Written Exam, Radiation damage in materials (SH2605)
09.00-13.00, March 15, 2010, KTH, Stockholm

Allowed aids: pocket calculator and handed out formula sheet.

To pass the exam, you need at least 9 points.
Grading is determined by the total number of points (where home assignments can sum up to a maximum of 9 points):
A:20.5-22, B:18-20, C:14-17.5, D:11-13.5, E:9-10.5, F:0-8.5

Half-points (0.5 etc) can be rewarded for partially correct answers

Motivate your answers by calculations and text (and pictures, if you want). Write clearly.

Make your own, reasonable assumptions, when necessary. It should be clear from your text what assumptions you make.

Good Luck!

Questions

1. A Batysphere is a spherical vessel designed to reach the bottom of the ocean (10 kilometers). If the vessel has a radius of 2 meters:

   i) What is the required thickness of the wall, in order for it to withstand the pressure at the greatest depths?

   ii) Would an empty batyspere float or sink?

   You can assume that the material is a high strength steel, with the bulk modulus $K = 160$ GPa, the density is 8 times that of water and the yield strength $\sigma_Y = 1000$ MPa. In addition, you may be helped by the Young-Laplace eqution for the pressure difference across a surface (e.g. the surface of a baloon),

$$\Delta p = \gamma \left(\frac{1}{R_x} + \frac{1}{R_y} \right) \tag{1}$$

   where Δp is the pressure difference, γ is surface tension, and R_x and R_y are two radii of curvature in each of the directions parallel to the surface. [3 p]

2. Youngs modulus E measures a materials resistance to small uniaxial strains, i.e., $\sigma = E\epsilon$. Below are listed values of the Youngs moduli for a few selected materials. As you know, the preferred material for use in internal parts and pressure vessels in nuclear reactors is steel (and Zr). What is the argument (apart from cost) for or against using e.g., diamond or silicon carbide which, after all, have much higher elastic stiffnesses? [1.5 p]

Material	E (GPa)
Al	69
Kevlar	100
Steel	200
SiC	450
Diamond	1220

3. Consider the following scenario: A person is driving his car straight into the wood with high speed. Write down expressions for, and calculate, the total cross section σ (for hitting a tree), and the mean free path λ. The mean distance between trees is 10 m. [2 p]

4. Assume instead that the car and the trees are electically charged point objects and interact by Coulomb interaction in the (x, y)-plane. Then you arrive at the counter intuitive conclusion that the faster you drive, the further you get.

   How fast do you have to drive in order to have a good chance of surviving through the wood, if it is 100 m across? Use $Z_1 = Z_2 = 10^{16}$.

   Make reasonable assumptions for instance about the energy absorption that the car can tolerate, and also ignore the contribution from trees far away. [4 p]

5. For a 1.5 MeV proton incident on a sheet of Al, calculate

   i) the energy transfer in a head-on collision, $\hat{T}$. [1 p]

   ii) The mean energy transfer $\bar{T}$. [1 p]

   iii) The mean free path λ. How does it compare with that for neutrons? [2 p]

   Assume Rutherford scattering, and use the atomic number of Al $Z = 13$, the atomic mass $A = 26.98$ and the lattice constant $a_0 = 4.05$ Å.

6. Consider a flux of 10^{15} neutrons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in Fe (mass number 56). The energy is 1 MeV. What will be the damage rate in units of dpa/s? You can assume a lattice constant of 2.85 Å, and a cross-section of 3×10^{-24} cm^2. In the simplest models, electron stopping dominates above a critical energy E_c, and can be ignored below that energy. Discuss, in this case, if electon stopping will be important or not. [2 p]

   The simplest formulation of the point defetct balance equations at steady state is

$$\begin{aligned} g - k_\mathrm{rec}C_\mathrm{i}C_\mathrm{v} - C_\mathrm{v}D_\mathrm{v}\rho_\mathrm{disl} &= 0 \\ g - k_\mathrm{rec}C_\mathrm{i}C_\mathrm{v} - C_\mathrm{i}D_\mathrm{i}z_\mathrm{i}\rho_\mathrm{disl} &= 0 \end{aligned} \tag{2}$$

   where g is the defect production rate, ρ_disl is the dislocation density, and k_rec is the recombination coefficient.

   i) Solve the above equations to give the steady state concentrations of vacancies and interstitials. [1.5 p]

   Assume the following parameters relevant for Fe in a fast reactor spectrum: $T = 500$ ^{o}C, $g = 10^{-6}$ dpa/s, lattice constant $a_0 = 2.87$ Å, $z_\mathrm{i} = 1.02$.

   ii) Calculate the steady state concentration of vacancies and interstitials, and compare with the corresponding concentrations at thermal equilibrium. [2 p]

   iii) What are the rates of recombination, and annihilation at dislocations, respectively? [2 p]

   Use

D_def	$D_{\mathrm{def},0}\exp(-E^\mathrm{m}_\mathrm{def}/k_\mathrm{B}T)$
$c^\mathrm{th}_\mathrm{def}$	$\exp(-E^\mathrm{f}_\mathrm{def}/k_\mathrm{B}T)$
E^f_v	1.6 eV
E^m_v	1.3 eV
E^f_I	4.3 eV
E^m_I	0.3 eV
$D_{\mathrm{v},0}$	1 cm^2/s
$D_{\mathrm{I},0}$	4×10^{-4} cm^2/s
k_rec	$4\pi r_\mathrm{rec}D_i/V_\mathrm{at}$, r_rec6.5 Å
ρ_disl	10^8/cm^2