Version GTP/8

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 28 April 2021 1.30 to 3.10

Module 4I10

NUCLEAR REACTOR 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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
Attachment: Nuclear Energy Data Book (21 pages).
You are allowed access to the electronic version of the Engineering Data Books.

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

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 An innovative core of a PWR is loaded with 500 circular fuel assemblies of the design shown in Fig. 1. Each assembly contains 19 fuel rods with a diameter of 10 mm and length of 5 m. The core radial peaking factor (P_r) is equal to 1.667, while the axial peaking factor (P_{ax}) is equal to 1. The reactor operates at a thermal power of 1400 MW, a pressure of 50 bar, and has a total flow rate at the core inlet of 40000 m^3/hr. The flow is distributed equally between the fuel channels, with an inlet temperature of 200 °C. The flow channels are circular with an internal diameter of 100 mm.

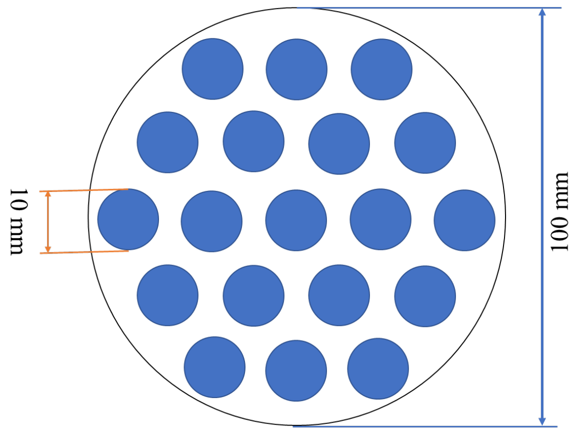

Fig. 1

(a) Calculate the maximum coolant outlet temperature. Assume that the water properties are those of saturated liquid at $T_{sat} = 200$ °C. [30%]

(b) Given that the hydraulic diameter is 28 mm, estimate the peak cladding temperature. [30%]

(c) Using the Jens-Lottes correlation, about which information is given below, calculate the minimum value of the departure from nucleate boiling ratio (DNBR). Based on the obtained minimum DNBR, is it possible to increase the reactor power? [40%]

Data: The Jens-Lottes correlation for critical heat flux is

$$q_c''\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] = 3.95 \cdot C \cdot \left(\frac{G[\mathrm{kg/s \cdot m^2}]}{1356}\right)^m (T_{sat} - T_b)$$

Water pressure, MPa	$C \times 10^6$	m
3.447	0.817	0.160
6.895	0.626	0.275
13.389	0.445	0.500

2 To uprate the power of its light water reactor fleet, an electric utility is considering the use of duplex fuel pellets. The duplex fuel pellet consists of two radial zones, loaded with UO_2 and mixed oxide (MOX) fuel (as illustrated in Fig. 2). The fuel surface temperature at R_o is fixed at 400 °C.

For a heat conduction problem in cylindrical coordinates, the governing equation is

$$\frac{1}{r}\left(\frac{\partial}{\partial r}\left(rk(T)\frac{\partial T}{\partial r}\right)\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k(T)\frac{\partial T}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+q'''=\rho C_p\frac{\partial T}{\partial t}$$

in which all symbols have their usual meanings.

(a) If the thermal conductivity (k) is constant (independent of temperature), show that a general expression for the radial temperature distribution is

$$k\cdot T(r)=-\frac{q'''}{4}\cdot r^2+C_a\cdot \ln(r)+C_b$$

where C_a and C_b are constants. State any assumptions. [10%]

(b) Derive expressions for the temperature profiles in the two zones of the duplex fuel pellet. [30%]

(c) Using only the properties in the table below and assuming that the volumetric heat generation rate in MOX is 50% higher than in UO_2, calculate the maximum linear power at which the pellet can be operated without melting the fuel. (Neglect the dependence of thermal conductivity on temperature.) Indicate clearly which fuel type should occupy which zone to achieve this goal [40%]

(d) How does the maximum linear power (obtained in (c)) compare with the maximum linear power for an all-UO_2 pin ($R_o = 5$ mm) with $k = 3.0$ W/m K independent of temperature. Is the decision of the utility to switch fuels justified? [20%]

Parameter	UO_2	MOX
Density [g/cc]	10.5	10.9
Thermal conductivity [W/m K]	3.0	2.5
Melting point [°C]	2800	2300
Specific heat capacity [J/kg K]	410	380

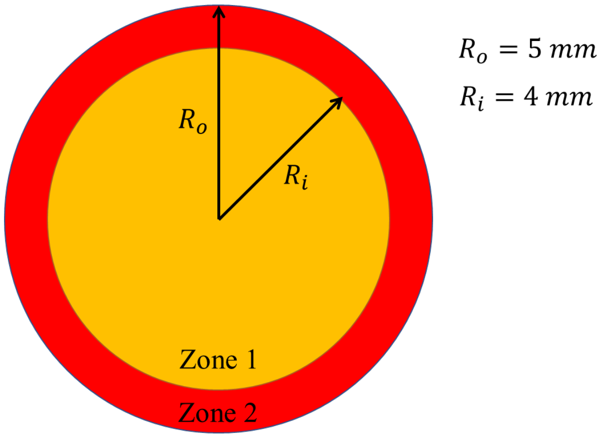

Fig. 2: Duplex fuel arrangement

3 (a) Reactivity measurement results from a PWR at different conditions are summarised in the table below.

	% of nominal power	**Moderator temperature, T_M, °C**	**Boron concentration, ppm**	**Control rod position**	**^{135}Xe concentration**	**k_{eff}**
1	50	300	500	Out	Equilibrium	1.004
2	50	300	500	In	Equilibrium	0.998
3	50	300	650	Out	Equilibrium	0.989
4	0	300	500	Out	Equilibrium	1.005
5	0	300	500	Out	Zero	1.025
6	0	100	500	Out	Zero	1.049
7	80	300	500	In	Equilibrium	1.001

From the presented data, estimate the following:

(i) The ^{135}Xe worth

(ii) The control rod worth

(iii) The moderator temperature coefficient

(iv) The soluble boron worth [25%]

(b) A PWR start-up procedure takes it from a cold zero power (CZP) state to a hot full power (HFP) state, as detailed in the table below. Discuss the relative sizes of the three boron concentration values (B_1, B_2, B_3) and explain the physical phenomena influencing the change in reactivity between states 1, 2 and 3. Assume that the start-up process is controlled only by boron concentration adjustment. [25%]

Condition	**Boron concentration**	**Fuel temperature**	**Moderator temperature**	**Time from start-up**
1. CZP	B_1	20 ℃	20 ℃	0
2. HFP	B_2	600 ℃	300 ℃	Several hours
3. HFP	B_3	600 ℃	300 ℃	Two days

(c) (i) Briefly discuss the considerations in the choice of water-to-fuel ratio (V_m/V_f) in the core of a pressurised water reactor. [10%]

(ii) Illustrate the effect chemical shim (soluble boron) will have on the moderator temperature coefficient as a function of moderator temperature by sketching an appropriate plot. [15%]

(d) Iodine-135 and xenon-135 are both direct fission products. However, iodine-135 is a source of xenon-135 through β decay (with a half-life of 6.6 hours). Sketch plots illustrating the variation with time in the concentrations of ^{135}I and ^{135}Xe at reactor start-up and shut-down. Provide explanations of your plots. [25%]

4 A typical PWR steam generator (SG) secondary flow path is schematically presented in Fig. 3. It operates at steady state.

(a) The recirculation ratio, r, of an SG is defined as:

$$r = \frac{\text{recirculation mass flow rate}}{\text{steam mass flow rate}}$$

Show that r can be expressed as

$$r = \frac{1 - x_e}{x_e}$$

where x_e is the equilibrium flow quality at the exit from the tube bundle. [20%]

(b) Show that the steam flow rate from the SG, $\dot{m}_s$, can be expressed as

$$\dot{m}_s = \frac{1}{h_{fg}}\left(\frac{Q}{N} - \dot{m}_i\left(h_f - h_i\right)\right)$$

where Q is the core power, N is the number of SGs, and $\dot{m}_i$ and h_i are the mass flow rate and specific enthalpy of secondary water entering the SG tube bundle, respectively. The specific enthalpy of saturated water is h_f, while h_{fg} is the specific enthalpy of vaporisation. [30%]

(c) Using the SG design data and operating conditions presented in the table below, show that the secondary coolant temperature at the inlet to the SG tube bundle is approximately 280 °C and calculate the steam mass flow rate from the SG. State clearly any simplifying assumptions made. [40%]

(d) In the context of heat exchangers, the term 'calorimetry' describes the product of mass flow rate and enthalpy change for a given side of the heat exchanger. Explain why the reactor power is, in practice, estimated through the steam generator secondary calorimetry and not by the core coolant calorimetry? [10%]

Parameter	**Value**
Number of SGs	4
Number of tubes per SG	10,000
Tube length	20 m
Tube outer diameter	0.016 m
Tube inner diameter	0.014 m
Tube conductivity	10 W m^{-1} K^{-1}
Primary coolant flow rate	17,500 kg s^{-1}
Primary circuit pressure	155 bar
Secondary circuit pressure	66 bar
Core inlet temperature	285 °C
Core outlet temperature	315 °C
Boiling heat transfer coefficient	24 kW m^{-2} K^{-1}

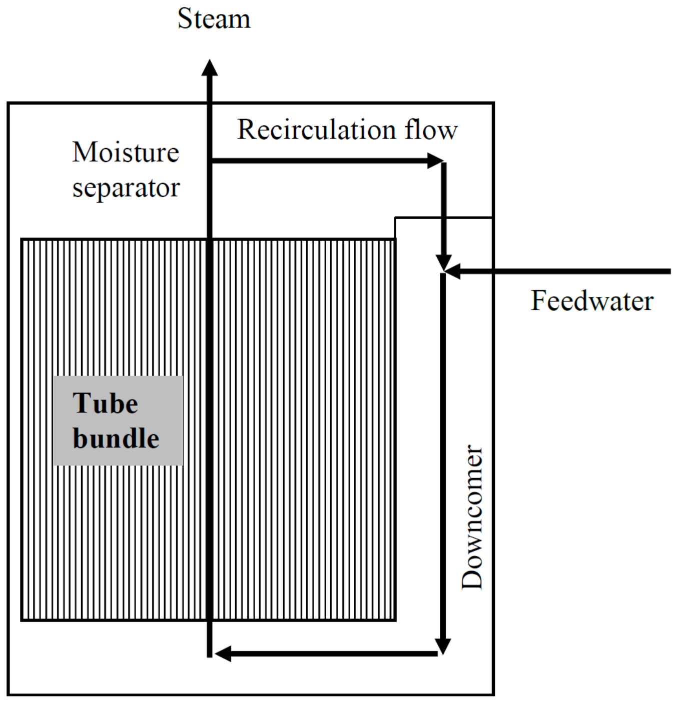

Fig. 3

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Answers

Q1 (a) 254.7 °C

(b) 321.4 °C

(c) 3.562

Q2 (b) $T_{UO_2}(r) = -\frac{q'''_{UO_2}}{4k_{UO_2}} \cdot r^2 + T_{max}$

$T_{MOX}(r) = -\frac{q'''_{MOX}}{4k_{MOX}}(r^2 - R_o^2) + \frac{R_i^2}{2k_{MOX}} \cdot \left(q'''_{MOX} - q'''_{UO_2}\right) \cdot \ln\left(\frac{r}{R_o}\right) + 400$

(c) 95.63 $\mathrm{kW\,m^{-1}}$

(d) 90.48 $\mathrm{kW\,m^{-1}}$

Q3 (a)(i) 10 pcm/%power

(a)(ii) 600 pcm

(a)(iii) –11.2 pcm/°C

(a)(iv) –10 pcm/ppm

(b) $B_1 > B_2 > B_3$

Q4 (c) 494 $\mathrm{kg\,s^{-1}}$