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ENGINEERING TRIPOS PART IIB - CRIB

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Module 4I5: NUCLEAR MATERIALS

ANSWER TO QUESTION 1

(a) i) The cladding provides mechanical support to the fuel, prevents fission products from leaving the fuel element and protects the fuel from corrosion caused by the coolant.

ii) The moderator slows down neutrons to sustain the fission reaction with thermal neutrons.

iii) The coolant removes the heat that is continually generated and is used to produce steam to drive turbines for electricity generation. A careful balance is needed between the reduction in neutron economy due to the presence of the coolant and the efficiency of heat removal.

iv) Outside, the reactor is surrounded by shielding that absorbs neutrons and gamma rays and reduces the external radiation intensity to a tolerable level.

(b) Control rods help to control the chain reaction by absorbing neutrons to maintain a steady state of operation.

There are usually two types of control rod in a nuclear reactor:

- rods for routine control, which can be raised or lowered to increase or decrease the amount of heat being generated
- safety rods, which can be lowered to shut the reactor down in an emergency.

Requirements for control rod materials:

- High neutron absorption
- Adequate strength
- Low mass (for rapid movement)
- Corrosion resistance
- Stability under heat and radiation
- Must not undergo fission

The most commonly used materials include silver-indium-cadmium alloys and boron. Due to the poor mechanical properties of boron, it is used in the form of boron steel or boron carbide.

Hafnium and dysprosium titanate were also mentioned in lectures, but are much less widely used.

(c) Zirconium alloys are principally of interest for their low neutron absorption cross-section. They also have adequate ductility and corrosion resistance.

The factor limiting the temperature range of use is the change of crystal structure from α to β at 865ºC in pure Zr, as cycling through the phase transformation would cause problems (shape changes, changes in mechanical and thermal properties etc).

The low symmetry of the hexagonal phase (compared to cubic phases) has significant consequences:

- the thermal expansion of α is strongly anisotropic, that parallel to the hexagonal axis being twice that in the basal plane; thus in a locally hot displacement cascade, the main compressive stress is parallel to [001]
- as a result, there is preferential formation of vacancy loops on the basal planes, and of interstitial dislocation loops on prismatic planes
- this non-random orientation of the different types of loops leads to irradiation growth in which a single crystal (each grain) changes shape under irradiation, contracting parallel to [001] and expanding in the basal plane
- zircaloys are processed by hot-rolling; this gives a strong crystallographic texture and growth of individual grains therefore gives overall growth of a polycrystalline component
- the tubes used for cladding increase in length, and their diameter and wall thickness decrease; this distortion limits the attainable burn-up.

ANSWER TO QUESTION 2

(a) During a displacement cascade:

- An incident neutron strikes an atom in the crystal
- If the transfer of kinetic energy to the atom is large enough to displace it from its lattice site, it becomes a *primary knock-on atom (PKA)*, leaving behind a vacant site
- The PKA moves through the lattice creating further knock-on atoms (the mean free path between displacement collisions is typically in the range 1 nm – 1 μm).
- Eventually the PKA and other knock-on atoms come to rest as interstitial atoms
- If the energy transferred to the atom is less than the displacement energy, the atom is not displaced and energy is dissipated as heat.

In principle, the vacancies and interstitials generated in displacement cascades might recombine to restore the equilibrium structure. However, in practice, several factors can give a substantial supersaturation of vacancies:

- Self-interstitial atoms form stable clusters and are ultimately removed by dislocation glide to other dislocations and grain boundaries; in effect, radiation damage has a bias towards the production of vacancies.
- Typically the vacancies and interstitials are created at a temperature high enough for them to be mobile. The interstitials are more mobile, which is an additional factor leaving the centres of displacement cascades vacancy-rich.
- Dislocations, through the process known as climb, can act as sinks for vacancies and interstitials, but the greater elastic strain around the latter again leads to their preferential removal.

(b) For $T < 0.2T_m$, the excess vacancies mainly condense out as stacking faults and dislocation loops. The displacement cascade can be thought of as a core of vacancies surrounded by a shell of interstitials. If the vacancy core or the interstitial shell condense onto a close-packed plane, dislocation loops can be generated: collapse of the vacancy core results in a vacancy loop (an intrinsic stacking fault), whilst collapse of the interstitial shell results in an interstitial loop (an extrinsic stacking fault).

The dislocation loops lead to an increase in dislocation density, hardening and embrittlement. Irradiation growth could also be mentioned.

For $T > 0.2T_m$, the excess vacancies condense out mainly as voids (cavities), the nucleation of which is related to supersaturation not only of vacancies but also of dissolved helium atoms. This helium arises from irradiation-induced transmutation reactions (of B, Ni and Fe) accompanied by the emission of alpha particles: since alpha particles are positively charged, they easily pick up electrons from the surrounding lattice and become elemental helium. The precipitation of helium atoms results in the formation of small bubbles, which can subsequently act as sinks for vacancies, thereby acting as a nucleation point for voids. The rate of swelling is much greater than can be accounted for solely by the helium production rate, and is mainly due to the condensation of vacancies.

Problems associated with the formation of voids include:

- swelling, loss of dimensional stability
- a fine dispersion of voids pin dislocations, leading to hardening and embrittlement. high levels of swelling (greater than ~20%) lead to catastrophic weakening and embrittlement
- embrittlement can be characterised as a decrease in fracture energy, and as an increase in the ductile-brittle transition temperature (DBTT) (for ferritic alloys)
- accelerated creep
- voids acting as sinks for vacancies lead to decomposition of austenitic stainless steels, for example, through the inverse Kirkendall effect.

(c) (Thermal) creep is time-dependent plastic deformation of a material that occurs at stresses lower than the macroscopic yield stress of a material. The creep rate depends on the applied stress and the temperature.

Radiation-induced creep occurs at lower homologous temperatures than thermal creep. At these lower temperatures, the vacancy concentration produced by atomic displacements due to irradiation could be large enough to induce creep deformation under an applied stress. The creep rate is proportional to the stress and the neutron flux.

Radiation-enhanced creep occurs at higher temperatures, at which thermal creep can also occur. The addition of extra vacancies augments the vacancy concentration and enhances the creep rate.

ANSWER TO QUESTION 3

(a) Alpha-decay event includes a 70-100 keV recoil of the heavy daughter, which accompanies the emission of the alpha particle. This heavy daughter travels around 20 nm within the material and undergoes primarily nuclear stopping $(-dE/dx)_{nucl}$. The energy of the particle does not allow the ionisation potential to be exceeded and thus, no ionisation is possible.

The energy is then dissipated by displacing several thousand atoms within the structure. The light, but more energetic, alpha-particle is arrested in the material through electronic stopping $(-dE/dx)_{elec}$. It creates ionisations and some vacancies on its track of ~10 µm and eventually displaces ~ 100 atoms at the end of its track when its energy falls below the ionisation potential and displaces atoms through nuclear stopping.

(b) V_i = volume of material amorphised (m^3) in a single decay event, D_α = cumulative dose of alpha decays per m^3.

The expression represents the increasing probability that a damaged region will overlap with preceding damaged regions, thus creating less total damage per decay event (2D sketch of overlapping regions for high and low D_α).

(c) For $ZrSiO_4$

$$\begin{aligned} f_a &= 0.50 = 1 - \exp\left(-V_i D_\alpha\right) \\ 0.5 &= \exp\left(-4.7\times10^{-25} D_\alpha\right) \\ D_\alpha &= \frac{\ln(0.5)}{-4.7\times10^{-25}} = 1.475\times10^{24}\ \alpha\ m^{-3} \end{aligned}$$

For ZrO_2

$$\begin{aligned} f_a &= 1 - \left[1 + V_i D_\alpha\right]\exp\left(-V_i D_\alpha\right) \\ f_a &= 1 - [1 + 4.7\times10^{-25}\times1.475\times10^{24}]\exp(-4.7\times10^{-25}\times1.475\times10^{24}) \\ f_a &= 1 - [1 + 0.693]\exp(-0.693) \\ f_a &= 1 - 0.846 \\ f_a &= 0.154 \end{aligned}$$

(d) In zircon, the volume of displaced atoms does not epitaxially recrystallise to reform the crystalline structure and remains amorphous. This is primarily because of a higher critical amorphisation temperature for zircon compared with ZrO_2, which has a low critical amorphisation temperature; rapid re-crystallisation can occur because the ionic mobility is sufficient to re-establish the structure. However, this structure is defect rich and a subsequent cascade can then amorphise the sample.