Version GTP/4

EGT3 / EGT2
ENGINEERING TRIPOS PART IIB
ENGINEERING TRIPOS PART IIA

Thursday 23 April 2015 2 to 3.30

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.

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

1 (a) What does the acronym ICRP stand for? Describe the part that organisation plays in radiation protection. What is the title of the relevant UK legislation? [10%]

(b) Detail the three criteria laid down by ICRP which form the basis of all radiological protection. [15%]

(c) What are the purposes of dose limits? What is the basic UK dose limit for registered radiation workers? What are the assumptions on which all dose limits are based? [25%]

(d) What are the three basic methods of protection against exposure to ionising radiation? [10%]

(e) A 1 mg cobalt-60 source is to be used for industrial radiography and is housed in a 150 mm thick lead shielded flask.

(i) Given that the half-life of cobalt-60 is 5.27 years and taking its atomic mass to be 60 u, calculate the activity (in Bq) of this source. [10%]

(ii) Treating the source as a point source and using the information below, estimate the surface dose in $\mathrm{mSv\,hr^{-1}}$ and comment on the result. [30%]

Cobalt-60 releases two γ-rays of energies 1.17 MeV and 1.33 MeV each decay. Take the density of human tissue to be $10^3\ \mathrm{kg\,m^{-3}}$ and the macroscopic absorption cross-section for γ-rays in human tissue to be $3\ \mathrm{m^{-1}}$. The exponential attenuation coefficient of γ-rays in lead is $0.046\ \mathrm{mm^{-1}}$.

The dose D in Gy due to γ-rays is given by

$$D = \frac{1.6 \times 10^{-13} \Sigma \phi E t}{\rho}$$

where Σ is the absorption cross-section for γ-rays in human tissue in $\mathrm{m^{-1}}$,

ϕ is the γ-ray flux in $\mathrm{m^{-2}s^{-1}}$,

E is the average γ energy in MeV,

t is the exposure time in s,

ρ is the density of human tissue in $\mathrm{kg\,m^{-3}}$.

2 (a) Using the information on page 6 of the 4M16 data sheet, show that the one-group, steady-state, source-free neutron diffusion equation for a cylindrical geometry, homogeneous reactor can be written as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \phi}{\partial r}\right)+\frac{\partial^2 \phi}{\partial z^2}+(\eta-1)\frac{\Sigma_a}{D}\phi=0$$

where all symbols have their usual meanings. [20%]

(b) Show that the criticality condition for this reactor is

$$\left(\frac{2.405}{R_0}\right)^2+\left(\frac{\pi}{H_0}\right)^2 = (\eta-1)\frac{\Sigma_a}{D}$$

where R_0 and H_0 are the extrapolated radius and height of the reactor. [40%]

(c) Prior to the criticality accident at Tokaimura on 30 September 1999, workers were dissolving 18.8% enriched uranium in nitric acid. The resulting solution contained 400 kg of uranium per m^3 of fluid. This fluid was then poured into a cylindrical precipitation tank (0.45 m in diameter, 0.66 m in height). When the depth of the liquid reached a certain level criticality was achieved.

(i) Using the following data, show that the macroscopic absorption cross-section of the solution is $22.47\ m^{-1}$ and find the corresponding macroscopic fission cross-section. You can assume that the macroscopic absorption cross-section of everything in the solution other than the uranium is $9.0\ m^{-1}$.
Data: ^{235}U: $\sigma_c = 107$ b, $\sigma_f = 580$ b; ^{238}U: $\sigma_c = 2.75$ b, $\sigma_f = 0$ b. [15%]

(ii) Given the average number of neutrons released in a ^{235}U fission reaction ν is 2.43, calculate η the average number of neutrons released in fission per neutron absorbed in the mixture. [5%]

(iii) Hence estimate the depth at which you would expect the criticality condition to have been met as the Tokaimura solution was poured into the precipitation tank. You can assume that extrapolation distances can be neglected and that the value of D is 0.03 m. [10%]

(iv) In fact, the precipitation tank was surrounded by a water-filled cooling jacket. What effect, if any, would you expect the presence of this jacket to have on the depth of solution at which the criticality condition is met? [10%]

3 (a) Show that the general form of Ginn's equation given on page 8 of the 4M16 data sheet implies that the temperature T at any point in a fuel pin is related to the coolant inlet and outlet temperatures, T_{ci} and T_{co}, by the expression

$$T = \tfrac{1}{2}\left[(\eta+1)T_{co} - (\eta-1)T_{ci}\right]$$

where $\eta = \theta \Big/ \sin\left(\dfrac{\pi L}{2L'}\right)$. [15%]

(b) The highest rated fuel pin in a Pressurised Water Reactor has a power of 180 kW(th). Each fuel pin consists of a UO_2 solid pellet of 9.3 mm diameter and 0.6 mm thick zircaloy cladding. The axial power distribution is cosinusoidal over the 4 m active fuel length. The flux half-length of the power distribution $L' = 2.5$ m. The temperature of the coolant rises from 285 ºC at inlet to 315 ºC at outlet.

(i) Show that the quantity $\dot{m}c_p$ is $6\,\text{kW}\,\text{K}^{-1}$ for the highest rated pin, where $\dot{m}$ is coolant mass flow rate per pin and c_p is the coolant specific heat capacity. [5%]

(ii) Using the data below show that the maximum temperature within the fuel in the highest rated pin is ~2100 ºC. Assume there is no scale on the cladding. You can assume without proof that the maximum non-dimensional temperature $\theta_{\max} = \sqrt{1+Q^2}$, where Q is as defined on page 8 of the 4M16 data sheet. [40%]

Data:	Heat transfer coefficient to coolant	$h = 35\ \text{kWm}^{-2}\text{K}^{-1}$
	Thermal conductivity of cladding	$\lambda_c = 12\ \text{Wm}^{-1}\text{K}^{-1}$
	Bond heat transfer coefficient, fuel to cladding	$h_b = 25\ \text{kWm}^{-2}\text{K}^{-1}$
	Thermal conductivity of fuel	$\lambda_f = 3\ \text{Wm}^{-1}\text{K}^{-1}$

(iii) Given that the melting point of UO_2 is 2840 ºC and assuming that $\dot{m}c_p$ and T_{ci} are unchanged, find the pin power at which the fuel would start to melt in the highest rated pin. [15%]

(c) Uranium silicide (U_3Si_2) is being considered as an alternative fuel form to UO_2. U_3Si_2 has a lower melting point (1665 ºC) but higher thermal conductivity than UO_2. Assuming that the UO_2 is replaced by U_3Si_2 in the above fuel design with the geometry unchanged and that T_{ci} and $\dot{m}c_p$ also remain unchanged, and taking the thermal conductivity of U_3Si_2 to be $12\ \text{Wm}^{-1}\text{K}^{-1}$, find the pin power at which this fuel would start to melt in the highest rated pin, and comment on the implications of this result. [25%]

4 (a) Explain what is meant by the term *delayed neutrons*. Why are delayed neutrons so important in nuclear reactor dynamics? [10%]

(b) In a 'lumped' model of the behaviour of a source-free reactor, the equations for the neutron population n and the precursor population c can be written as

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

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

where ρ is the reactivity, β is the delayed neutron fraction, Λ is the neutron reproduction time and λ is the decay constant of the precursors.

Show that, for this model, the *in-hour equation* relating the inverse periods p_i to the reactivity ρ is

$$\rho = p\left[\Lambda + \frac{\beta}{(p+\lambda)}\right]$$ [40%]

(c) Show that, for small changes in reactivity $\Delta\rho$ about the critical state, the effective time constant T for the dominant behaviour in this model can be approximated by

$$T = \frac{\Lambda\lambda + \beta}{\lambda\Delta\rho}$$ [30%]

(d) A critical, source-free reactor that has been operating in steady state for some time is subject to a step increase in reactivity to $\rho = 0.001$. If $\beta = 0.007$, $\lambda = 0.12\ \text{s}^{-1}$ and $\Lambda = 1.25\ \text{ms}$, find the dominant time constant given by the in-hour equation for the subsequent excursion and compare this with the approximate result from (c). [20%]

END OF PAPER

4M16 Nuclear Power Engineering 2015

Answers

Q1 (e)(i) 4.186×10^{10} Bq

(e)(ii) 0.645 mSv hr^{-1}

Q2 (c)(i) 11.18 m^{-1}

(c)(ii) 1.209

(c)(iii) 0.483 m

Q3 (b)(iii) 253.2 kW

(c) 393.0 kW

Q4 (d) 51.45 s from the in-hour equation; 59.58 s from the part (c) result.