Ultimate Temperature of Pulse Tube Cryocoolers

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Consultant

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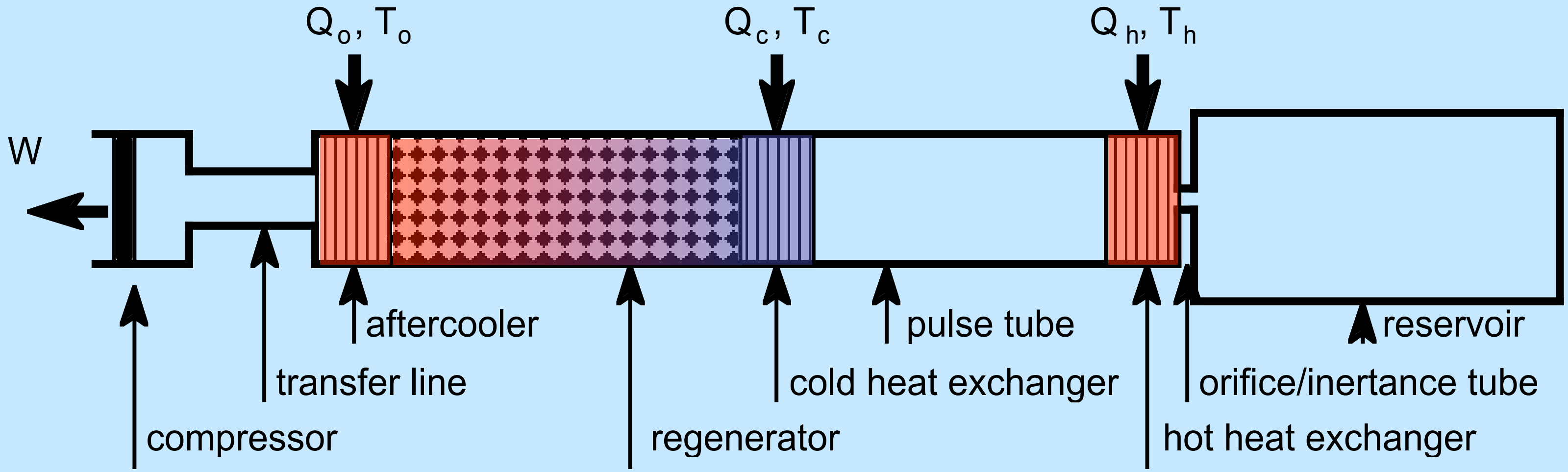
Introduction

- Ideal pulse tube cooler with real gas
  - No losses (entropy generation) except in orifice / inertance tube

- T_{min} ; result of real gas properties



Regenerator Thermodynamics

Constraint: $dT = 0$

General expression	Ideal gas	Real gas
$ds = c_P\, dT/T - R\, dP/P$	$ds = (V/T)\, dP$	$ds = -V\beta\, dP$
$dh = c_P\, dT + [1 - T\beta]V\, dP$	$dh = 0$	$dh = [1 - T\beta]\, V\, dP$

Volume expansivity: $\beta = 1/V\, dV/dT|_P$

Ideal gas: $T\beta = 1$

Pulse Tube Thermodynamics

Constraint: $ds = 0$

General expression	Ideal gas	Real gas
$ds = c_P\, dT/T - R\, dP/P$	$ds = 0$	$ds = 0$
	$dT/dP = V/c_P$	$dT/dP = T\beta\, V/c_P$
$dh = c_P\, dT + [1 - T\beta]V\, dP$	$dh = V\, dP$	$dh = V\, dP$

Volume expansivity: $\beta = 1/V\, dV/dT|_P$

Ideal gas: $T\beta = 1$

Cooling Power

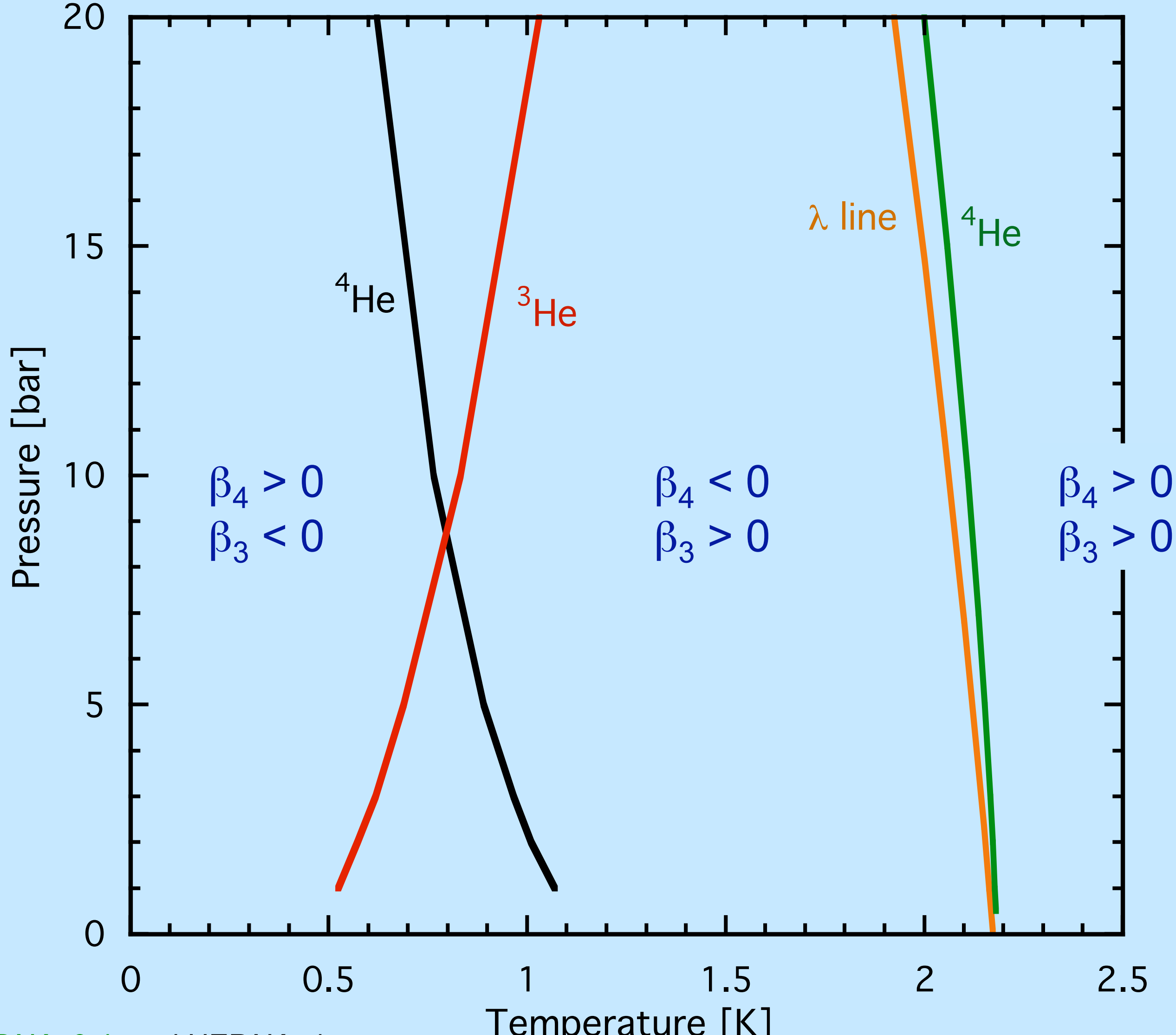
Change in Enthalpy flow at cold heat exchanger

General expression	**Ideal gas**	**Real gas**
$dq = \Delta\, dh$	$dq = V\, dP$	$dq = T\, \beta\, V\, dP$
minimum T	$T_{min} = 0$	when $\beta = 0$
		$(dV/dT\,|_P = 0)$

Volume expansivity: $\beta = 1/V\, dV/dT\,|_P$

Ideal gas: $T\,\beta = 1$

Calculated Loci of $\beta = 0$

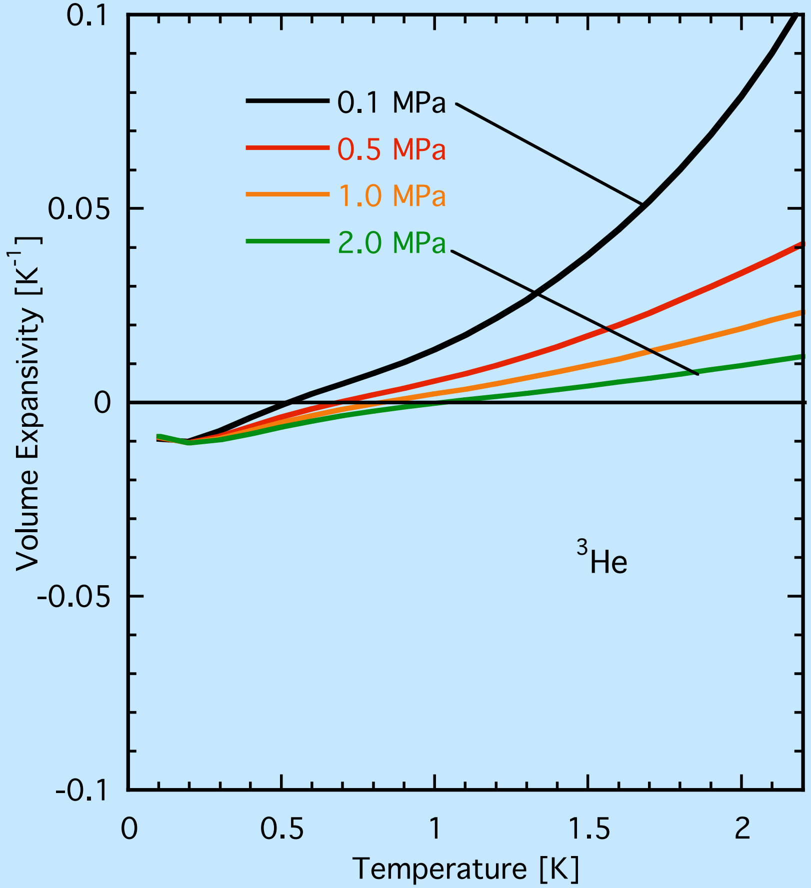


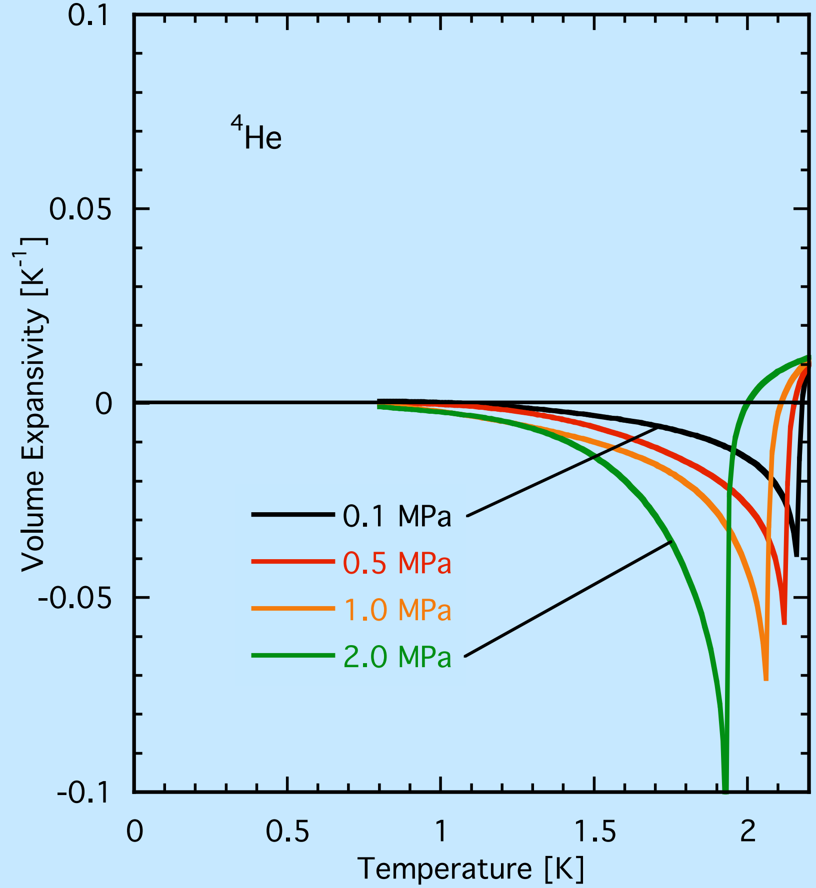
ref: HE3PAK v1.2, HEPAK v3.4, and HEPAK v4a

? Meaning of $\beta \neq 0$?

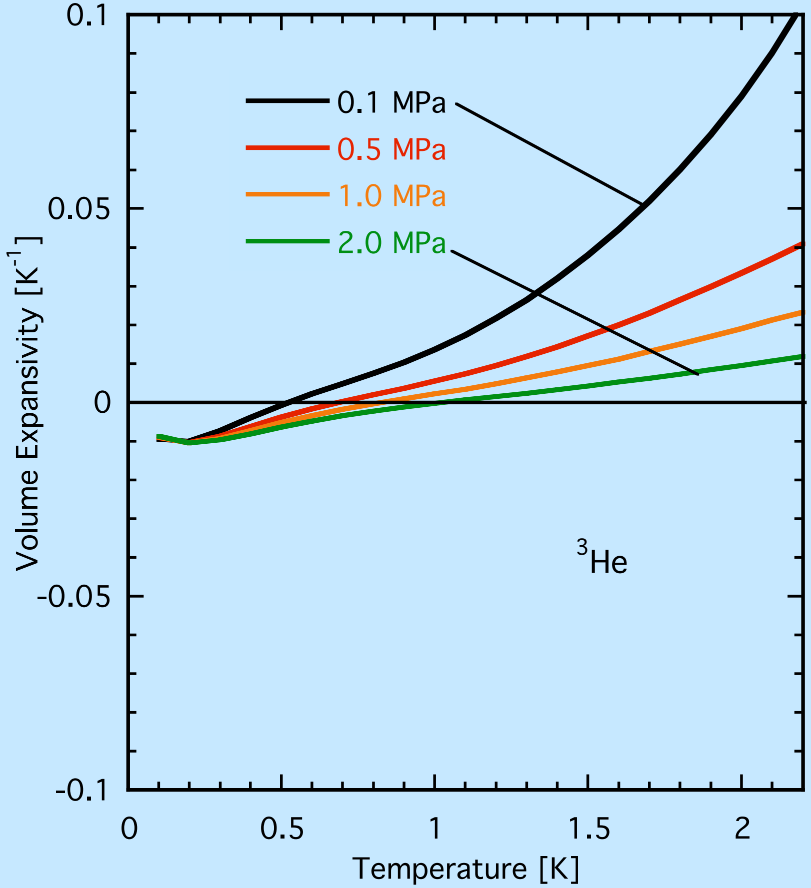
- $\beta > 0$ ➔ Conventional PT
  - Can PT operate below 0.5 K ?
- $\beta < 0$ ➔ What does this mean ?
- Efect of mixing ^{3}He and ^{4}He ?

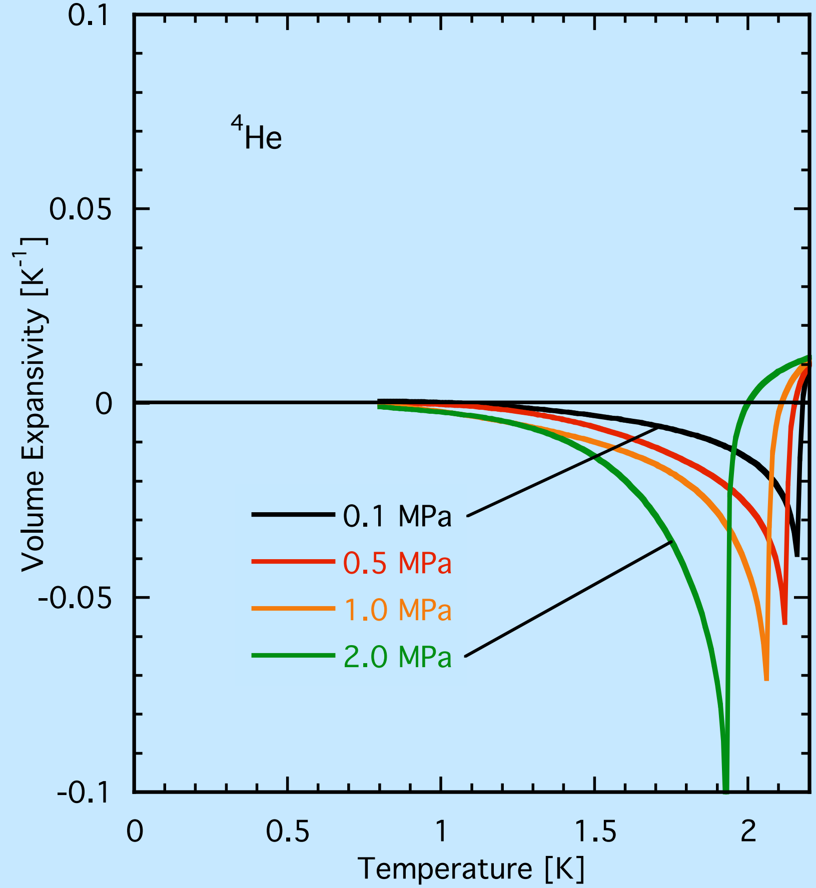
β of ^{3}He and ^{4}He





β of ^{3}He and ^{4}He



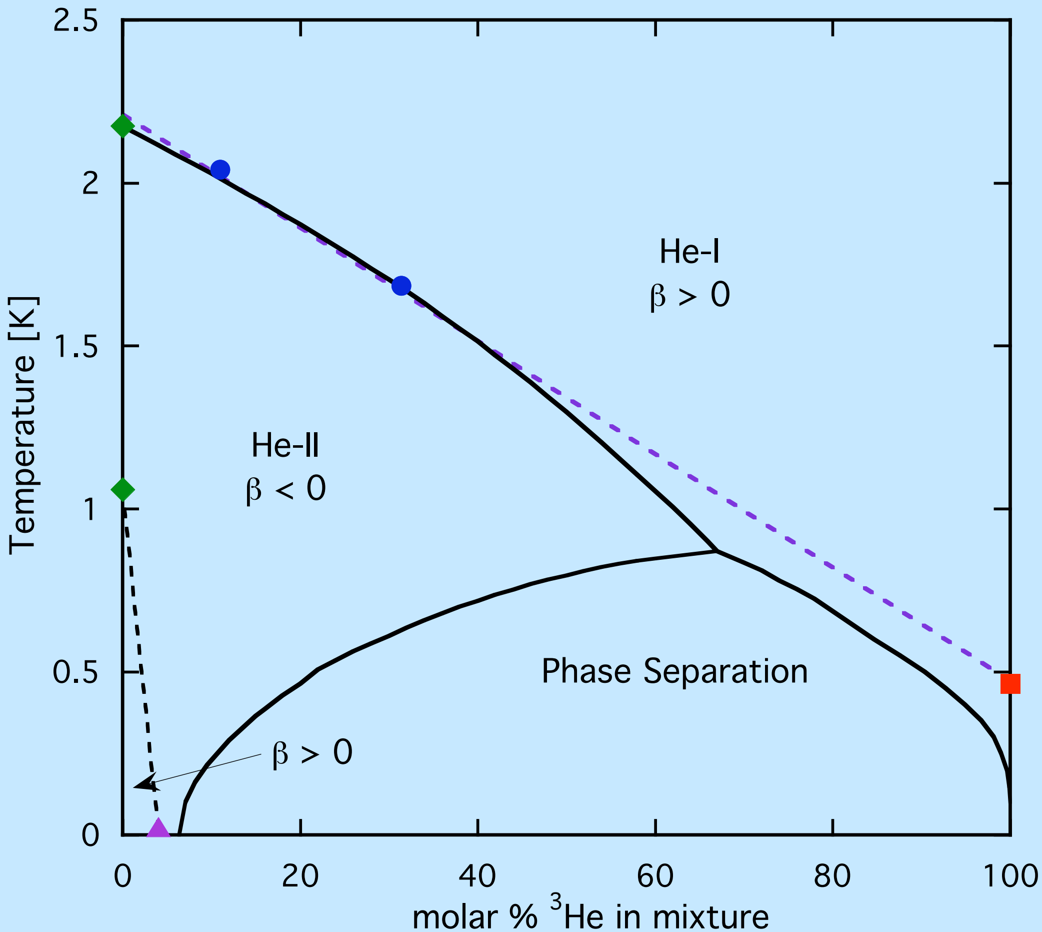


- $\beta < 0$: reverse enthalpy flow or ΔΦ between $\dot{m}$ and P by ~180°
- $\beta_3 < 0$, $T < 1$ K: β is small
- $\beta_4 > 0$, $T < 1$ K: β is very small

} to small to be useful

β = 0; Mixed ^{3}He / ^{4}He

- all data at SVP
- limited data in He-I region
  ≈ straight line fit
- more data in He-II region
- lower $\beta > 0$ region
  over estimated



Esel'son, B.N., et.al.,
Solutions of He³ - He⁴ Quantum Liquids,
Nauka, Moscow, 1973 (in Russian) p. 424.

Ebner, C. and Edwards, D.O.,
"The Low Temperature Thermodynamic Properties of Superfluid Solutions of ^{3}He in ^{4}He,"
Physics Reports **2**, pp. 77-154 (1971)

Los Alamos superfluid pulse tube

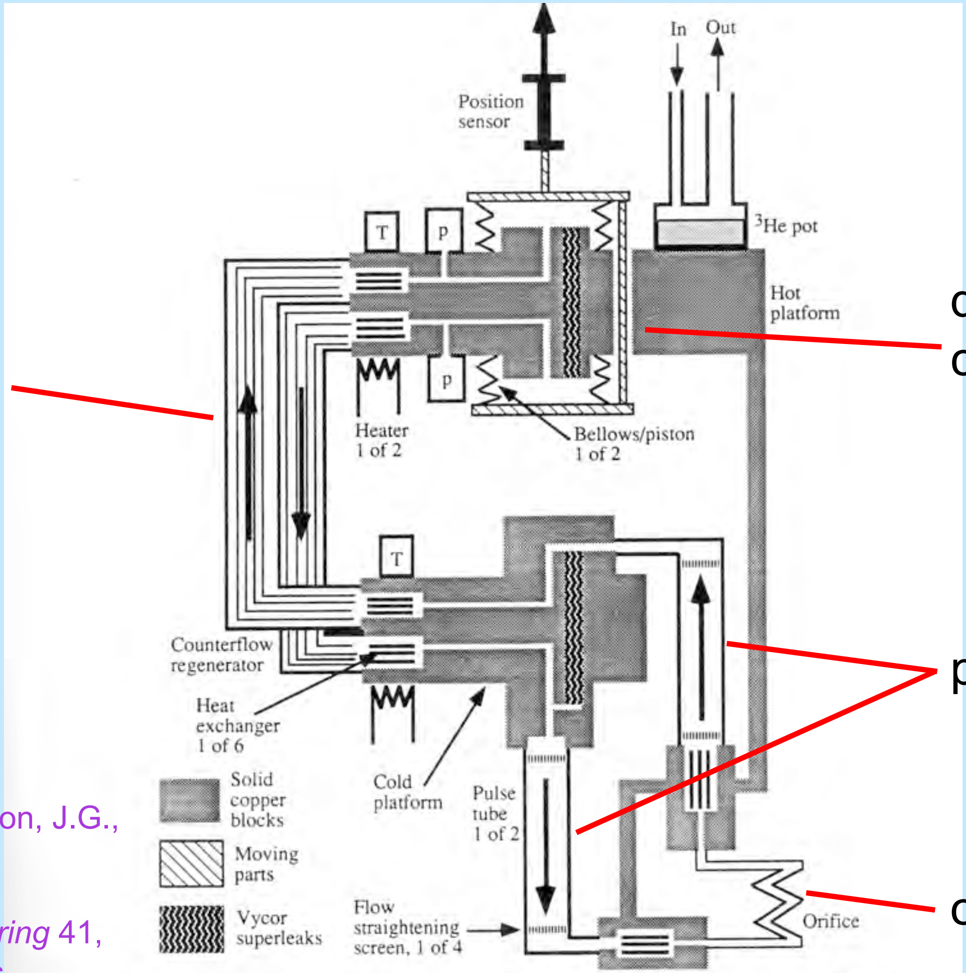


Fig. 2. Schematic of the superfluid orifice pulse tube refrigerator. Pressure sensors are indicated by "p"; thermometers by "T".

Watanabe, A., Swift, G.W., Brisson, J.G., "Superfluid Orifice Pulse Tube Refrigerator below 1 Kelvin," in *Advances in Cryogenic Engineering* 41, edited by P. Kittel, Plenum Press, New York, 1996, pp. 1519-1526.

^{3}He in Superfluid ^{4}He

- 2-fluid behavior
  - T < 1 K: ^{3}He low-density gas moving in fixed ^{4}He background
  - Los Alamos pulse tube cooler
    - filled with 17% ^{3}He and operated between 1 K and 0.6 K
  - Compressor does not cause pressure oscillations
    - causes the ^{3}He concentration, x_3, and the osmotic pressure, Π_3, to oscillate.
    - in regenerator, heat exchangers, and orifices
      - ∇P replaced by $\nabla \Pi_3$
    - In the pulse tube
      - constraint that $\nabla P = 0$ is replaced by $\nabla \mu_4 = 0$
        μ_4 is the chemical potential of the ^{4}He.

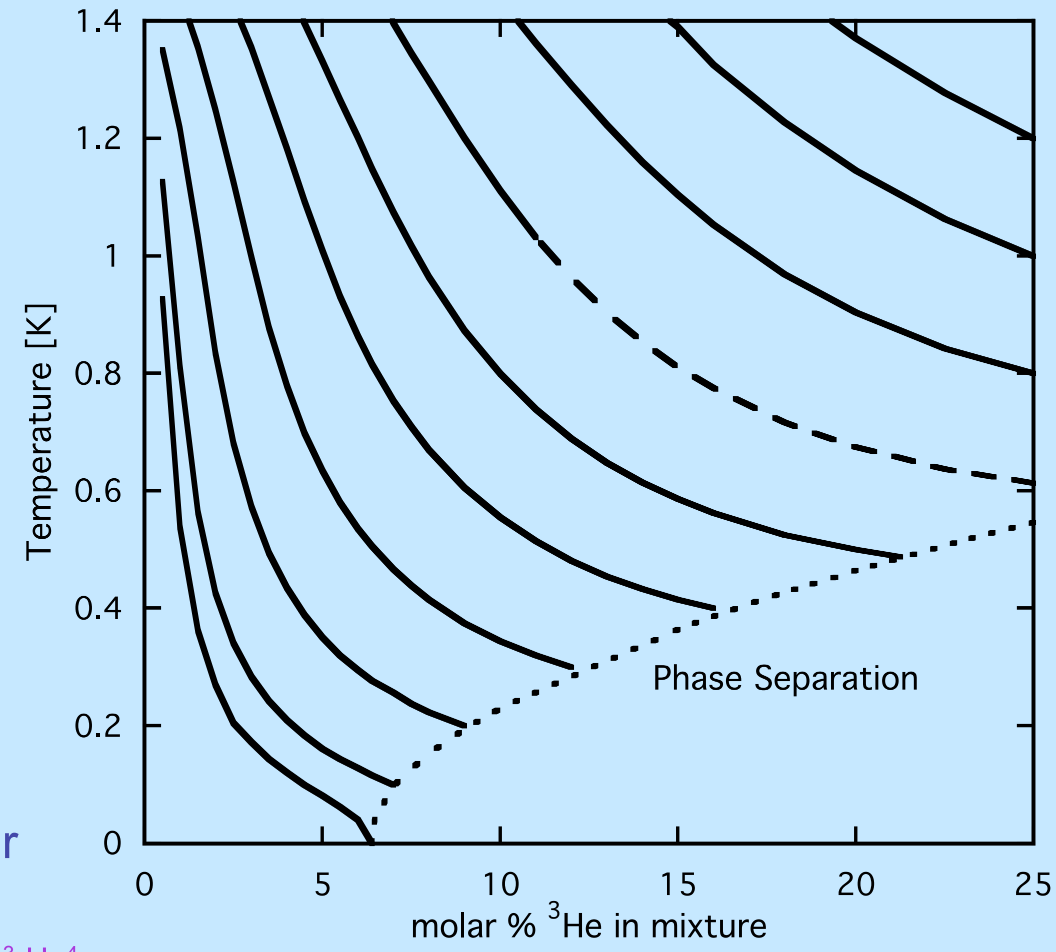
Loci of Constant μ_4

- Dashed line: approx operation of Los Alamos cooler

- T_{min} = phase separation

- Lowest T ⇒
  $x_3 < 6.4$ % @ cold hx
  $x_3 < 1$ % @ 0.6 K

  - Low density of ^{3}He limits the mass flow and cooling in practical cooler



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Summary

- Below ≈ 1 K, ^{3}He concentration driven pulse tube
  - possible with no known ultimate limiting temperature
  - lack of thermodynamic data at very low *T*
- Limit of conventional pulse tube cryocoolers: $\beta = 0$
  - ^{4}He limit $T >\approx 2.2$ K
  - ^{3}He limit $T >\approx 1$ K.
  - mixture of ^{4}He and ^{3}He:
    - limit adjustable
  - mixing ratio not constant throughout the cooler
    - because $\mu_4\,(T, P)$
  - T_{min} depends on the mixing ratio at the cold hx