Version ES/7

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 24 April 2014 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

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

1 The divertor is the structure in a fusion power plant that handles exhaust from the plasma. As such, it is subject to very high heat and particle fluxes. In a typical 2.5 GW fusion power (D-T) demonstration power plant design, there may be 150 MW of exhaust power reaching the divertor. Current designs limit the maximum heat flux to $10\ \mathrm{MW\ m^{-2}}$.

(a) What are the main exhaust products from D-T fusion reactions that have to be removed by means of the divertor and what are the main challenges in designing the device? [30%]

(b) If the incident energy of particles is 20 eV, sputtering of the tungsten surface will occur at a rate of $0.1\ \mathrm{nm\ s^{-1}}$.

(i) Estimate the total sputtering of tungsten in kg per year for the fusion reactor above, if the heat flux in the divertor is limited to $10\ \mathrm{MW\ m^{-2}}$, given the density of tungsten is $19.25\ \mathrm{g\ cm^{-3}}$. [20%]

(ii) Comment on this value and what might happen to the tungsten. [10%]

(c) To suppress tungsten sputtering, the incident particle energy must be reduced below 10 eV.

(i) What would be the particle throughput required to reach this value? [20%]

(ii) Compare this divertor limit to the ion production rate based on the fuelling which is 1.8×10^{21} particles per second and comment on the ratio between that calculated in (i) and this value. [20%]

2 When the self-heating of a plasma by fast particles from the fusion reaction exceeds the power losses from radiation and conduction, the plasma is said to be ignited.

(a) Calculate the total energy per D-T fusion reaction. How much of the energy released per fusion heats the plasma? [20%]

(b) To achieve ignition, the temperature of the plasma must be raised by external means until the fusion reaction rate is high enough to achieve self heating. Describe the main ways in which energy is added to a plasma in current Tokomaks to reach ignition energy levels. [20%]

(c) Write down expressions for the ohmic (resistive) heating and the stored energy in a plasma. Assume the plasma has a flat temperature profile (with resistivity η proportional to $T^{-3/2}$, where T is the plasma temperature) and the geometry, magnetic field, and density are all fixed. Make use of the Tokomak H-mode confinement time scaling law given in the NE Data Book. [30%]

(d) Experiments in the past have used ohmic heating to raise the temperature of the plasma. However, ohmic heating is not enough to achieve significant fusion power.

(i) Using the relation obtained in (c), derive the relationship between plasma temperature and heating current and discuss the limits on ohmic heating to achieve fusion power. [15%]

(ii) What additional factors apply to the power balance at high temperatures? What means of additional heating are used and why? [15%]

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3 It is suggested that the molten salt cooled Advanced High Temperature Reactor (AHTR) would supply heat to industrial processes in addition to generating electricity. The reactor is connected to a simple Brayton power conversion cycle with Helium as the working fluid. The cycle operates between pressure limits of 2.5 and 7 MPa.

After exiting the turbine, Helium flows through a steam boiler leaving it at 120 $^\circ$C (see Fig. 1 below). Liquid water enters the boiler at 25 $^\circ$C and leaves it as saturated steam at 200 $^\circ$C. Both the turbine and compressor have isentropic efficiencies of 90%.

The cycle produces net power of 400 MW. Using the data provided in Fig. 1 and stating any assumptions made:

(a) Sketch the cycle diagram in T-s coordinates. [20%]

(b) Calculate the Helium temperature at the turbine and compressor outlets and the mass flow rate of Helium. [30%]

(c) Calculate the thermal efficiency of the power conversion cycle and the rate of steam production in the boiler (kg/s). [30%]

(d) For the same minimum and maximum cycle temperatures and the same pressure ratio, suggest other gas coolant candidates. Discuss what effect the choice of gas coolant might have on the power conversion system design and power output. [20%]

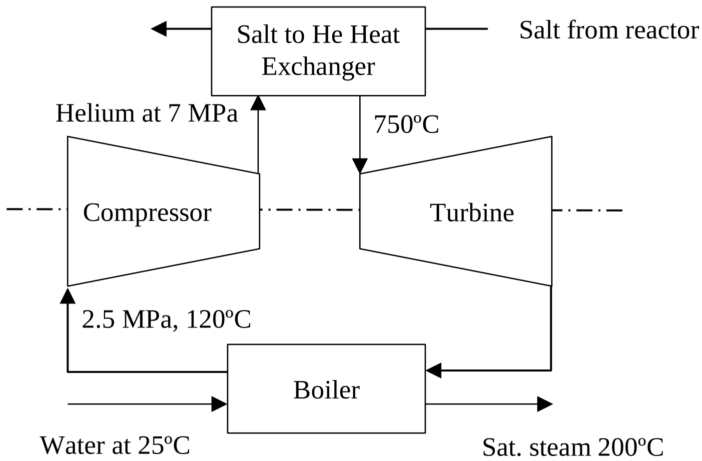

Fig. 1 Power Cycle

4 A metal-fuelled sodium-cooled fast reactor is designed to consume weapons-grade plutonium. The fuel is an alloy of ^{239}Pu and natural uranium. Reactor analysis indicates that nuclear reactions take place in the core in the following proportions:

Material	^{235}U	^{238}U	^{239}Pu
Fission	0.0062	0.0388	0.2945
Capture	0.0012	0.1040	0.0474

The remaining neutrons are lost by capture in other core materials or by diffusion out of the core.

(a) If the reactor operates at a thermal power of 2500 MW, what is the total fission rate? Assume that each fission reaction liberates 200 MeV of thermal energy. [20%]

(b) If the reactor's annual load factor is 80%, estimate the net rate of loss of ^{239}Pu per year in kg? Clearly state any assumptions made. [20%]

(c) Estimate the annual rate of production of ^{240}Pu in kg (ignoring fission and neutron capture in the ^{240}Pu formed). [15%]

(d) ^{240}Pu decays by spontaneous fission with a half-life of 6569 years, producing on average 2.21 neutrons per fission. What is the resulting neutron source strength (neutrons per second) from the ^{240}Pu produced after one year? [15%]

(e) ^{239}Pu also decays by spontaneous fission with a half-life of 24,100 years, producing on average 2.16 neutrons per fission. If the reactor is loaded with 9 tonnes of fuel (uranium + plutonium), and the enrichment Pu/(U+Pu) is 21.8%, what is the initial source strength from spontaneous fission in the ^{239}Pu? [15%]

(f) What effect is the build-up of ^{240}Pu likely to have on the behaviour of the reactor after it is shut down at the end of a year's operation? [15%]

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