Version ES/8

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 23 April 2014 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

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 (a) Explain why PWR power cycles convert about only a third of the energy released in the core to electricity, and explain giving reasons, what limits PWR cycle efficiency. [20%]

(b) This low thermal efficiency of PWRs leads to consideration of their use in a combined heat and power system in which the lower temperature heat from the exhaust of the turbine is used for district heating.

A PWR system (conditions below) is cooled by rejecting heat to a condenser at 29 °C with feed heating which raises the feed temperature to 140 °C generating electricity sold at a price of £80/MWh.

PWR Plant Conditions

Hot leg temperature	320 °C	Cold leg temperature	280 °C
Steam Generator pressure	75 bar abs		
Turbine efficiency	75 %	Generator efficiency	95 %
Feed pump work	7 kJ kg^{-1}	Station loads	50 kJ kg^{-1} of steam

(i) Calculate the net thermal efficiency of this normal PWR cycle. [20%]

(ii) For a PWR which both generates electricity and rejects heat to a district heating system at 152 °C, calculate the net thermodynamic efficiency of this modified cycle, assuming the turbine efficiency improves to 84 % and the water returning from the district heating system is at 20 °C. [20%]

(iii) If only 40 % of heat supplied to the district heating is usable, because of temperature and heat losses, at what price (£/MWh) would the usable heat need to be sold to the end customer to achieve the same reactor economics? [20%]

(iv) Would there be economic merit in increasing the temperature at which heat is delivered to the district heating system? Why? How would the system be optimised? [20%]

2 The fuel rods in a reactor contain solid cylindrical fuel pellets of outer radius r_f without any cladding. The volumetric energy release rate within the pellets is. q''' The thermal conductivity of the fuel may be assumed to have a constant value k.

(a) Given that the Fourier equation in cylindrical coordinates is

$$\frac{1}{r}\cdot\frac{d}{dr}\left(k\cdot r\cdot\frac{dT}{dr}\right)+q'''=0$$

show that the temperature difference (ΔT) between the centre line and the outside of the fuel pellet is dependent only on the linear rating of the fuel rod, q', as follows: [25%]

$$\Delta T=\frac{q'}{4\pi k}$$

(b) Explain briefly why, considering each of the main elements, the temperature difference between the outer surface of the fuel and the bulk fluid in the coolant passages can be written as $\Delta T_c \approx a.q'$ where a is a constant. What assumptions are involved and what factors influence the value of a ? [25%]

(c) The linear rating of the fuel rods varies according to

$$q'(z)=q'_{\max}\cos(\beta z)$$

where: β is a constant and z is the distance along the fuel rod measured from its midpoint. The coolant has a constant specific heat capacity C_P, and the mass flow rate of coolant associated with each fuel rod is $\dot{m}$.

(i) Derive an expression for the rate of change of the fuel centreline temperature (T_f) with distance z along the fuel rod in terms of the linear rating (q') and the two temperature differences. [20%]

(ii) Hence show that the position along the fuel rod where the centreline temperature is maximum satisfies the relationship: [20%]

$$\tan(\beta z)=\left[\dot{m}C_p\left(a+\frac{1}{4\pi k}\right)\right]^{-1}$$

(iii) Without further calculations, sketch a graph of how you would expect the coolant temperature and fuel centreline temperature to vary with z. [10%]

3 (a) Nuclear reactor systems often include a heat exchanger between the reactor core and the steam or gas turbine. Explain why this is a common arrangement and discuss the main advantages and disadvantages of such a design. [20%]

(b) A gas cooled (carbon dioxide at 40 bar) reactor system with a single pressure (170 bar) steam power cycle employs a once-through steam generator operating under conditions and with dimensions given opposite.

(i) Sketch the $T - s$ diagram for the cycle and explain the different flow and heat transfer conditions on the gas side and in the three main sections of the steam side of the steam generator. [20%]

(ii) Estimate the tube lengths of the economiser, evaporator and super-heater sections of the steam generator using the correlation below for the gas side cross-flow heat transfer. Ignore the pressure drop through the secondary side of the steam generator and any fouling.

$Nu = 0.33\, Re^{0.6} Pr^{0.33}$, where Re is based on the minimum flow area. [40%]

(iii) How could the thermodynamic efficiency of the system be improved by using a re-heater? When sizing re-heater tube banks to operate at 40 bar between the same temperatures as the super-heater, what additional factors are to be considered? [20%]

Core design power:		600 MW
Number of steam generator units		12
Primary coolant:	Core outlet temperature	640 °C
	Core inlet temperature	340 °C
Secondary coolant:	Feed water temperature	160 °C
	Super-heater outlet temperature	570 °C
Plain tubes:	Outside diameter	28 mm
	Inside diameter	21 mm

Gas side mean values at 500 °C and 40 bar:

Density	27 kg m^{-3}
Specific heat capacity	1.1 kg kJ^{-1} K^{-1}
Dynamic viscosity	35×10^{-6} kg s^{-1} m^{-1}
Prandtl Number	0.75
Thermal conductivity	55×10^{-6} kW m^{-1} K^{-1}
Characteristic velocity	2.8 m s^{-1}

Secondary heat transfer coefficients:

Economiser	20 kW m^{-2} K^{-1}
Evaporator	50 kW m^{-2} K^{-1}

The ratio of mean economiser (ec) and super-heater (sh) properties are:

Gas conductivity	$\frac{k_{sh}}{k_{ec}} = 0.4$
Gas viscosity	$\frac{\mu_{sh}}{\mu_{ec}} = 1$
Prandtl Number	$\frac{Pr_{sh}}{Pr_{ec}} = 1.5$

Tube materials:

Economiser and Evaporator:	ferritic steel
Super-heater:	stainless (austentic) steel

4 (a) (i) What are the three main tenets of nuclear safety? [15%]

(ii) Explain the concept of defence in depth for nuclear safety and illustrate this with an example for Loss of Coolant Accident (LOCA) protection. [15%]

(iii) Describe three main phases of the short-term (less than an hour) LOCA protection for a PWR. What are the key protection criteria that have to be demonstrated during these early stages of a LOCA? [10%]

(iv) How is the LOCA protection of a CANDU system different in principle from that of a PWR? [10%]

(b) In designing the long term LOCA protection of an advanced light water reactor system, the volume of cooling water to be stored inside the containment is to be established. The design basis is that not more than 50% of the stored water may be boiled off by decay heat before the overall system is in thermal equilibrium under the influence of the passive containment cooling. Using the data given below:

(i) Show that the containment cooling reaches equilibrium in about 20 days [25%]

(ii) Estimate the required mass of stored water, initially at $20\ ^{\circ}\mathrm{C}$, required to provide protection over this period, ignoring the heat removed before equilibrium, if the saturation pressure in the containment reaches 2.5 bar by day 20. [25%]

Reactor System

Operating power output	1 GWe
Thermal efficiency	35%
Operating time prior to LOCA	3 years
Containment passive cooling removal rate	up to 5.5 MW

END OF PAPER