**Tfy-3.4801 Low temperature physics:**
**Basics of cryoengineering** **Examination, 14.12.2011**

1. Give short answers to the following questions:
   a) What determines the lowest temperature of evaporative cooling by liquid $H_2$, $^4$He or $^3$He?
   b) Why are superconducting metals poor thermal conductors?
   c) Why is helium gas used for leak testing?
   d) Give at least four different uses for aluminum in cryogenics.
   e) Why is it not possible to use iron for demagnetization cooling?

2. The performance of a dilution refrigerator was examined by applying heat into the mixing chamber and measuring its temperature at two different circulation rates. The resulted data is given in the following table. Make a plot of these data and deduce if the refrigerator is performing as expected. Are the heat exchangers appropriate for these circulation rates? Is there sufficient thermal contact between the mixing chamber body and liquid inside? Is there any notable amount of $^4$He in the circulation? What is the optimal circulation rate if there is no additional heating to the mixing chamber? Justify your conclusions. Heat capacities of rich and dilute phases are $C_3 = 22\,T$ J/(mol K) and $C_d = 106\,T$ J/(mol K) per mole of $^3$He, respectively.

| $P$ (μW) | $T$ @ 750 μmol/s (mK) | $T$ @ 1500 μmol/s (mK) |
|---|---|---|
| 1.0 | 5.2 | 4.7 |
| 3.0 | 7.5 | 6.0 |
| 5.0 | 9.5 | 7.5 |
| 10 | 12.9 | 9.8 |
| 20 | 18.3 | 13.3 |
| 40 | 25.9 | 18.1 |
| 60 | – | 22.0 |
| 80 | – | 25.7 |

3. One mole of both $^3$He and $^4$He is enclosed into a 1 dl volume. Describe the state of such mixture in that fixed volume at different temperatures: 300 K, 30 K, 3 K, ... etc. downwards by steps of factor ten, until no phase changes in the system are expected to occur any more. What phases exist at different temperatures? What kind of phase transitions take place on the way? Roughly how much heat has to be removed from the helium system to reduce the temperature? Assume that the volume remains the same irrespective of temperature and that the helium isotopes can be set to the given temperature to arbitrarily low values. The gas constant is $R = 8.31$ J/(mol K) and the molar volumes of $^4$He and $^3$He at saturated vapor pressure at 0 K are 25.4 cm$^3$/mol and 34.4 cm$^3$/mol, respectively. You may sketch various phase diagrams to help describing the situation.

4. A thermometer is attached to one end of a 40 mm long piece of copper, whose thickness is 0.2 mm and width is 8 mm. The residual resistivity ratio of that copper is 100. The other end of the copper piece is attached to a copper nuclear demagnetization refrigerator. There are negligible contact resistances at the joints to the copper piece. Operation of the thermometer results in heating of 1 pW. How large is the error in the thermometer reading due to this heating, when the refrigerator temperature is 10 μK, 100 μK, or 1 mK? The Lorentz number is $L_o = 24.4$ nWΩ/K$^2$ and the nominal resistivity of copper is $\rho_o = 16.7$ nΩm.