Version GTP/3

EGT3 / EGT2
ENGINEERING TRIPOS PART IIB
ENGINEERING TRIPOS PART IIA

Friday 26 April 2019 2 to 3.40

Module 4M16

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.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: 4M16 data sheet (8 pages)
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

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

1 (a) Define the terms α decay, β decay and γ decay, and state how the mass number and atomic number of the decaying nucleus change in each case. [15%]

(b) What basic principles are used to minimize exposure when working with sources of ionising radiation? What type of radiological protection would be required when working with each of the three sources of radiation listed in (a)? [25%]

(c) Americium-241 decays by α emission with a half-life of 432 years. ^{241}Am has an atomic mass of 241.05682 u. In an americium-beryllium (Am-Be) neutron source, α particles of energy 5.49 MeV from the decay of ^{241}Am interact with ^{9}Be through the following reaction:

$$^{9}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \mathrm{n}$$

Estimate the maximum energy (in MeV) of the neutron released in this reaction. Relevant atomic masses can be found in the 4M16 data sheet. [15%]

(d) An Am-Be source contains 10 g of ^{241}Am. Assuming that 25% of the α particles emitted give rise to a neutron, that all neutrons released escape the source and that they are emitted equally in all directions, estimate the neutron flux in $\mathrm{m^{-2}s^{-1}}$ at a distance of 1 m from the source, stating any additional assumptions made. [25%]

(e) Discuss the components needed for an effective shield to protect against neutrons like those emitted by the Am-Be source. [20%]

2 (a) What are the main limitations of one-group diffusion theory in describing the distribution of neutrons in a reactor? [10%]

(b) Starting from the general version of the neutron diffusion equation given in the 4M16 data sheet, derive the neutron diffusion equation for a steady-state, source-free, homogeneous system

$$\nabla^2\phi + \frac{(\eta - 1)\Sigma_a}{D}\phi = 0$$

stating any assumptions made. [15%]

(c) A source-free, uniformly loaded, unreflected nuclear reactor in the shape of a right circular cylinder of radius R and height H is critical in steady state.

(i) Assuming that extrapolation distances can be neglected, show that the one-group diffusion theory flux distribution in the reactor is

$$\phi(r,z) = \phi_0 J_0(\alpha r)\cos(\beta z)$$

where J_0 is an ordinary Bessel function of zero order, ϕ_0 is the flux at the centre of the reactor, $\alpha = \dfrac{2.405}{R}$ and $\beta = \dfrac{\pi}{H}$. [40%]

(ii) How are α and β related to the neutronic properties of the core? [5%]

(d) Find the ratio of height to radius (H/R) that will, according to one-group diffusion theory, minimize the volume of the reactor in (c). [30%]

3 (a) Describe the phenomenon of xenon poisoning and explain its effect on the reactivity requirements for the steady-state operation of a thermal nuclear reactor and for restarting the fission chain reaction after reactor shutdown. [20%]

(b) The equations governing the behaviour of xenon-135 in a 'lumped' reactor model can be written as

$$\frac{dI}{dt} = \gamma_i \Sigma_f \phi - \lambda_i I$$

$$\frac{dX}{dt} = \lambda_i I - \lambda_x X - \phi \sigma X$$

where all symbols have their usual meanings.

(i) Show that the steady-state loss of reactivity due to xenon poisoning in a high power reactor approaches $-\gamma_i / \nu$, where ν is the mean number of neutrons per fission. State any assumptions made. [20%]

(ii) A high power reactor is shut down rapidly after a prolonged period of operation at constant flux level ϕ. Find a general expression for the post-shutdown variation of the xenon-135 concentration with time, and hence show that, if the flux level is sufficiently high that $|\lambda_x + \phi\sigma| >> |\lambda_i - \lambda_x|$, the post-shutdown variation of xenon-135 is given approximately by

$$X = \frac{\gamma_i \Sigma_f \phi}{\lambda_x - \lambda_i}\left[\exp(-\lambda_i t) - \exp(-\lambda_x t)\right]$$ [40%]

(iii) Using this approximate result, find the time after the shutdown at which the xenon-135 concentration is at its maximum. Take the half-life of iodine-135 to be 6.7 hours and the half-life of xenon-135 to be 9.2 hours. Comment briefly on the practical significance of your result. [20%]

4 (a) Draw the basic flowsheet for the reprocessing of spent nuclear fuel using the 'Purex' process showing the principal waste streams. Describe the steps involved in the process. [30%]

(b) Discuss the advantages and disadvantages of reprocessing spent nuclear fuel in light of the recent closure of the Sellafield Thermal Oxide Reprocessing Plant (THORP). Why is it essential to reprocess the spent fuel arising from the former UK Magnox reactors? [20%]

(c) A 1600 MW(e) Pressurised Water Reactor has an overall efficiency of 33% and a utilisation factor of 0.9. It is fuelled with enriched oxide at 4.0% ^{235}U produced from a concentrate at 0.7% ^{235}U and the enrichment plant tails have a ^{235}U content of 0.3%. The losses in stages other than enrichment tails can be ignored.

(i) If the discharge burn-up of the fuel is $45\,\mathrm{GWd\,te^{-1}}$, calculate the annual fuel requirement and the amount of uranium ore concentrate (UOC) required, as the total mass of U or heavy metal (HM) in each case. [20%]

(ii) Estimate the savings in UOC if a closed fuel cycle is employed. Assume that the spent fuel contains $33\,\mathrm{te\,yr^{-1}}$ of uranium with a ^{235}U content of 0.85% and that it is necessary to enrich the recycle stream to 4.3% ^{235}U to compensate for the effects of ^{236}U. Take the total reprocessing loss to be 1.5% and neglect other losses. [15%]

(iii) If reprocessing costs \$1200 per kg HM, including wastes and recycled fuel costs, and spent fuel disposal costs \$400 per kg HM, at what price for UOC would reprocessing become economic? Ignore any savings in separative work units (SWU) and assume that the plutonium is not recycled. Comment on the result. [15%]

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Answers

Q1 (c) 11.19 MeV

(d) $2.529 \times 10^{10}\ \mathrm{m^{-2}s^{-1}}$

Q2 (c)(ii) $\alpha^2 + \beta^2 = \dfrac{(\eta - 1)\Sigma_a}{D}$

(d) $\dfrac{H}{R} = \dfrac{\pi\sqrt{2}}{2.405} = 1.847$

Q3 (b)(ii) $X = \dfrac{\gamma_i \Sigma_f \phi}{\lambda_x - \lambda_i} \exp(-\lambda_i t) + \left[\dfrac{\gamma_i \Sigma_f \phi}{\lambda_x + \phi\sigma} - \dfrac{\gamma_i \Sigma_f \phi}{\lambda_x - \lambda_i} \right] \exp(-\lambda_x t)$

(b)(iii) 11.28 hours

Q4 (c)(i) 35.40 te; 327.45 te

(c)(ii) 41.35 te

(c)(iii) $684.9 per kg