Cooling Below 4.2 K
1. Evaporative Cooling
2. Dilution Refrigeration
3. Heat exchangers
4. Pomeranchuk Cooling
5. Adiabatic Demagnetization Refrigeration
6. Acoustic/Pulse Tube Refrigeration
7. Laser Cooling

Evaporative Cooling
Latent heat (also known as enthalpy change of vaporization)
Change in energy as system particle goes from liquid state to vapor state

\[ \ln p_v = -\frac{\Delta H_v}{RT} + B \]

- \( p_v \) is the vapor pressure
- \( \Delta H_v \) is the heat of vaporization (kJ/mole)
- \( R \) is the gas constant
- \( T \) is the temperature (Kelvin)
- \( B \) depends on the substance

- Responsible for cooling by sweating
- Building AC
- Power Plant Cooling

Energy Distribution of Atoms in Equilibrium at Two Temperatures

Phase Diagram of H₂O

Vapor Pressure of Water
Evaporation Cryostats

Principle of Operation
Technical Realization
Cooling Power

Evaporation Cryostat-Principle of Operation

$^4$He

Continuous Filling pot

Evaporation Cryostats

$^4$He

Single-Shot
Continuous

$^4$He pump
$^4$He pump
$^4$He return
$^4$He return

Constriction
Impedance
$^4$He bath at 4.2 K
$^4$He bath at <1.3 K
$^4$He bath at <0.3 K
Space for experiments

Pumping on Bulk Liquid

Capable of reaching temperatures of about 300mK in $^3$He and approx 1K in $^4$He.
Main disadvantage is that the amount of liquid $^4$He is reduced by close to 50% to reach 1 Kelvin.
Used in cascade to reach lower temperatures.

Evaporation Cryostats-Cooling Power

Clausius-Clapeyron Equation

$\frac{dp}{dT} = \frac{L}{\Delta VT}$

$^3$He

$\dot{Q} = \dot{h} \times L \times p \times e^{-L/RT}$

$\ln p_x = -\frac{\Delta H_x}{RT} + B \quad \Rightarrow \quad p_x = p_0 e^{-\frac{\Delta H_x}{RT}}$

Minus sign in exponential implies lowering $p$ leads to lowering $T$—many ways to accomplish this

- Bulk liquid: Pumping the vapor away from above the liquid, induces more liquid to vaporize, thus cooling the liquid

- Mechanical - Adsorption - Turbo molecular - Diffusion pumps

* BEC: Bose-Einstein condensates from magnetic trapping of field
**Dilution Refrigeration—What an Idea!**

Proposed by Heinz London in 1951 (Later at Duke University).
Enthalpy(pure $^3$He)<Enthalpy(dilute phase)
Like “expanding” $^3$He into the dilute phase—a mechanical vacuum

*P* 1962

**Phys. Rev.** 100, 324 (1955)

An experimental study has been made of the vapor pressure of solutions of helium $^3$He in liquid $^4$He at temperatures, between 5.0 and 4.2°K. A properly made tube packed with $^3$He perfectly saturated with a gas mixture which contains only the gas $^3$He is used. The mixture thus contained is then isolated from the atmosphere. The gas mixture is then slowly cooled to a temperature at which the solubility of $^3$He is very low. As the gas mixture is cooled, the solubility of $^3$He decreases and the fraction of $^3$He is increased.

**Where is the Cooling Power?**

Define:

Enthalpy (pure $^3$He)= $H_3$
Enthalpy (dilute phase)=$H_D$

Circulation rate of $^3$He = $n$

What is the cooling power of an ideal dilution refrigerator?

A. $n$
B. $nH_3$
C. $nH_D$

D. $n(H_3 - H_D)$
E. $nH_D - H_3$

$Q = 82nT^3$ watts

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**Dilution Refrigeration Development**

1965—Das, DeBruyn, & Tacoris (Leiden)
$T = 220$ mK

—Hall et al (England) $T = 50$ mK

1966—Neganov (Russia) $T = 50$ mK

1998—Lowest recorded temperature by dilution refrigeration is 1.7 mK (Cousins et al-Lancaster).

Can have enormous cooling power: 1μW at 10 mK

Can cool tons of matter—CERN

Can cool quickly—few hours from room temperature

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**Remember the Phase Diagram**

- $^3$He / $^4$He mixture at low temperature
- Phase separation for more than 6.5% $^3$He in $^4$He
- High phase: 100% $^3$He
- Higher entropy in heavy phase
- Transfer of $^3$He from light to heavy phase similar to evaporation

Image from: www.cern.ch
Dilution Refrigerators–Phase Separation

How many places in a standard dilution refrigerator use evaporative cooling?

A. One  
B. Two  
C. Three  
D. Four  
E. Five

Dilution Refrigerators–Building One

Dilution Refrigerator—Cooling Power

It's all Evaporative Cooling
**Metal/He Thermal Boundary Resistance**

- Acoustic Impedance: \( Z = p \nu \)
  - \( p \) density, \( \nu \) acoustic velocity

- \( Z_{Cu} > Z_{He} \)

- Transmission coefficient for phonons with perpendicular incidence:
  \[
  t = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2}
  \]

- For Cu/He: \( t = 10^{-3} \)

  → High thermal boundary resistance
  Kapitza Resistance \( R_K \sim T^{-3} \)

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**Dilution Refrigerator Heat Exchangers**

- Continuous Heat Exchanger
- Step Heat Exchanger

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**Heat Exchangers are the Key**

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**What does the impedance do below the pot on the condensing line?**

A. Slow down the helium atoms  
B. Cause the required pressure drop  
C. Allow the required temperature drop for condensation  
D. All of the above  
E. None of the above

Image from www.oichta.co

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**Other Parts**

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**Where is the Cooling Power?**

Define:
- Enthalpy (pure $^3\text{He}$) = $H_1$ - Enthalpy (dilute phase) = $H_D$
- Circulation rate of $^3\text{He}$ = $n$

What is the cooling power of an ideal dilution refrigerator?

- A. $n$
- B. $nH_3$
- C. $nH_D$
- D. $n(H_3 - H_D)$
- E. $n(H_D - H_3)$

$\dot{Q} = 82nT^2$ watts

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**Evaporation Vs. Dilution Power**

Curves are for the same $^3\text{He}$ Circulation rate

QUIZ: What is the approximate proportion between $H_D$ and $H_3$ at 0.35 K²?

- A. $H_D = H_3$
- B. $H_D = 0.5 H_3$
- C. $H_D = 2H_3$

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**Pomeranchuk Cooling**

- Principle of Operation
- Technical Realization
- Cooling Power

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**Pomeranchuk Cooling--Principle of Operation**

Phase diagram of $^3\text{He}$

- $\text{dp/dT} < 0$ for $T < 0.3K$
- Entropy of solid $^3\text{He}$ is higher than that of liquid $^3\text{He}$
- Heat of solidification is negative

→ Solidifying by applying pressure adiabatically leads to reduced temperature

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**Pomeranchuk Cooling--Apparatus**

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**Pomeranchuk Cooling--Power**