

# A REALIZATION OF A LONDON-CLARKE-MENDOZA TYPE REFRIGERATOR<sup>1</sup>

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The refrigerator uses the heat of mixing at constant osmotic pressure between  $^3\text{He}$  and  $^4\text{He}$ , and has attained a temperature of 0.22°K in preliminary runs. The eight (probably) essential parts of the cycle are the condenser (C), expansion valve (V), heat exchanger (I), mixing chamber (M), superfluid duct (D), helium mixture funnel (F), evaporator (E), and circulation pump (see Fig. 1).

In the condenser (C) the  $^3\text{He}$  gas is cooled from room temperature down to the temperature of the outer helium bath, 1.3°K, and is liquefied. It enters the heat exchanger (I) after passing the expansion valve (V) and is further cooled successively by thermal contact with the evaporator (E) and by counterflow with the helium mixture funnel (F); subsequently, it arrives in the mixing chamber (M). Here, the  $^3\text{He}$  joins the upper layer of high  $^3\text{He}$  concentration, which is in equilibrium with the lower (phase-separated) layer of low  $^3\text{He}$  concentration. At the interface between the two layers, the mixing takes place; the lower layer can feed itself with pure superfluid  $^4\text{He}$  through a special superfluid duct (D) connected to the evaporator (E). The mixture produced streams to the evaporator through the helium mixture funnel (F), which is part of the heat exchanger (I). In the funnel much extra cold is produced by expansion of the diluted  $^3\text{He}$  on its way to the evaporator (E) under the influence of the temperature rise. The evaporator is kept at about 0.8°K by pumping off the  $^3\text{He}$  vapor from it by means of a diffusion pump at room temperature. The output of the rotary pump which backs the diffusion pump is connected to the condenser so that the cycle is closed. The thermodynamics of the refrigeration cycle described is fully discussed by K. W. Taconis and R. de Bruyn Ouboter in Chapter II of *Progress in Low Temperature Physics*, volume IV (1964), edited by C. J. Gorter.

In Fig. 2 the refrigeration cycle is presented in the  $T$ - $X$  diagram operating between 0.1° and 0.8°K. All quantities shown in this diagram refer to the case in which 1 mole of solute ( $^3\text{He}$ ) is taken through the whole cycle.  $V/X$  is the volume of solution containing 1 mole of solute ( $^3\text{He}$ ).

We will discuss the enthalpy balance of the whole cycle. The numbers between brackets refer to the position in question in Fig. 2.

## Evaporator to Condenser [1] → [2]

$T = 0.8^\circ\text{K}$ . In the evaporator [1]  $^3\text{He}$  is evaporated ( $C_V/C_L \gg 1$ ), and in the condenser [2] the pure  $^3\text{He}$  vapor is condensed. The condensation energy is greater than the evaporation energy, and the system loses an amount of energy

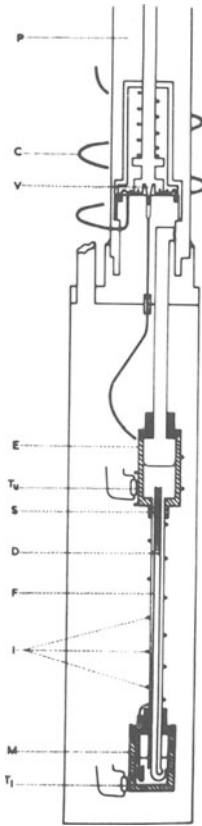


Fig. 1.

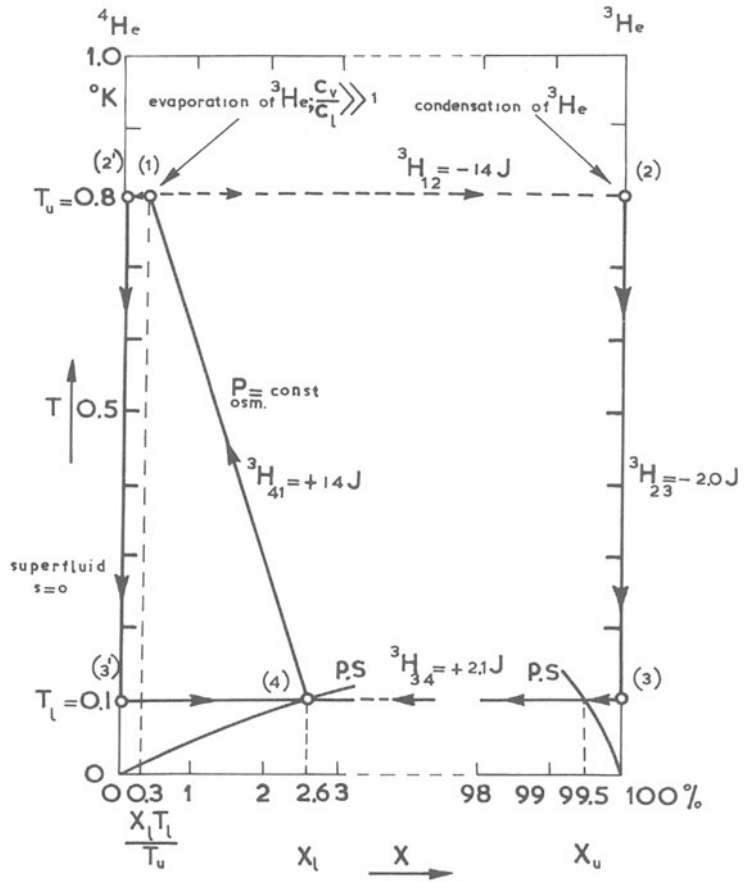


Fig. 2.

equal to

$$(-H_3^0 - \int_0^{T=0.8} C_3^0 dT) - (-NE_{0.3} - \frac{3}{2}RT) \approx -7 J$$

In addition, the work done in the evaporator [1] is  $-\int P_{osm} dV = -RT_u \approx -7 J$  to keep the mixture in [1] at the fixed concentration of 0.3%. Thus, the total loss of energy is  $-14 J$ .

**Heat Exchanger [2] → [3]**

The liquid  $^3He$  has to be cooled from  $0.8^\circ$  to  $0.1^\circ K$  by an amount of energy equal to:

$$-\int_{0.1}^{0.8} C_3^0 dT = -2.0 J$$

This is done by a heat exchanger, using the amount of cold produced during [4] → [1].

**Mixing Chamber [3] → [4]**

$T = 0.1^\circ\text{K}$ . The  $^3\text{He}$  solution is diluted by adding superfluid  $^4\text{He}$  ( $S = 0$ ) through a superleak ([2'] → [3'] → [4]); cooling can result from the external work done during the expansion of the solute "gas"  $^3\text{He}$  ( $\approx P_{\text{osm}} \times V/X_1 \approx RT_L$ ) and from the heat of transition from the concentrated to the dilute phase ( $\approx H^E/X_1 \approx \frac{3}{2}RT_1$ ). In total, an amount of heat of  $\approx \frac{5}{2}RT_1 \approx +2.1 \text{ J}$  can be absorbed at  $0.1^\circ\text{K}$ .

**Heat Exchanger Backflow [4] → [1]**

The steady-state condition requires that the osmotic pressure  $P_{\text{osm}} = RTX$  is constant along the capillary leading from [4] to [1], since one may neglect the fountain pressure at low enough temperatures. In [4] we have a 2.6% mixture at  $0.1^\circ\text{K}$ , so at [1] at  $0.8^\circ\text{K}$  we have a mixture with a concentration of  $2.6 \times 0.1/0.8 \approx 0.3\%$ . During this process an amount of heat

$$\int_{0.1}^{0.8} C_{P_{\text{osm}}} dT = \int_{0.1}^{0.8} \frac{5}{2}R dT \approx +14 \text{ J}$$

can be absorbed when 1 mole of  $^3\text{He}$  is transported.

We like to remark that it may be possible that the cooling capacity is somewhat disappointing. This may be due to the fact that at absolute zero the effective potential well of an  $^3\text{He}$  atom in an  $^4\text{He}$  II surrounding ( $10\% \rightarrow NE_{03} = -23.6 \text{ J/mole}$ ) is somewhat deeper than the effective potential of an  $^3\text{He}$  atom in an  $^3\text{He}$  surrounding ( $H_{03} = -21.5 \text{ J/mole}$ ). Hence, the heat of mixing for a dilute mixture is not simply  $\frac{3}{2}RX$  but is given by the relation:<sup>2</sup>

$$H^E = X[NE_{03} + \frac{3}{2}RT - H_{03}^0 - \int_0^T c_3^0 dT]$$

There is no restriction with respect to the sign for the heat of mixing at absolute zero. If  $H^E/X$  becomes negative, we will find a finite stratification concentration at absolute zero. Certainly, the heat of mixing is very small in the limit  $T \rightarrow 0^\circ\text{K}$ . The thermodynamic analysis of the cooling cycle mentioned above was based on the assumption that at absolute zero the heat of mixing was zero and that at finite temperature for a dilute mixture  $H^E/X \approx \frac{3}{2}RT$ , or if the osmotic pressure was kept constant ( $H^E/X$ )  $\approx \frac{5}{2}RT$ .

**References**

1. H. London, G. R. Clarke, and E. Mendoza, *Phys. Rev.* **128**, 1992, 1962.
2. R. de Bruyn Ouboter, K. W. Taconis, C. le Pair, and J. J. M. Beenakker, *Physica* **26**, 853, 1960 (especially equation 14 and Fig. 17).