Version ES/8

EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 5 May 2015 9.30 to 11

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 (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 (a) List and explain the relative advantages and disadvantages of sodium and lead-bismuth eutectic as coolants for a fast reactor core. [50%]

(b) The core of a 3000 $\mathrm{MW_{th}}$ fast reactor can be taken to be a circular cylinder 2 m in diameter. Half of its cross-sectional area is occupied by the coolant flow passages. The mean core outlet temperature (fixed by considerations of material strength) is $550\,^{\circ}\mathrm{C}$ and the core inlet temperature is $350\,^{\circ}\mathrm{C}$. The primary coolant is sodium.

(i) What is the primary coolant mass flow rate? What is the mean sodium flow velocity in the core? [15%]

(ii) Lead-bismuth eutectic is being considered as an alternative coolant. If the core geometry and temperatures were to remain the same, what would be the flow rate and mean velocity in the core? [10%]

(iii) It is found that to avoid damage by erosion, the mean velocity for lead-bismuth has to be limited to 4 m $\mathrm{s^{-1}}$. If the core geometry and outlet temperature are not to be changed, what is the inlet temperature? [10%]

(iv) A low inlet temperature is undesirable because of the effect on the overall thermal efficiency of the plant. Discuss the alternatives available to the designer if lead-bismuth is still to be used. [15%]

Use the following physical property data:

	Sodium	**Lead-bismuth eutectic**
Density, kg $\mathrm{m^{-3}}$	817	10,100
Specific heat capacity, J $\mathrm{kg^{-1}\,K^{-1}}$	1260	142

2 In tokamak plasmas, *neutral beam injection* (NBI) is frequently used for heating and current drive.

(a) Describe briefly the concept behind NBI for heating and current drive. Why must the beam be neutralised? [20%]

(b) What are the advantages and disadvantages of positive-ion and negative-ion systems? Which are needed for future fusion power plants and why? [20%]

(c) Estimate the beam shine-through fraction (the proportion of the neutral beam particles that penetrate the plasma) for the International Thermonuclear Experimental Reactor (ITER). Assume the following parameter values:

$$E_b = 1000 \text{ keV},\ \ n_p = 1\times10^{20} \text{ m}^{-3},\ \ R_0 = 6.2 \text{ m},\ \ a = 2.0 \text{ m},$$

where E_b is the beam energy, n_p is the plasma electron density, and R_0 and a are the plasma major (toroidal) and minor (poloidal) radii.

Assume that the neutral beam is injected horizontally, tangential to the plasma centre. The following equations may be useful:

$$n_b(x) \propto \exp\left(-\frac{x}{\lambda}\right)$$

$$\frac{1}{\lambda} = n_p\times(\sigma_\mathrm{c} + \sigma_\mathrm{i})$$

$$(\sigma_\mathrm{c} + \sigma_\mathrm{i}) = 3\times10^{-18}/E_{\mathrm{b,\,keV}}$$

where σ_c and σ_i are cross-sections for charge-exchange and ionisation of the beam particles, $n_b(x)$ is the beam particle density after travelling a distance x in the plasma, and λ is the beam decay length. [40%]

(d) What might happen if the value of the beam shine-through fraction is too high, as would occur if the beams were turned on when the plasma density was much lower? [20%]

3 (a) Describe the rationale behind a need for developing Generation IV reactors. [10%]

(b) A high coolant core outlet temperature is required to achieve some of the Generation IV goals. Why? [15%]

(c) High Temperature Gas-cooled Reactors have core power densities 20 times lower than Pressurized Water Reactors. Why? [15%]

(d) In a Depressurised Loss of Forced coolant Circulation (DLOFC) accident in a Pebble Bed Helium Gas-cooled Reactor, the fuel temperature must not exceed $1600\,^{\circ}\mathrm{C}$. Negative reactivity feedbacks stabilize the reactor power at 1% of the nominal power. This power is removed by heat conduction through the pebble bed towards the reactor pressure vessel surface, which is cooled by natural circulation of air on the outside such that the surface temperature is kept at $400\,^{\circ}\mathrm{C}$. Other reactor design parameters are listed in Table 1 opposite. The following assumptions can be made:

- The temperature drop across TRistructural-ISOtropic (TRISO) fuel particle coating layers can be neglected;
- Pebbles are in direct contact with the pressure vessel wall;
- The axial power distribution $q(z)$ can be approximated by $q(z) = A\cos\left(\frac{\pi z}{H}\right)$, where H is the core height, A is a constant and z is measured from mid height of the core;
- The core power distribution in the radial direction is uniform.

(i) By estimating the parts of the temperature cascade from the hottest fuel zone to the reactor vessel wall, calculate the maximum reactor power if the fuel temperature is not to exceed the DLOFC accident limit. State clearly any additional assumptions you make. [40%]

(ii) A solid graphite reflector is introduced into the centre of the core while preserving the original core outside dimensions. How would the reflector diameter affect the maximum achievable power of the reactor? Discuss both the benefits and drawbacks of introducing the central reflector. [20%]

Table 1: Pebble Bed Reactor Parameters

Parameter	Value
Active core height, m	15.0
Active core diameter, m	3.0
Pebbles packing fraction	60%
TRISO particles per pebble	10,000
Pebble diameter, m	0.06
Pebble fuel zone diameter, m	0.05
TRISO particle diameter, m	0.0005
Pebble bed effective thermal conductivity, W m^{-1} K^{-1}	20
Graphite thermal conductivity, W m^{-1} K^{-1}	50
Fuel kernel (UO_2) thermal conductivity, W m^{-1} K^{-1}	4

4 The planned fuels for nuclear fusion, at least in present power plant concepts, are deuterium and tritium.

(a) Where do these fuels come from? List some potential problems with obtaining the fuels. [30%]

(b) Average electricity consumption per capita in the UK is ~20 kWh per day. Assuming all this energy is supplied through D-T fusion reaction and life expectancy of 80 years, estimate the amount of tritium required to supply a lifetime's energy needs. [30%]

(c) Why is D-T used as the target reaction in current reactor concepts? [20%]

(d) Are there disadvantages in the use of D-T, and why don't we target other reactions? [20%]

END OF PAPER