ENGINEERING TRIPOS PART IIB
ELECTRICAL AND INFORMATION SCIENCES TRIPOS PART II
ENGINEERING TRIPOS PART IIA

Friday 2 May 2003 2.30 to 4

Module 4A1

NUCLEAR POWER ENGINEERING

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

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1 It is believed that a natural fission reactor operated near Oklo in Gabon 2×10^9 years ago. At the time isotopic abundance of U-235 in natural uranium was higher than it is now because of the difference in the half-lives of U-235 and U-238.

(a) Given that the isotopic abundance of U-235 is now 0.0072 and that the half-lives of U-235 and U-238 are 7.1×10^8 years and 4.5×10^9 years, respectively, show that the isotopic abundance of U-235 2×10^9 years ago was about 0.0362. [20%]

(b) For thermal fission criticality to be established and maintained what other essential "ingredients" (other than fissile material) are required? [15%]

(c) The average number of neutrons released in a U-235 fission reaction ν is 2.43. If the isotopic abundance of U-235 is 0.0362, find the minimum mass of natural uranium required per cubic metre of soil such that η, the average number of neutrons released per neutron absorbed in the soil, is greater than unity. You can assume that the combined macroscopic absorption cross-section of everything in the soil other than the uranium is $10\ \text{m}^{-1}$.
Data: U-235: $\sigma_\text{c} = 107$ barns, $\sigma_\text{f} = 107$ barns; U-238: $\sigma_\text{c} = 2.75$ barns, $\sigma_\text{f} = 0$ barns. [30%]

(d) A spherical reactor gives the smallest volume critical mass. The solution of the one-group, homogeneous, steady-state neutron diffusion equation in spherical geometry is $\phi = \frac{A}{r}\sin(B_m r)$, where ϕ is the neutron flux, A is a constant, r is the radial co-ordinate and the material buckling $B_m{}^2 = (\eta - 1)\frac{\Sigma_\text{a}}{D}$, with Σ_a being the overall macroscopic absorption cross-section.

Estimate the radius R of a minimum volume natural reactor with the properties given in part (c) but a uranium concentration of $2000\ \text{kgm}^{-3}$. Take the value of the diffusion coefficient D to be 0.01 m. [20%]

(e) What variations in naturally occurring isotopic abundances might be evidence of a natural fission reactor having operated at some point in the past? [15%]

2 (a) Explain what is meant by the term *delayed neutrons*. Why is the phenomenon of delayed neutrons so important in nuclear reactor dynamics? [15%]

(b) The equations for the neutron $n(t)$ and precursor $c(t)$ populations in a lumped, one-group reactor model are:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \lambda c + s$$

$$\frac{dc}{dt} = \frac{\beta}{\Lambda} n - \lambda c$$

where all symbols have their usual meanings. Explain the physical significance of each term. (You do not have to explain the meaning of each symbol.) [15%]

(c) If $\beta = 0.007$, $\lambda = 0.1\,\mathrm{s}^{-1}$ and $\Lambda = 10^{-3}\,\mathrm{s}$ in a typical thermal reactor, estimate the ratio of the precursors to neutrons in steady-state operation. [10%]

(d) While in steady-state, source-free, critical operation the reactor is subject to a step increase in reactivity of 0.003. Find the dominant time constant of the resulting excursion. [50%]

(e) What would the dominant time constant be without the beneficial effect of the delayed neutrons? [10%]

3 (a) Assuming that the reactivity, ρ, of the fuel for a particular Pressurised Water Reactor varies linearly with time, t, as:

$$\rho = \rho_0 \left(1 - \frac{t}{T}\right)$$

derive an expression for the equilibrium cycle length μ if an M-batch refuelling scheme is employed. In an M-batch refuelling scheme, a fraction $1/M$ of the reactor's fuel is replaced at each refuelling. [20%]

(b) The length of a refuelling outage, Δ, depends linearly on the number of fuel elements to be replaced as:

$$\Delta = \alpha + \frac{\beta}{M}$$

Show that, if $T = 120$ weeks, $\alpha = 2$ weeks and $\beta = 18$ weeks, a 3-batch strategy, i.e. $M = 3$, maximises the reactor's availability (the fraction of time the reactor spends at power). [35%]

(c) If the equilibrium values of batch size and cycle length for a 3-batch refuelling strategy are to be employed immediately, what should the reactivity inventory of the reactor be at start-up? [25%]

(d) What is the total cycle length, including the refuelling outage? From an economic and operational perspective is this cycle length optimal? If not, what changes would you recommend? [20%]

4 (a) Why is it necessary to enrich the U-235 content of fuel used in a Pressurised Water Reactor (PWR)? If enriched uranium was not available, what changes would need to be made to the materials used in the reactor? [30%]

(b) Describe briefly the two commercial methods of enrichment and discuss possible newer enrichment technologies. [30%]

(c) A 1100 MW(e) PWR has an overall efficiency of 30%. It is fuelled with enriched uranium oxide containing 3.5% w/w U-235, produced from a concentrate (UOC) at 0.7% w/w U-235. The enrichment plant tails have a U-235 content of 0.3% w/w. Estimate the mass (as uranium) of the initial charge and the number of separation work units (kg SWU) for the following reactor conditions:

Average neutron flux:	$4.0\times10^{17}\ \mathrm{n\,m^{-2}s^{-1}}$
U-235 fission cross-section:	580 barn
Energy per fission:	200 MeV

Neglect all losses except those in the enrichment plant tails, and ignore the differences in the atomic weights of the two uranium isotopes. Avogadro's number is $6.022\times10^{26}\ \mathrm{kmol^{-1}}$. [40%]

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