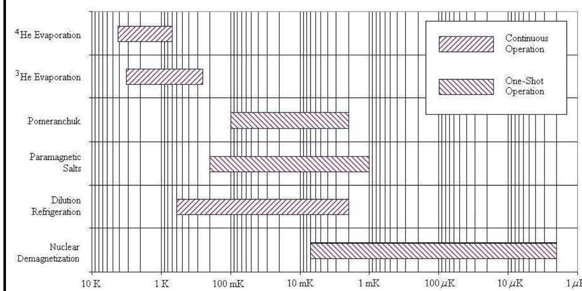
Cooling Below 4.2 K

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

Refrigeration Methods for Very Low Temperatures



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^* is the vapor pressure

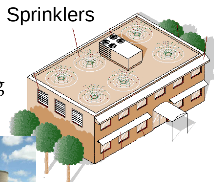
ΔH is the heat of vaporization (kJ/mole)

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

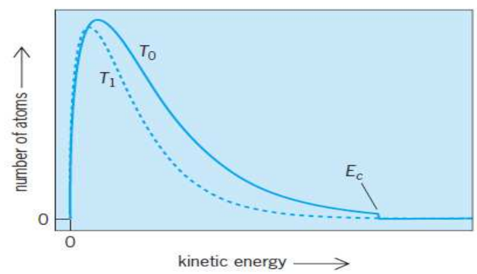
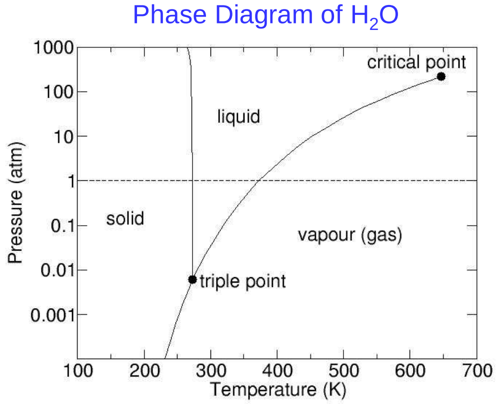
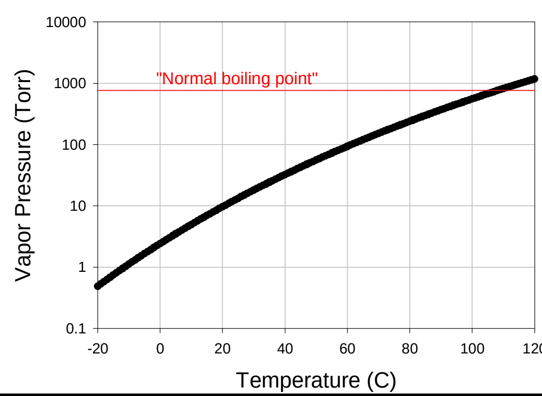


Fig. 2. Evaporative cooling. The graph shows the distributions of the kinetic energies of atoms at an initial temperature T_0 and at a lower temperature T_1. After the removal from the distribution at T_0 of all atoms with energies above E_c, collisions among the atoms cause the gas to rethermalize to the lower temperature T_1.

Phase Diagram of H_2O



Vapor Pressure of Water

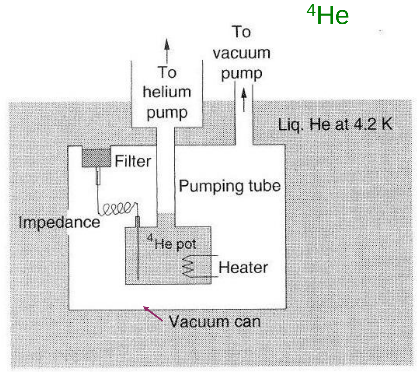


Evaporation Cryostats

- Principle of Operation
- Technical Realization
- Cooling Power

Evaporation Cryostat–Principle of Operation

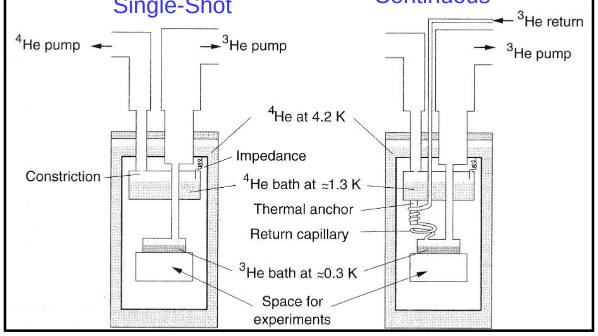
^4He



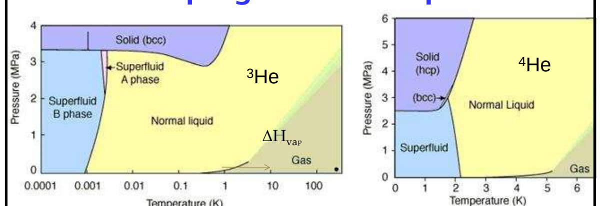
Continuous
Filling pot

Evaporation Cryostats

^4He



Pumping on Bulk Liquid

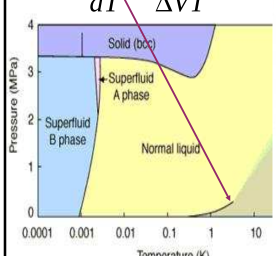


- Capable of reaching temperatures of about 300mK in ^3He and approx 1K in ^4He
- Main disadvantage is that the amount of liquid ^4He is reduced by close to 50% to reach 1 Kelvin
- Used in cascade to reach lower temperatures

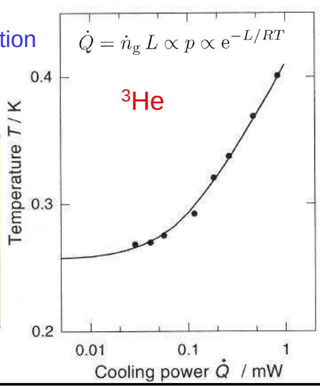
Evaporation Cryostats–Cooling Power

Clausius-Clapeyron Equation

$$\frac{dp}{dT} = \frac{L}{\Delta V T}$$



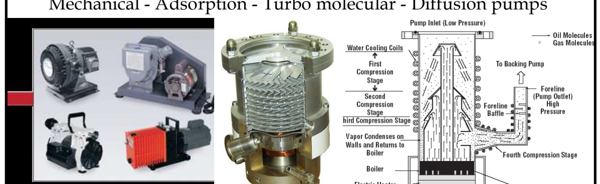
$$\dot{Q} = \dot{n}_g \, L \propto p \propto e^{-L/RT}$$



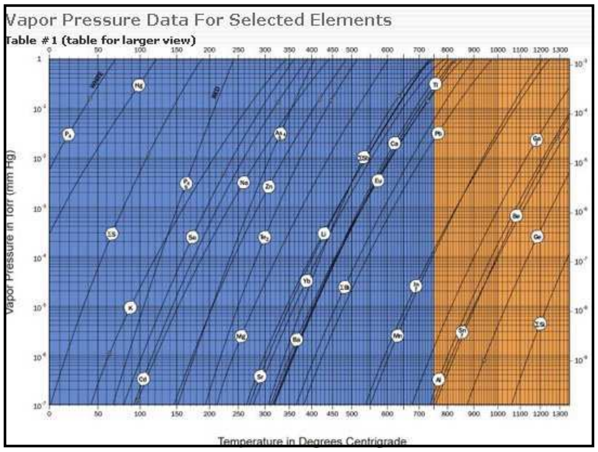
$$\ln p_v = -\frac{\Delta H_v}{RT} + B \longrightarrow p_v = p_0 e^{-\frac{\Delta H_v}{RT}}$$

- 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



o BECs: Remove atoms from magnetic trap using rf field



$^3He/^4He$ Dilution Refrigeration

1. Evolution of Art
2. Physics
3. Mechanics
4. Cooling Power
5. Heat Exchangers

Dilution Refrigeration–What an Idea!

Proposed by Heinz London in 1951 (Later at Duke University).
Enthalpy(pure ^3He)<Enthalpy(dilute phase)
Like "expanding" ^3He into the dilute phase--
a mechanical vacuum 1962

PHYSICAL REVIEW VOLUME 128, NUMBER 5 DECEMBER 1, 1962

Osmotic Pressure of He^3 in Liquid He^4, with Proposals for a Refrigerator to Work below 1°K

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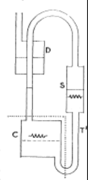
ERIC MENDOZA
Physical Laboratories, University of Manchester, Manchester, England

(Received September 21, 1961; revised manuscript received May 14, 1962)

An experimental study has been carried out of the osmotic pressure of solutions of the isotope He^3 in liquid He^4 at low temperatures, between 0.8 and 1.2°K. A superleak, a tube packed with a fine powder, acted as a semipermeable membrane which allowed only the superfluid He^4 to pass. The conclusion from these experiments was that the measured osmotic pressures were in reasonable agreement with values expected from the thermodynamic relations with other equilibrium properties of the mixtures, notably their vapor pressures. Thermodynamic equilibrium therefore seemed to have been attained under the conditions of the experiments. The second half of this paper concerns a study of the cooling which must take place during the adiabatic dilution of He^3 by He^4. If the dilution is carried out at low temperatures where the solutions separate into two phases, the absorption of heat is estimated to be usefully large. After dilution the solution can be distilled, condensed and recirculated so as to make a continuously acting refrigerator. It should be possible to operate at temperatures of 0.1°K or below.



Where is the Cooling Power?

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

Circulation rate of ^3He= $\dot{n}$
What is the cooling power of an ideal dilution refrigerator?

A. $\dot{n}$ B. $\dot{n}\,H_3$ C. $\dot{n}\,H_D$

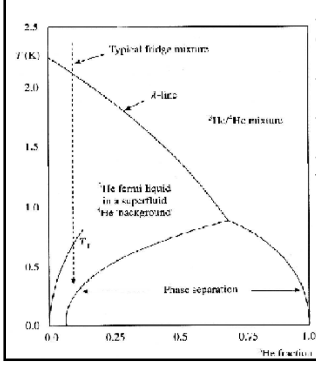
D. $\dot{n}\,(H_3 - H_D)$ E. $\dot{n}(H_D - H_3)$

$$\dot{Q} = 82\,\dot{n}\,T_m^2 \text{ watts}$$

Dilution Refrigeration Development

1965--Das, DeBruyn, & Taconis (Leiden)
T= 220 mK
--Hall et al (England) T=~50
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

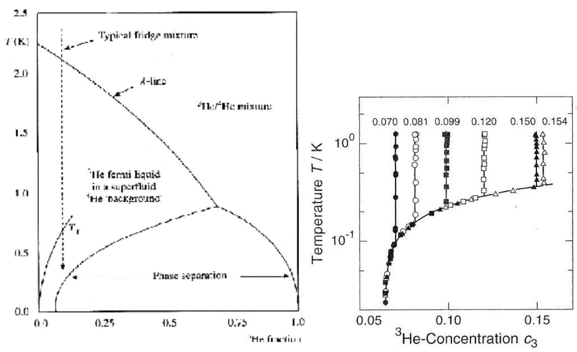
Remember the Phase Diagram



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

Image from: www.cresst.de

Dilution Refrigerators–Phase Separation



It's all Evaporative Cooling

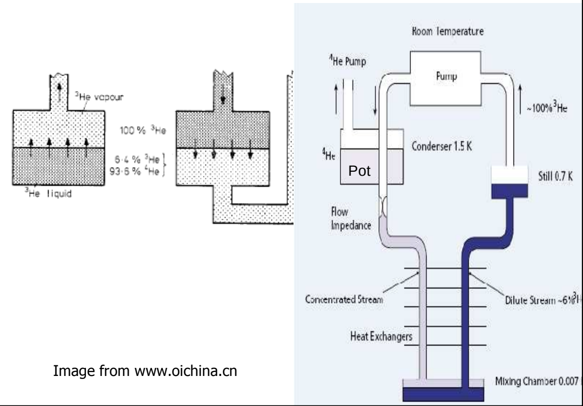


Image from www.oichina.cn

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

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

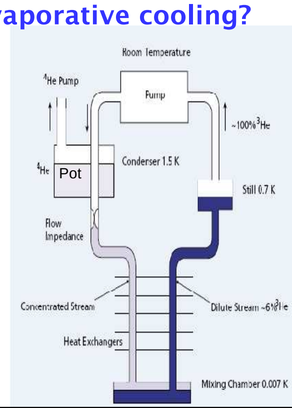
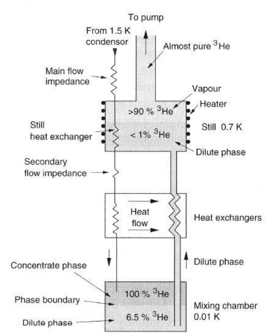
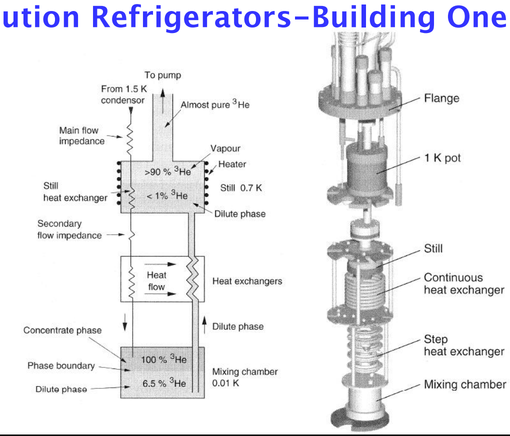


Image from www.oichina.cn

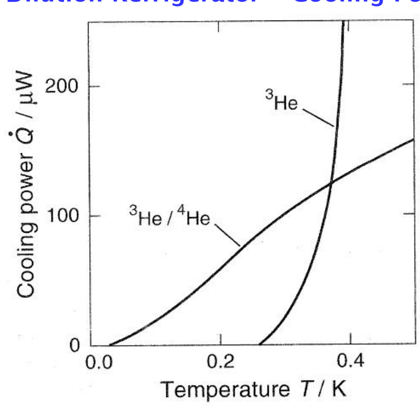
Dilution Refrigerators–Building One



Dilution Refrigerators–Building One



Dilution Refrigerator--Cooling Power



Metal/He Thermal Boundary Resistance

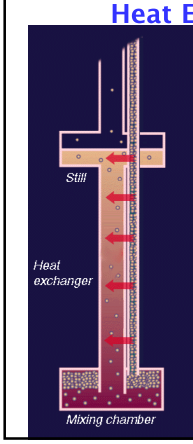
- Acoustic Impedance: $Z = \rho * v$
  ρ density, v acoustic velocity
- $Z_{Cu} > Z_{He}$
- Transmission coefficient for phonons with perpendicular incidence:

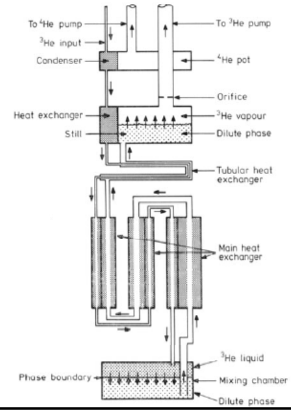
$$t = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2}$$

- For Cu/He: $t \approx 10^{-3}$

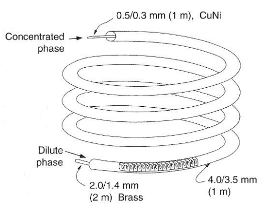
→ High thermal boundary resistance
Kapitza Resistance $R_K \sim T^{-3}$

Heat Exchangers are the Key



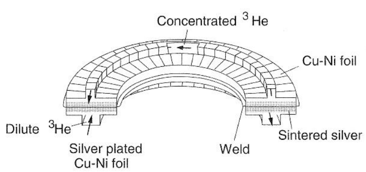


Dilution Refrigerator Heat Exchangers



Continuous Heat Exchanger

Step Heat Exchanger



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

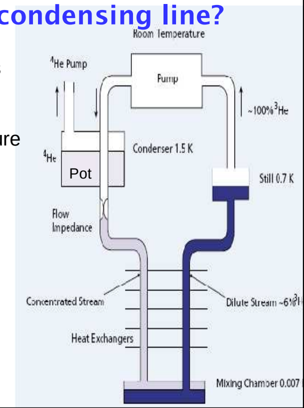
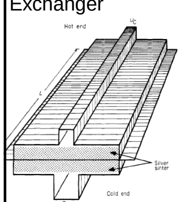
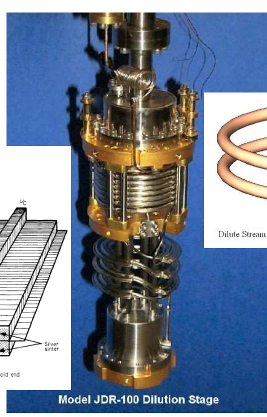


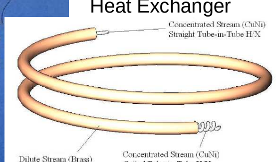
Image from www.oichina.cn

Block Heat Exchanger



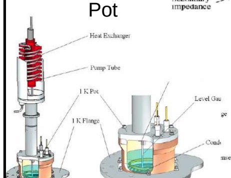


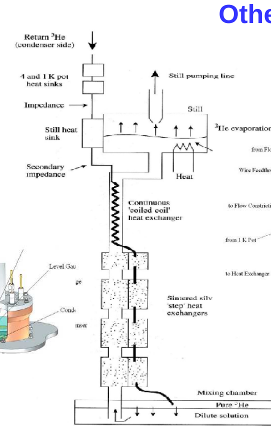
Counterflow Heat Exchanger



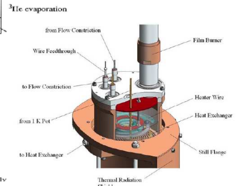
Other Parts

Pot





Still



Where is the Cooling Power?

Define:

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Circulation rate of ^{3}He = $\dot{n}$

What is the cooling power of an ideal dilution refrigerator?

A. $\dot{n}$

B. $\dot{n} H_3$

C. $\dot{n} H_D$

D. $\dot{n} (H_3 - H_D)$

E. $\dot{n} (H_D - H_3)$

$$\dot{Q} = 82\,\dot{n}\,T_m^2 \text{ watts}$$

Evaporation Vs. Dilution Power

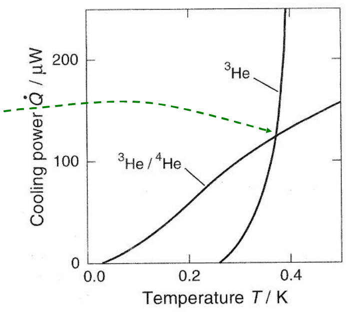
Curves are for the same ^{3}He Circulation rate

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

A. $H_D = H_3$

B. $H_D = 0.5\,H_3$

C. $H_D = 2H_3$

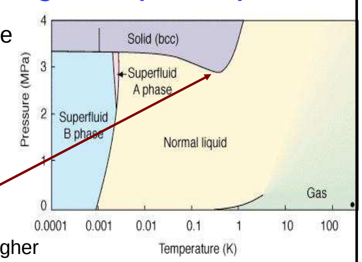


Pomeranchuk Cooling

- Principle of Operation
- Technical Realization
- Cooling Power

Pomeranchuk Cooling–Principle of Operation

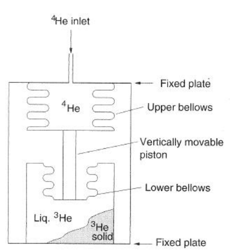
Phase diagram of ^{3}He

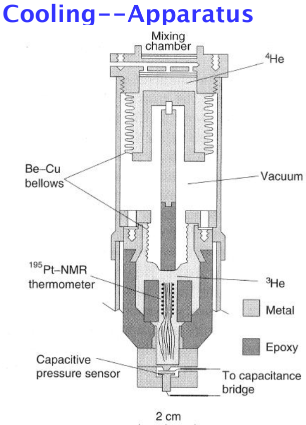


- dp/dT < 0 for T < 0.3K
- Entropy of solid ^{3}He is higher than that of liquid ^{3}He
- Heat of solidification is negative

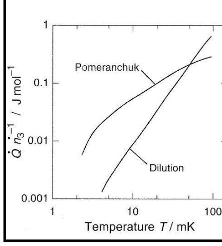
→ Solidifying by applying pressure adiabatically leads to reduced temperature

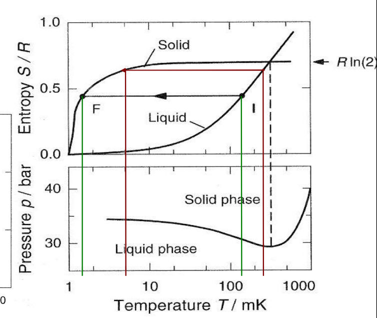
Pomeranchuk Cooling--Apparatus

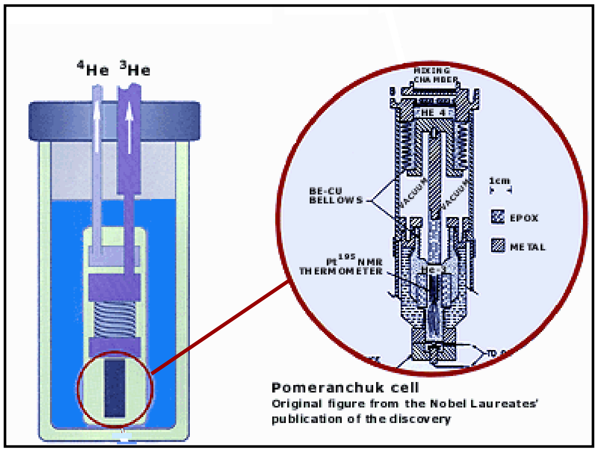




Pomeranchuk Cooling–Power



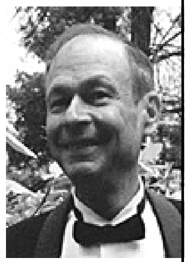




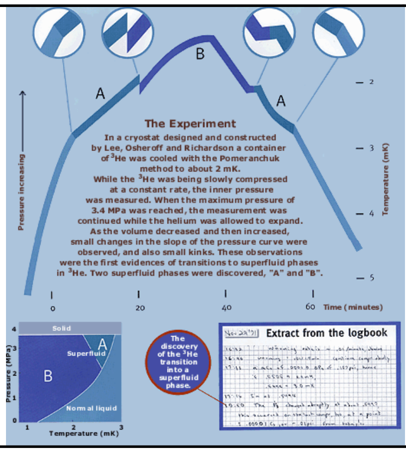
1971 – Superfluidity discovered in 3He (US)

David M. Lee
Cornell University
Ithaca, NY, USA

Douglas D. Osheroff
Stanford University
Stanford, CA, USA



Robert C. Richardson
Cornell University
Ithaca, NY, USA



John Wheatley