EGT3
ENGINEERING TRIPOS PART IIB

Thursday 4 May 2017 2 to 3.30

Module 4I11

ADVANCED FISSION AND FUSION SYSTEMS

*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) List the main advantages of advanced high temperature reactors. Compare and contrast these advantages against the Gen-IV International Forum objectives. [15%]

(b) Graphite-moderated gas-cooled pebble-bed reactors are relatively neutronically inefficient. They require higher enrichment than Light Water Reactors and have lower fuel utilisation. Explain the reasons for these inefficiencies. [15%]

A graphite-moderated He-cooled pebble-bed reactor has a cylindrical core and is operating at a power Q = 600 MW. The dimensions and other relevant data are given in Table 1. The axial power distribution follows the cosine shape $q'''(z) = q_0 \cos\left(\pi z / H\right)$, where H is the core height and z is the axial distance from the centre of the core. The radial power distribution is uniform.

(c) Show that the He coolant temperature as a function of axial elevation is

$$T_{He}(z) = T_{in} + \frac{Q}{2\,\dot{m}\,c_{\mathrm{p}}}\left(1 + \sin\left(\frac{\pi z}{H}\right)\right)$$

where $\dot{m}$ is the He mass flow rate. [30%]

(d) Estimate the mass flow rate of He through the reactor core. [10%]

(e) Estimate the surface temperature of the pebbles a distance of 15 m downstream of the coolant entry into the core. [30%]

Table 1

Core height	20 m
Core radius	1.5 m
He inlet temperature, T_{in}	400 °C
He outlet temperature	900 °C
He to pebble heat transfer coefficient	1000 W $\mathrm{m}^{-2}\,\mathrm{K}^{-1}$
He specific heat capacity, c_{p}	5200 J $\mathrm{kg}^{-1}\,\mathrm{K}^{-1}$
Pebble radius	0.03 m
Number of pebbles in the core	750,000

2 (a) Explain how the reactivity of a sodium-cooled oxide-fuelled fast reactor is affected by the temperatures of the fuel and the coolant. [30%]

(b) A 3000 $\mathrm{MW_{th}}$ sodium-cooled pool-type fast reactor is operating at full power. Coolant flows through the core at a total rate of 15,000 kg $\mathrm{s^{-1}}$ and the inlet temperature is 400 °C. Other relevant data can be found on pages 11 and 12 of the NE Data Book.

(i) Estimate the mean coolant outlet temperature. [5%]

(ii) What would be the implications of using lead-bismuth eutectic as the coolant instead of sodium, while keeping the coolant mass flow rate the same? [10%]

(iii) Discuss considerations for choosing the coolant flow rate in liquid metal-cooled fast reactors. [10%]

A series of tests is done with fixed coolant inlet temperature. If the coolant flow rate is increased by 1%, it is found that the control rods have to be adjusted to reduce the reactivity by 2 cents to keep the power steady. If the coolant flow rate is kept constant, a 5 cent decrease in reactivity is found to reduce the power by 1% after the transients have decayed.

(c) The coolant flow rate is increased by 1% without moving the control rods.

(i) By how much would the core power change? [15%]

(ii) What would the mean coolant outlet temperature be? Assume that reactivity changes are proportional to changes in flow rate and temperature, and that there is no overshoot. [10%]

(d) The above-core structure would suffer damage if the mean coolant outlet temperature were to exceed 600 °C. Use the above test data to estimate the maximum allowable change in the coolant flow rate if, without moving the control rods, damage is to be avoided. Why might this estimate be unreliable? [20%]

3 Fusion reactors employ a Deuterium-Tritium (D-T) fuel mixture because of the large fusion cross-section at achievable plasma temperatures. While deuterium is readily available, tritium must be produced in sufficient quantity to fuel a reactor.

(a) List and explain three additional problems arising from the use of tritium as a fuel. [15%]

(b) Each D-T fusion reaction releases 17.6 MeV of energy and tritium costs $30,000 per gram. For a 3 GW_{th} reactor, what is the tritium fuel cost per year, assuming operation at full power? State any other assumptions you make. [25%]

(c) The tritium fuel must be bred within the reactor using a lithium blanket. Lithium has two stable isotopes Li^6 and Li^7. How do the neutron-induced reactions that generate tritium differ between these nuclides? [20%]

(d) Describe a spatially heterogeneous enrichment strategy that would maximise tritium production in a fusion reactor blanket. What else could be added to increase the tritium production rate? [20%]

(e) Describe one of the European tritium blanket module designs. Identify the fundamental material choices and their roles. Explain how heat and tritium are extracted. [20%]

4 The plasma in a magnetically confined fusion reactor will require heating systems to bring it to the temperatures for fusion to occur. To harness fusion power for energy production, it is expected that these heating systems would be turned off and the plasma must then sustain the necessary heating by itself.

(a) Name the three main heating systems employed in current fusion reactors such as the Joint European Torus (JET). Briefly explain how they inject energy by describing how they interact with the plasma constituents. [30%]

(b) From the definition of confinement time τ, the kinetic energy content of an equal mix Deuterium-Tritium (D-T) plasma, and the fusion power of alpha particles, derive the Lawson criterion

$$n_e \tau \geq \frac{12}{E_{ch}} \frac{kT}{\langle \sigma v \rangle}$$

where the terms have their usual meaning. Explain why the energy value E_{ch} is not the total fusion energy, and why it is not precisely the energy of the alpha particles for D-T fusion. [35%]

(c) Consider a tokamak plasma with ion density of 10^{20} m^{-3} and a total volume 1000 m^3. What is the total fusion power from D-T reactions where the velocity average reaction rate is 10^{-22} $\mathrm{m}^3\mathrm{s}^{-1}$? Approximately what fraction of this power is retained in the plasma? [20%]

(d) If the confinement time for the reactor described in (c) is 10 seconds and $kT = 10$ keV, will the fusion power be sufficient to maintain the plasma temperature? [15%]

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