EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 25 April 2018 2.00 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 (22 pages)
Engineering Data Book

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.

1 Replacing zirconium metal with silicon carbide (SiC) composite ceramic is one of the leading Accident Tolerant Fuel concepts. SiC has a lower thermal conductivity than zirconium but it is much more resistant to oxidation, does not lose strength with a rise in temperature and does not change dimensions during irradiation. Also, Si has a lower absorption cross section than Zr. However, fuel swelling, due to the accumulation of fission products, leads to eventual contact between the fuel and the cladding. Since SiC is a brittle ceramic, such contact must be avoided. Therefore, SiC-clad fuel is designed to have a smaller fuel pellet diameter to ensure a larger gap between the pellet and cladding than conventional Zr-clad fuel. All other fuel lattice dimensions remain unchanged.

(a) List all the effects that the new SiC-clad fuel could have on reactor safety and thermal limits. Provide a brief explanation of each effect. [30%]

(b) List all the effects that the new SiC-clad fuel could have on core reactivity, reactivity control and fuel cycle. Provide a brief explanation of each effect. [30%]

(c) The thermal conductivity, k in W cm^{-1} °C^{-1}, of a UO_2 fuel pellet, as a function of temperature, T, in °C, can be approximated by the following expression:

$$k(T) = -2 \times 10^{-5}\, T + 0.09$$

The power density distribution, $q'''(r)$ in W cm^{-3}, peaks towards the outside surface of the pellet due to the "rim effect" and has the following radial dependence:

$$q'''(r) = 200 + 1.5 \times 10^{3}\, r^{4}$$

where r is in cm.

(i) Define the "rim effect" and explain why the radial power distribution may peak towards the pellet surface. [10%]

(ii) Calculate the maximum fuel temperature if the pellet surface temperature is 350 °C and the pellet radius is 0.5 cm. [30%]

The heat conduction equation in cylindrical coordinates has the following form:

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(kr\frac{\mathrm{d}T}{\mathrm{d}r}\right) + q''' = 0$$

2 (a) Describe two important functions that burnable poisons perform in a commercial power reactor. [20%]

(b) List and justify the desired characteristics of a burnable poison. [20%]

(c) Rank PWR, BWR, AGR and CANDU-type reactor systems in terms of each of their core power density, discharge fuel burnup and fuel cycle length. Qualitatively explain and justify your ranking. [20%]

(d) A 3200 MWth power reactor core contains 10^5 kg of uranium, refuelled in a single-batch, and operates on a 14-month fuel cycle. The power generation history during the cycle is shown in Fig. 1.

(i) Calculate the discharge fuel burnup. [10%]

(ii) Calculate the fresh fuel enrichment, if the U-235 fission cross section is 35 b, energy release per fission is 200 MeV and assuming that all the energy in the reactor comes from fissions of U-235. Just before shutdown, the core average neutron flux was 4.5×10^{14} $s^{-1}cm^{-2}$. [30%]

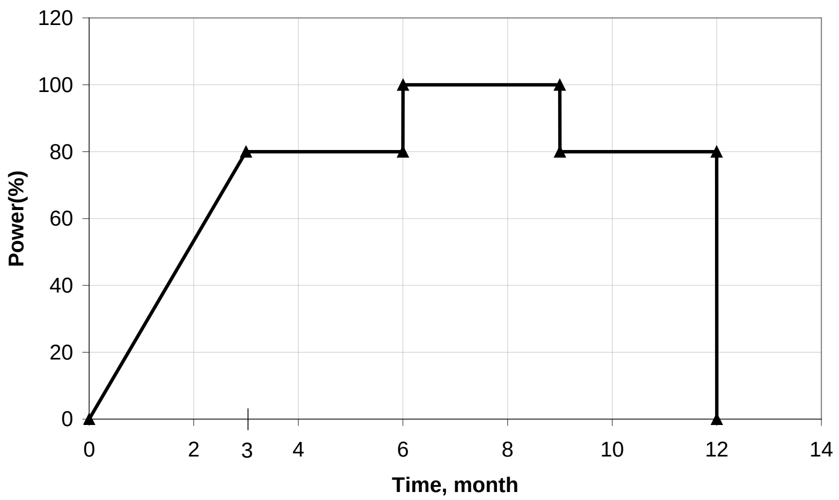

Fig. 1

3 A PWR core operates on a 3-batch fuel management scheme with a 12-month fuel cycle. The core power is 3000 MWth. Due to an unexpected event, the reactor is shut down one month into the equilibrium cycle. The main coolant circulation pumps are stopped and the Decay Heat Removal System (DHRS) initiated 60 s after shutdown, taking over the heat removal function and circulating the primary water coolant through a dedicated external heat exchanger (Fig. 2). The primary coolant remains pressurised at a nominal system pressure of 150 bar. In the following calculations clearly state any simplifying assumptions you are making.

(a) Estimate the core decay heat at the time the DHRS starts operation, if refuelling outage times are disregarded. [30%]

(b) The DHRS is designed to maintain the primary coolant temperature 100 °C below saturation. Estimate the flow rate that the DHRS pump needs to provide in order to satisfy this design requirement, if the coolant water returns from the external heat exchanger at 200 °C. [30%]

(c) Using the reactor data provided below and the flow rate obtained in (b), estimate the power consumed by the DHRS pump. The hydraulic resistance of the external heat exchanger and other piping is such that it requires the same pumping power as that needed to circulate the coolant through the reactor core. Assume water density and dynamic viscosity are ρ = 850 kg m^{-3} and μ = 0.00152 Pa s respectively. [20%]

(d) Suggest alternative options for removing decay heat from the core by passive means, i.e. without the need for electric motor driven pumps. [20%]

Reactor Data:

Number of fuel assemblies	193
Fuel pins per assembly	256
Fuel pin diameter, cm	1.0
Fuel pins lattice type	Square
Fuel pins lattice pitch, cm	1.5
Fuel pin length, cm	400

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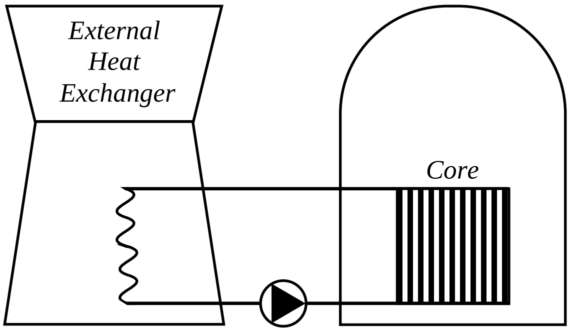

Fig. 2

4 (a) List the distinctive design features of the power conversion cycle for each of the following reactor systems: PWR, BWR and AGR. Highlight the main differences and identify comparative advantages of each power cycle arrangement in terms of costs of equipment and thermodynamic efficiency. [25%]

(b) It is proposed to increase the electric power generation of a PWR by 5% through increasing the core thermal power by the same percentage.

(i) List and justify any possible modifications that might need to be made to the core and primary coolant system in order to allow safe operation of the plant at higher power. [25%]

(ii) List and justify any possible modifications that might need to be made to the secondary loop in order to allow safe and efficient operation of the plant at higher power. [25%]

(c) A PWR operates on a simple Rankine cycle, between a 60 bar turbine inlet and a 0.1 bar condenser pressure with no superheat. Assuming an ideal feedwater pump, calculate the isentropic efficiency of the turbine if the thermal efficiency of the cycle is 33%. [25%]

END OF PAPER