator** is a simple device used in experimental physics for obtaining temperatures down to about 0.2 kelvins. By evaporative cooling of helium-4 (the more common isotope of helium), a 1-K pot liquefies a small amount of helium-3 in a small vessel called a helium-3 pot. Evaporative cooling of the liquid helium-3, usually driven by adsorption since due to its high price the helium-3 is usually contained in a closed system to avoid losses, cools the helium-3 pot to a fraction of a kelvin.



Phase diagram of liquid ^{3}He-^{4}He mixtures.
Above 0.87K the two phase in a same phase and miscible.
Below 0.87K, two distinct phases, lighter or upper He3 and denser is He4.
At these T, the entropy of superfluid He4 is small compared to He3. So when He4 is mixed with He3, He3 behaves as an expanding gas and the process is endothermic. The whole process is adiabatic.
He3 diffuse through He4 where He3 conc is smaller.
At 0.6K, vapour pressure of He3 is > He4, so He3 will evaporate preferentially.



The vac. Pump 1 which cirulates He3 delivers He3 gas at P~67-80kPa. This stream is first cooled in an LN2 bath and an Lhe bath and then to about 1K in a pumped Lhe bath. The liquified He3 is then passed through a capillary which controls its flow rate. Next this stream enters a coil type still, 4, whose temperature is 0.6 to 0.7K. Then this stream passes through a batch of heat exchanger where it is cooled and enters a mixing chamber. In the mixing chamber the feed separates into two phases, lighter is pure He3 and lower denser is dilute mixture of He3 in He4.

Inside the chamber, the ^3He is diluted as it flows from the concentrated phase through the phase boundary into the dilute phase. The heat necessary for the dilution is the useful cooling power of the refrigerator, as the process of moving the ^3He through the phase boundary is endothermic and removes heat from the mixing chamber environment. The ^3He then leaves the mixing chamber in the dilute phase. On its way up, the cold, dilute ^3He cools the downward flowing ^3He via the heat exchangers until it enters the still. In the still, the ^3He flows through superfluid ^4He which is at rest. The ^3He then leaves the mixing chamber in the dilute phase. On its way up, the cold, dilute ^3He cools the downward flowing ^3He via the heat exchangers until it enters the still. In the still, the ^3He flows through superfluid ^4He which is at rest.The pressure in the still is kept low (about 10 Pa) by the pumps at room temperature. The vapor in the still is practically pure ^3He, which has a much higher partial pressure than ^4He at 500–700 mK. The pump therefore creates an osmotic pressure difference, which drives more ^3He from the concentrated to dilute phases in the mixing chamber, and then up from the mixing chamber to the still. Heat is supplied to the still to maintain a steady flow of ^3He. The pumps compress the ^3He to a pressure of a few hundred millibar and feed it back into the cryostat, completing the cycle.

At not to low temperatures the cooling power at the mixing chamber is approximately given by,

$$\dot{Q}_m = \dot{n}_3\left(12T_i^2 - 96T_m^2\right)$$

$$T_m = \frac{T_i}{2.8}$$

N is 3He molar circulation nrate, Tm is the mixing chamber temperature, Ti is the 3He temperature in entering stage.. Above shows the relation between Tm and Ti in zero load. Therefore a low Tm can be reached if Ti is low.

In dilution refrigerators T_i is reduced by using heat exchangers as shown in the schematic diagram of the low-temperature region above. However, at very low temperatures this becomes more and more difficult due to the so-called Kapitza resistance. This is a heat resistance at the surface between the helium liquids and the solid body of the heat exchanger. It is inversely proportional to T^4 and the heat-exchanging surface area *A*. In other words: to get the same heat resistance one needs to increase the surface by a factor 10,000 if the temperature goes down by a factor 10. In order to get a low thermal resistance at low temperatures (below about 30 mK) a large surface area is needed. The lower the temperature, the larger the area. In practice one uses very fine silver powder.

There is no fundamental limiting low temperature of dilution refrigerators. Yet the temperature range is limited to about 2 mK for practical reasons. At very low temperatures both the viscosity and the thermal conductivity of the circulating fluid become larger if the temperature is lowered. To reduce the viscous heating the diameters of the inlet and outlet tubes of the mixing chamber must go as T_m^{-3} and to get low heat flow the lengths of the tubes should go as T_m^{-8}. That means that, to reduce the temperature by a factor 2, one needs to increase the diameter by a factor 8 and the length by a factor 256. Hence the volume should be increased by a factor 2^{14}=16384. In other words: every cm^3 at 2 mK would become 16.384 liter at 1 mK. The machines would become very big and very expensive. Fortunately there is a very powerful alternative for cooling below 2 mK and that is nuclear demagnetization.