EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 26 April 2023 2 to 3.40

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.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Nuclear Energy Data Book
Engineering Data Books

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.

You may not remove any stationery from the Examination Room.

1 Thermal power produced by a micro-reactor core is removed by a coolant with specific heat capacity c_p. The coolant temperature at the core outlet is limited to T_{out}. The coolant passes through a heat exchanger where heat is transferred with effective heat transfer coefficient U to a secondary circuit. The coolant is then recirculated into the core by means of a pump with operational characteristic given by $W = A\dot{m}\Delta p$, where W is the power consumed by the pump, $\dot{m}$ is the mass flow rate, A is a constant, and the pressure loss in the primary coolant loop can be characterised by the expression $\Delta p = B\dot{m}^2$ where B is a constant.

(a) Using the data provided in Table 1 below, estimate the heat transfer area of the heat exchanger if the effective mean temperature of the secondary coolant was to be kept at 200 °C and the pump consumes 5 kW of power. [35%]

(b) The heat exchanger upfront cost is £8500 per m^2 of heat exchange area, while the electricity cost for operating the pump is £0.1 per kWh, charged annually at the year end. If the upfront cost of the pump can be neglected and the reactor lifetime is 3 years, would it be economically beneficial to increase the power of the pump to 10 kW? The cost of borrowing money for this project is 10% per annum. [35%]

(c) For a realistic system, list any other positive and negative effects on the reactor economics that would be expected from increasing the power of the pump. [30%]

Table 1

Reactor power, MW_{th}	5
Coolant specific heat capacity, c_p, J kg^{-1} K^{-1}	4000
Coolant outlet temperature, T_{out}, °C	350
Effective heat transfer coefficient, U, W m^{-2} K^{-1}	5000
A, m^3 kg^{-1}	1
B, kg^{-1} m^{-1}	5

2 A rectangular prism shaped research reactor core is composed of 100 cylindrical fuel pins arranged in a square lattice with a moderator to fuel volume ratio of 2. The core base is a square with 80 cm sides as shown in Fig. 1 below. The reactor is to produce 1 MW of thermal power. It is cooled by light water at 50 °C. The coolant temperature rise across the core is negligible. Radial heat transfer between the fuel pellet surface and the coolant can be characterised by a heat transfer coefficient $h = 5000\,\mathrm{W\,m^{-2}\,K^{-1}}$. The thickness of the cladding and the gap are much smaller than the fuel pin radius.

Assume that the fuel is uniform and no burnable or control poisons are used. Assume Diffusion Theory can be applied, and extrapolated boundaries can be neglected, leading to a cosine-shaped power distribution in each dimension, e.g. $q'''(z) \sim \cos(\pi z/L)$, where L is the reactor height and z is a position along the height, spanning from $-\frac{L}{2}$ to $\frac{L}{2}$.

(a) Explaining your reasoning, show that the maximum fuel centreline temperature can be approximated by

$$T_{\mathrm{CL}} = T_{\mathrm{coolant}} + q'_{\mathrm{max}} \left(\frac{1}{2\pi R h} + \frac{1}{4\pi k} \right)$$

where q'_{max} is the maximum linear heat rate, R is the fuel pin radius and k is the fuel average thermal conductivity. [20%]

(b) Given the expression in (a), estimate L if the maximum fuel temperature should not exceed 1500 °C in normal operation and $k = 3\,\mathrm{W\,m^{-1}\,K^{-1}}$. [30%]

(c) If the critical heat flux for this core is constant at $q''_C = 10^5\,\mathrm{W\,m^{-2}}$, estimate the Minimum Departure from Nucleate Boiling Ratio (MDNBR) for this core. [20%]

(d) How can MDNBR be improved? [30%]

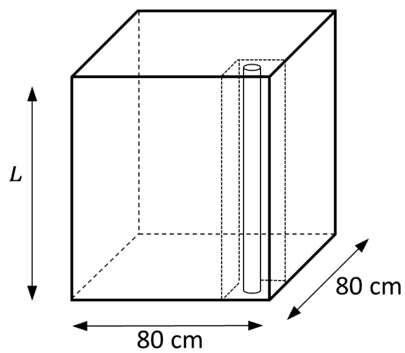

Fig. 1

3 A PWR core produces 3000 MW of thermal power. The coolant flow rate is 15000 kg s^{-1}. The core average linear heat generation rate is $q' = 18\,\mathrm{kW\,m^{-1}}$. The thermal conductivity of the fuel is $k = 3\,\mathrm{W\,m^{-1}\,K^{-1}}$ and can be assumed constant. At the Hot Zero Power (HZP) condition, the coolant temperature is 280 °C. The coolant specific heat capacity is $c_p = 5400\,\mathrm{J\,kg^{-1}\,K^{-1}}$.

Clearly state any assumptions you are making for the analysis.

(a) Estimate the core average coolant temperature and core average fuel temperature at Hot Full Power (HFP) conditions. [40%]

(b) The fuel Doppler reactivity Coefficient (DC) per unit Kelvin is given by $-3 \times 10^{-4} T^{-1/2}$, where T is in K, while the Moderator Temperature Coefficient of reactivity (MTC) is $-5 \times 10^{-4}\,\mathrm{K^{-1}}$. Estimate the reactivity decrement associated with the core heat-up from HZP to HFP. [20%]

(c) List possible ways in which reactor operators can affect MTC and DC. [20%]

(d) List possible ways in which reactor designers can affect MTC and DC. [20%]

4 The EPR and AP1000 are examples of modern reactor designs.

(a) List the differences between the two reactor designs in their approach to cooling a molten reactor core in a severe accident, along with advantages and disadvantages of each approach. [25%]

(b) List the differences between the two reactor designs in their approach to responding to a Large-break Loss of Coolant Accident along with advantages and disadvantages of each approach. [25%]

(c) List the main sources of stored energy within a PWR containment and comment on the significance of each source. [25%]

(d) List all the barriers that prevent the release of fission products into the environment in the case of a severe accident in an LWR, along with strategies to maintain their integrity. [25%]

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