Version ES/5

EGT3
ENGINEERING TRIPOS PART IIB

Monday 2 May 2016 2 to 3.30

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
NE Data Book
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 research reactor core contains 25 square fuel assemblies with plate-type fuel elements. The core geometry can be approximated by a cube with a side length of 0.5 m. The core is located in a large pool of water 10 m below the pool water surface. The cooling water flows from the pool downwards through the reactor core, then to a heat exchanger and back into the pool. Additional reactor design data is presented in the table below.

Core thermal power	5 MW
Coolant volume fraction in the core	30 %
Pool temperature	25 °C
Nominal core outlet coolant temperature	50 °C
Number of fuel plates per assembly	20

Answer all the questions below, clearly stating any simplifying assumptions you make.

(a) Estimate the heat transfer coefficient between the cooling water and the fuel plate surface. [20%]

(b) Estimate the coolant pressure drop as it flows through the core neglecting the entry and exit form losses. [20%]

(c) Estimate the pumping power required to cool the reactor core and comment on the result. [15%]

(d) If the coolant pump fails, an automatic flap isolates the cooling loop and simultaneously opens a flow path for water in the pool to circulate through the reactor core upwards by natural convection as shown in the Fig. 1 opposite. Assume that a circular pipe 0.5 m in diameter and 3 m tall is mounted above the core to improve the natural convection. The safety requirements state that no bulk coolant boiling should occur anywhere within the pool.

(i) Discuss the purpose of and list the design considerations for the above-core pipe. [15%]

(ii) Determine whether the “no bulk coolant boiling” requirement will still be met if the reactor fails to shut down and continues to operate at nominal power in the natural convection cooling mode. Assume that the water pool has infinite heat capacity. [30%]

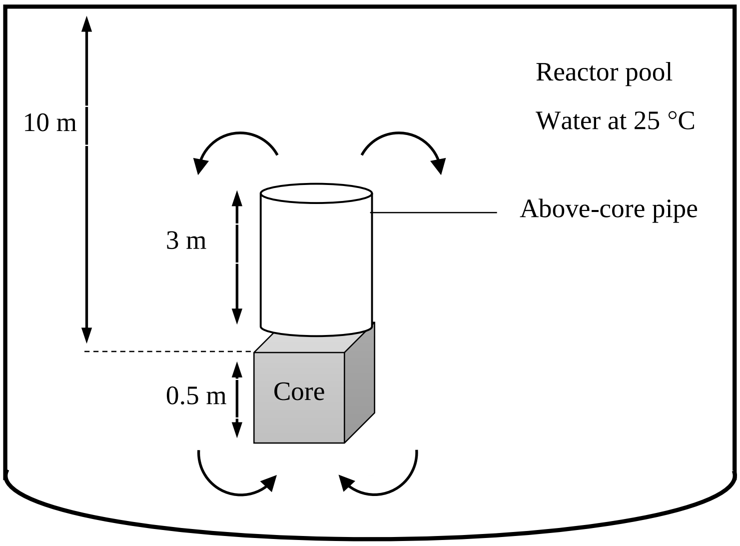

Fig. 1: Schematic (not to scale) view of coolant circulation by natural convection

2 It is proposed to introduce a new annular-shaped fuel pin with internal, as well as external, cooling. The new fuel is compared with conventional solid pellet fuel in Fig. 2 below:

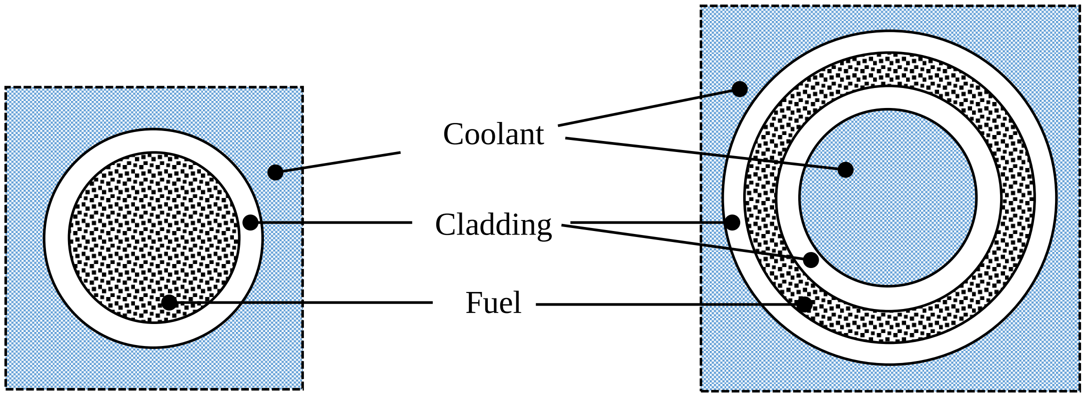

Fig. 2: Schematic view of solid and annular fuel cell

(a) List all the benefits that such annular fuel geometry might offer. [20%]

(b) If the conventional solid fuel core and annular fuel core have the same power density, fuel enrichment and hydrogen to heavy metal atoms ratio (H/HM), discuss the effects the transition from solid pellet to the annular internally cooled fuel geometry would have on the following:

(i) reactivity decrement between Cold Zero Power and Hot Full Power operating conditions; [20%]

(ii) discharge fuel burnup; [15%]

(iii) fuel cycle length. [15%]

 (cont.

(c) For the annular pin design, determine the ratio of the inner fuel pin to the outer fuel pin radius so that the flow velocities in the inner and outer flow channels will be the same. The distance between the centres of adjacent fuel pins (pin pitch) is $1.1D_o$, where D_o is the outer diameter of the annular pin. Assume that frictional pressure drop dominates such that all other pressure drop components can be neglected and that the flow is turbulent. Clearly state any other assumptions. [30%]

3 A PWR system is used to propel a freight ship. The ship power plant operates on a simple Rankine cycle using saturated steam at 40 bar at the turbine inlet and the condenser pressure is 0.1 bar. The power plant is to deliver 30 MW to the ship propeller shaft. At this power, the ship achieves a cruising speed of 40 km/h.

(a) Determine the steam flow through the power plant at the maximum cruising speed if the steam turbine isentropic efficiency is 80%. [20%]

(b) Determine the reactor thermal power if the feed water pump work per unit feed water mass flow is 45 kJ/kg. [20%]

(c) The reactor is to operate for 25 years without refuelling (a single fuel batch core) with a capacity factor of 80%. The reactivity versus burnup relationship for the fuel is presented in Fig. 3 opposite. Determine the initial fuel inventory in kg of uranium required. [20%]

(d) Stating any assumptions, calculate the mass of fissile ^{235}U that will be consumed during a 60,000 km trip around the world if the average fission and capture cross sections of ^{235}U are 40 and 7 barns respectively. [20%]

(e) The fuel reactivity is initially much higher than required to keep the reactor core critical. List possible ways of supressing the initial excess reactivity. Discuss potential disadvantages of each option in the context of a marine power plant. [20%]

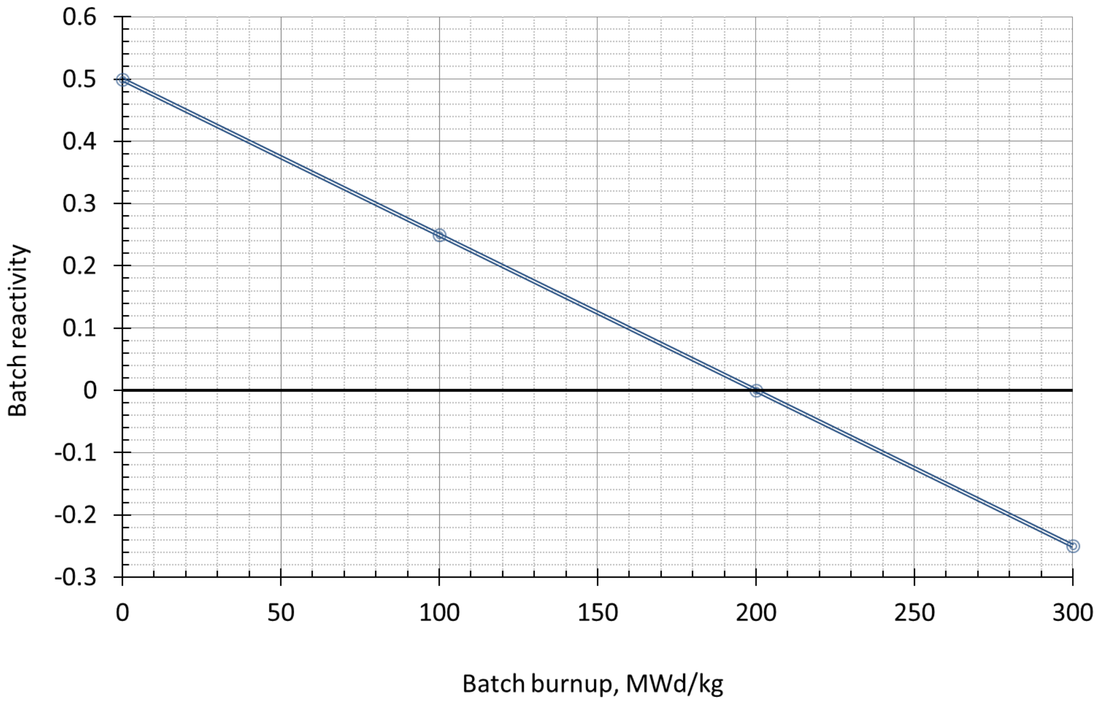

Fig. 3: Single batch core reactivity versus burnup

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4 Consider a Loss of Coolant Accident (LOCA) in a PWR following a large break of one of the primary loop pipes. The primary coolant is discharged from the system into the containment and partially flashed into steam, pressurising the containment.

(a) List all potential sources of energy inside the containment following a large break LOCA. [20%]

(b) List typical PWR engineered safety systems and natural phenomena that can remove the energy from the containment. [20%]

(c) List potential PWR containment failure modes and corresponding phenomena due to which the containment might fail. [20%]

(d) Sketch the primary coolant system depressurisation process on a *T*-*s* diagram noting the initial and final state. [10%]

(e) Some PWR containments have thermally isolated compartments with water ice at –10 °C which open automatically allowing thermal contact with the containment space in case of an accident. Estimate the mass of ice required to maintain the containment steam partial pressure under 4 bar for 4 hours after the accident. Assume infinite reactor operation before shutdown at the time of the accident and no other means of removing heat from the containment are available. Clearly state any simplifying assumptions you are making. Additional data is given in the table below. [30%]

Primary water inventory	500,000 kg
Primary water temperature (nominal)	300 °C
Primary water pressure (nominal)	150 bar
Reactor nominal thermal power	3000 MW
Containment free volume	50,000 m^3
Ice heat capacity	4.2×10^3 J/kg/K
Water heat of fusion	3.3×10^5 J/kg

END OF PAPER