EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 21 April 2015 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 (21 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 Consider Pressurized and Boiling Water Reactors (PWR and BWR) that produce the same thermal power of 3000 MW. The reactors have similar reactor physics characteristics due to their identical fuel lattice Hydrogen to Heavy Metal ratios (H/HM). The reactors also have an identical fuel pin diameter. Use the physical data and thermal constraints in Table 1. Make the following simplifying assumptions and clearly state any other assumptions you are making.

- The temperature drop across the cladding is much smaller than that across the fuel.
- The coolant temperature rise is small and can be neglected in the design estimates.
- Peak fuel temperature and peak cladding heat flux occur at the same axial location.

(a) Estimate the number of fuel pins in the core of each reactor type. [35%]

(b) Discuss the validity of the assumption that the peak fuel temperature and peak cladding heat flux occur at the same axial location. [10%]

(c) If the coolant flow velocity in the PWR is 5.5 m/s and the coolant temperature rise across its core is 30 K, estimate the core average power density for each reactor type. [30%]

(d) Explain why, despite the difference in core power density, the reactor types have similar economics. [10%]

(e) Propose practical ways of increasing the power density of the PWR. [15%]

Table 1: Reactor design data

	PWR	BWR
Core average void fraction, %	0	40
System pressure, bar	150	70
Fuel height, m	4	4
Fuel pin radius, cm	0.5	0.5
Radial core power peaking factor	1.6	1.6
Axial power peaking factor	1.4	1.4
Fuel effective thermal conductivity, W m^{-1} K^{-1}	4	4
Departure from Nucleate Boiling (DNB) heat flux, kW m^{-2}	900	-
Critical Power (for 10×10 pins fuel bundle), MW	-	6.0
Minimum DNB or Critical Power Ratio	1.3	1.3
Maximum fuel temperature, K	2200	2200
Average coolant temperature, K	583	583

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2 Figure 1 shows the effective neutron multiplication factor, k_{eff}, as a function of Hydrogen to Heavy Metal ratio (H/HM) in a typical Pressurized Water Reactor. The value of H/HM = 5 represents the Cold-Zero-Power state of the reactor at which the water coolant is at $50\,°\mathrm{C}$. The coefficient of thermal expansion for water is given by:

$$\beta = \frac{1}{V} \times \frac{\partial V}{\partial T} = 1.55 \times 10^{-3}\ °\mathrm{C}^{-1}$$

(a) Estimate the Moderator Temperature Coefficient (MTC) of the core.
$\mathrm{MTC} = \dfrac{\partial \rho}{\partial T_m}$, where the symbols have their usual meaning. [40%]

(b) Calculate the core reactivity decrement associated with coolant heat up from Cold-Zero-Power to the Hot-Zero-Power state at which the coolant temperature rises to $300\,°\mathrm{C}$. [10%]

(c) Sketch the k_{eff} versus H/HM curve expanded beyond the range shown in Fig. 1 and describe the main effects responsible for the behaviour you have indicated. [20%]

(d) On the same graph as in part (c) of this question, plot two additional curves corresponding to:

(i) The same core loaded with lower enrichment fuel. Describe the main effects responsible for changes in the shape and/or location of the curve. [15%]

(ii) The same core with higher soluble boron concentration. Describe the main effects responsible for changes in the shape and/or location of the curve. [15%]

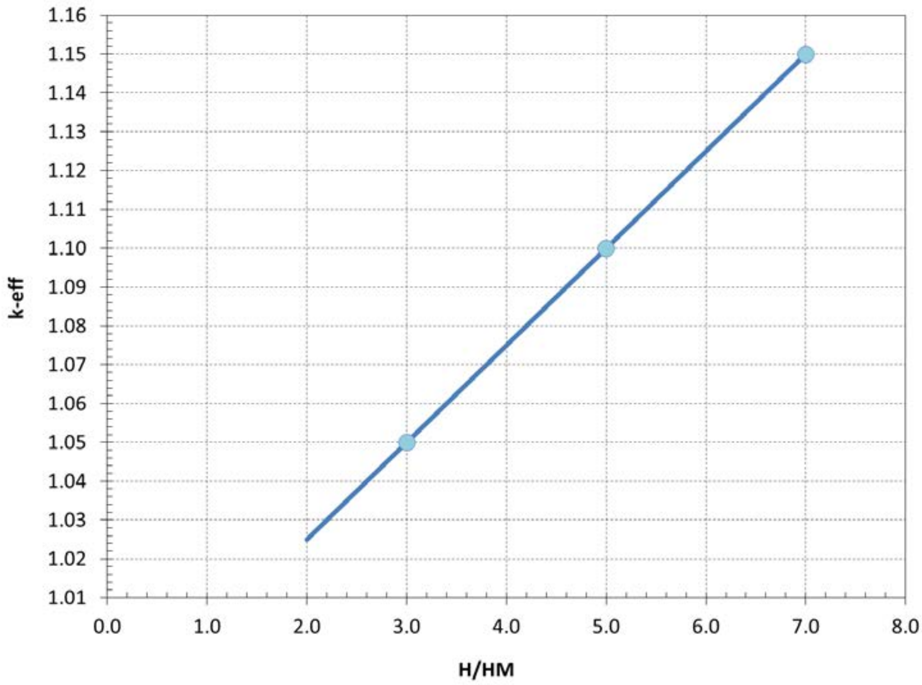

Fig. 1 – Core effective neutron multiplication factor versus Hydrogen to Heavy Metal atoms ratio.

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3 A new Pressurized Water Reactor (PWR) concept with steam generators integrated into the Reactor Pressure Vessel (RPV) has been recently proposed to improve safety. However, manufacturing very large RPVs is problematic. Therefore, in order to save space, it was decided to use steam flashing drums outside the RPV.

The secondary coolant enters and exits the RPV in a single phase at high pressure. The secondary coolant, after being heated inside the RPV by the primary water, is directed into a flashing drum, where it expands through a series of nozzles to a much lower pressure and is thus flashed into wet steam. The steam is dried and directed into a turbine, while the liquid is recirculated back into the RPV using a recirculation pump. The steam flashing drum and the power conversion cycle are schematically presented in Fig. 2 opposite. Relevant data is provided in the table within Fig. 2.

(a) Sketch the *T*-*s* diagram of the power cycle labelling points 1 through 8 as indicated in Fig. 2. [20%]

(b) Calculate the specific work of both recirculation and condensate water pumps and the thermodynamic efficiency of the cycle. [40%]

(c) Calculate the steam mass flow rate through the turbine and the water mass flow rate through the heat exchanger inside the RPV if the plant generates 1000 MW_e. [15%]

(d) How would the thermodynamic efficiency of this cycle compare with that of a conventional PWR cycle with a steam generator operating at the same pressure and same operating parameters for the rest of the cycle. Explain the difference. [15%]

(e) How would integrating all the primary cooling circuit components into the RPV improve the safety of the reactor? [10%]

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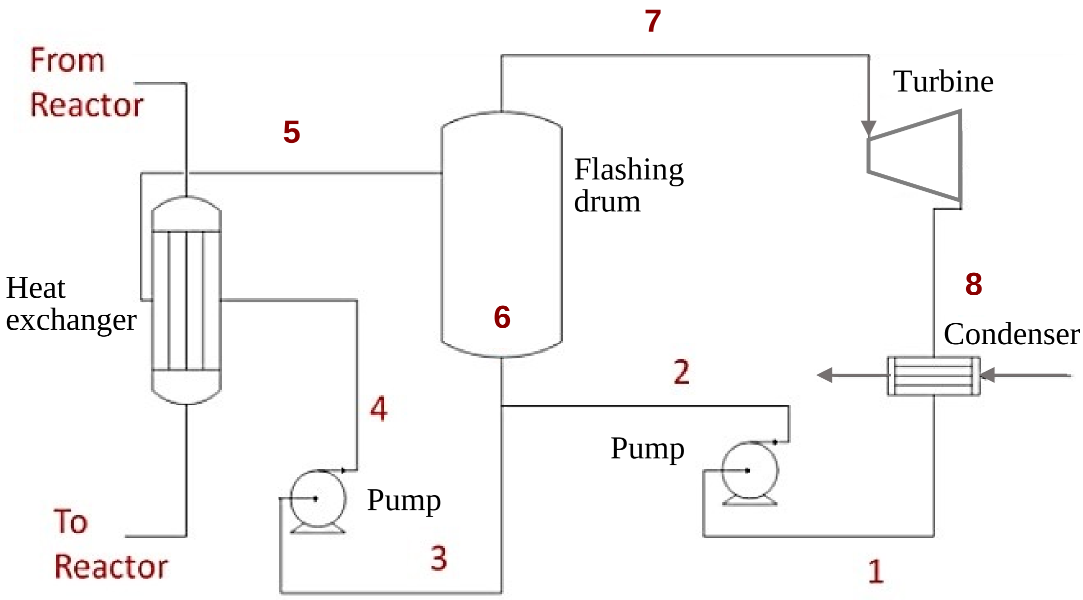

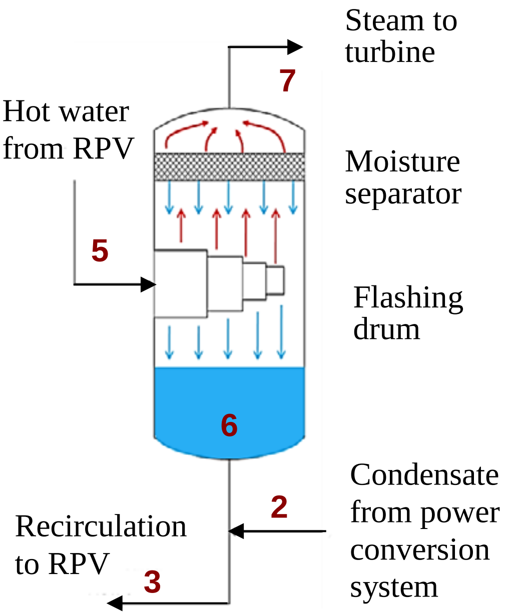

Flashing drum data	
Water inlet temperature, °C	325
Water inlet pressure, bar	140
Steam drum pressure, bar	86
Water mass fraction flashed	10%
Steam cycle data	
Condenser pressure, bar	0.1
Turbine isentropic efficiency	90%
Condensate pump isentropic efficiency	85%
Recirculation pump isentropic efficiency	85%

Fig. 2 – Schematic view of the power conversion system with flashing drum and its design parameters.

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4 (a) Describe the main differences in strategies employed in Pressurized and Boiling Water Reactors (PWRs and BWRs) for coping with a Loss of Coolant Accident. [15%]

(b) Many existing BWRs are equipped with a Reactor Core Isolation Cooling (RCIC) system, designed to provide cooling in situations when the core is isolated from the power plant. The RCIC is a passive system, which requires only DC power to operate the valves. It consists of a steam turbine driven pump, which draws cold water at $25\,°C$ from an open storage tank at atmospheric pressure and injects it into the core. Part of the steam from the reactor at 7 MPa drives the turbine and the exhaust steam is discharged into a large suppression pool through a sparge pipe where it is condensed by mixing with cold water, initially at $25\,°C$. The steam sparge pipe is located at 5 m depth below the pool surface. The surface of the suppression pool is also at atmospheric pressure. The rest of the steam from the reactor is dumped directly into the suppression pool. The steam turbine and the pump both have isentropic efficiencies of 80%.

Assume "infinite" core operation prior to shutdown.

(i) Sketch the RCIC system, labelling all the components and state points. [10%]

(ii) If the nominal reactor power is 2000 MW_{th}, estimate the following quantities one hour after reactor shutdown:

a. Core cooling water flow rate,
b. Steam flow rate through the RCIC turbine,
c. Power consumed by the RCIC pump. [50%]

(iii) Estimate the minimum volume of the feed water storage tank required to provide the core cooling for 24 hours of RCIC system operation, assuming that the RCIC is actuated one hour after the reactor shutdown. [10%]

(iv) Estimate the volume of the suppression pool such that the water in the pool will remain below the saturation point during the 24 hours of RCIC system operation, again assuming that the RCIC is actuated one hour after the reactor shutdown. [15%]

END OF PAPER