ENGINEERING TRIPOS PART IIB
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Wednesday 2 May 2012 2.30 to 4

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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.*

*Attachment:*
4M16 data sheet (8 pages).

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

**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**

gtp03

1 (a) A nuclear engineer is making some preliminary design calculations for a novel thermal uranium-fuelled accelerator-driven subcritical reactor (ADSR). The engineer has calculated that in order to ensure the reactor is subcritical, the parameter $\eta$, the number of neutrons released in fission per neutron absorbed in the fuel, must be less than 1.5.

For the proposed design, the number density of uranium atoms in the core will be $5 \times 10^{27}\ \text{m}^{-3}$.

Given that the average number of neutrons released in a U-235 fission reaction $v$ is 2.43, find the maximum possible enrichment level for the fuel.

Data: U-235: $\sigma_c = 107$ b, $\sigma_f = 580$ b

U-238: $\sigma_c = 2.75$ b, $\sigma_f = 0$ b [20%]

(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 system

$$\nabla^2\phi + B_m{}^2\phi = 0$$

stating any assumptions made.

Explain the difference between *material buckling* $B_m{}^2$ and *geometric buckling* $B_g{}^2$. [25%]

(c) The ADSR has a symmetrical spherical geometry with a spallation target of radius $R_1$ at its centre. The spallation target is surrounded by a subcritical core of outer radius $R_2$. The beam tube transporting the proton beam to the spallation target is sufficiently narrow that it can be neglected in modelling the flux distribution. The spallation process generates a flux $\phi_1$ at radius $R_1$. Assuming that the extrapolation distance of the core can be neglected, solve the steady-state neutron diffusion equation to show that the flux distribution in the subcritical core of the ADSR will be

$$\phi = \frac{\phi_1 R_1}{r} \frac{\sin[B_m(R_2 - r)]}{\sin[B_m(R_2 - R_1)]}$$

where $r$ is the distance from the centre of the spallation target. [45%]

(d) Briefly discuss the advantages and disadvantages of surrounding the core of this ADSR with a reflector. [10%]

2 The equations governing the behaviour of iodine-135 and xenon-135 in a 'lumped' reactor model can be written as

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

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

(a) Explain the meaning of each term in these equations. [15%]

(b) A reactor has been operating for a prolonged period with a constant flux of $\phi_0$. Find expressions for the corresponding equilibrium iodine-135 and xenon-135 populations. [10%]

(c) The flux level in the reactor is then reduced to $\frac{1}{2}\phi_0$. Show that the iodine-135 population will subsequently vary as

$$I = \frac{\gamma_i \Sigma_f \phi_0}{2\lambda_i}\left[1 + \exp(-\lambda_i t)\right]$$

Here the change in flux is taken to occur at time $t = 0$. [20%]

(d) Find an expression for the corresponding variation with time after the change in flux of the xenon-135 population. [45%]

(e) Comment on the implications of these variations for reactor control. [10%]

3 (a) What are the principal advantages and disadvantages of on-line refuelling? Which types of nuclear reactor currently in service worldwide are refuelled on-line and which off-line? [20%]

(b) The reactivity $\rho$ of a particular design of Pressurised Water Reactor (PWR) fuel varies linearly with burn-up $\tau$ as

$$\rho = \rho_0 \left(1 - \frac{\tau}{T_1}\right)$$

where $T_1$ is the equilibrium cycle length (in units of burn-up) in one-batch operation.

Using the *partial reactivity model*, show that, if the reactor is operated at constant power in an *M*-batch refuelling strategy, the equilibrium cycle length $T_M$ (in units of burn-up) is given by

$$T_M = \frac{2}{M+1} T_1$$ [20%]

(c) A PWR using this fuel has been operating a 3-batch refuelling strategy for many years. The station manager decides to change to a 4-batch refuelling strategy using the same fuel. The change in strategy is to be implemented by replacing 25% of the fuel assemblies at each refuelling and varying the cycle length appropriately until equilibrium operation is established again.

(i) Show that the length (in units of burn-up) of the first cycle following the change will be $\frac{3}{8} T_1$. [30%]

(ii) Find the length of the second cycle following the change. [20%]

(d) What are the main advantages and disadvantages of this change in refuelling strategy? [10%]

4 (a) (i) Why is it necessary to enrich the U-235 content of Advanced Gas-cooled Reactor (AGR) fuel when it is not necessary for Magnox reactor fuel? [10%]

(ii) Describe two commercial methods of enrichment and discuss possible newer technologies. Highlight the advantages and disadvantages of the two commercial processes. Why was uranium hexafluoride selected for the two commercial processes? [60%]

(b) A 660 MW(e) AGR has an overall efficiency of 35% and is fuelled with uranium oxide with an average enrichment of 3%. If the burn-up is $20\,\mathrm{GWd\,te^{-1}}$ and the reactor runs at the equivalent of 95% full load, calculate the annual fuel requirement. Qualitatively, how would this change if the enrichment could be increased? [10%]

(c) If the 3% enriched fuel is produced from natural uranium containing 0.7% U-235 and the enrichment tails are 0.3% U-235, calculate the annual amount of uranium ore concentrate and the number of separation work units required. Neglect all losses during the processes. [20%]

**END OF PAPER**

4M16 Nuclear Power Engineering 2012

Answers

Q1 (a) $e < 0.01077$

Q2 (b) $I_0 = \dfrac{\gamma_i \Sigma_f \phi_0}{\lambda_i}$; $X_0 = \dfrac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0}$

(d) $$X = \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} + \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}\exp(-\lambda_i t) + \left[\frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{\lambda_x + \sigma\phi_0} - \frac{(\gamma_x + \gamma_i)\Sigma_f \phi_0}{2\lambda_{eff}} - \frac{\gamma_i \Sigma_f \phi_0}{2(\lambda_{eff} - \lambda_i)}\right]\exp(-\lambda_{eff} t)$$

where $\lambda_{eff} = \lambda_x + \frac{1}{2}\sigma\phi_0$

Q3 (c) (ii) $\frac{37}{96}T_1$

Q4 (b) 32.69 te

(c) 220.66 te; 111.7 te SWU