Version ES/5

EGT3
ENGINEERING TRIPOS PART IIB

Friday 22 April 2016 9.30 to 11

Module 4I11

ADVANCED FISSION & FUSION REACTOR 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) Describe the rationale for the partitioning and transmutation of spent nuclear fuel. [15%]

(b) Compare qualitatively the advantages and disadvantages of pyro-chemical and aqueous solvent extraction processes for the partitioning of spent nuclear fuel. [20%]

(c) Explain why fast spectrum reactors are preferable to thermal reactors for the purpose of nuclear waste transmutation. [15%]

(d) Estimate the mass of plutonium produced in a typical PWR per GW(electric)-year of energy produced using the relevant data listed in Table 1 below and assuming that, at the time of fuel discharge, the Pu production rate has reached equilibrium. [30%]

(e) The sodium cooled fast reactor PRISM is proposed to burn 140,000 kg of the UK plutonium stockpile with the characteristics presented in Table 1 below. Estimate the time needed to put the entire legacy stockpile of Pu through the reactor. [20%]

Table 1. Design Characteristics of PWR and PRISM reactors

	PWR	PRISM
Reactor electric power output, MW	1000	600
Thermal efficiency, %	33	42
Core specific power, kW/kg	40	180
Fuel in-core residence time, years	4.5	0.5
Fissile enrichment, % (fissile material)	5.0 (^{235}U)	100.0 (Pu)
Fertile fuel component	^{238}U	None
Microscopic fission cross section of Pu, b	60	1.6
Microscopic capture cross section of ^{238}U, b	0.8	-

2 A sodium cooled fast reactor has metal fuel that consists of an alloy of uranium and plutonium, the isotopic compositions of which are:

^{235}U	0.72%	^{239}Pu	56%
^{238}U	99.28%	^{240}Pu	20%
		^{241}Pu	15%
		^{242}Pu	9%

The critical enrichment (total Pu/total (U + Pu)) is 13.45%
A neutron balance calculation indicates that the neutrons from fission are consumed in the following ratios (normalised to unity):

	capture	fission
^{235}U	0.002	0.0104
^{238}U	0.177	0.0593
^{239}Pu	0.0297	0.182
^{240}Pu	0.0114	0.0186
^{241}Pu	0.0054	0.0585
^{242}Pu	0.0051	0.008
Capture in structure, coolant and control absorbers	0.1221	
Leakage from the core	0.3105	

(a) If breeding ratio is defined as (total fissile atoms produced)/(total fissile atoms consumed), what is the internal breeding ratio in the core? [35%]

(b) What is the importance of the internal breeding ratio for operation of the reactor? [20%]

(c) Assuming the core is surrounded by a blanket in which 70% of the leaking neutrons are captured in fertile material, what is the overall breeding ratio? [20%]

(d) If the metal fuel were replaced with mixed oxide (U,Pu)O_2 the critical enrichment would be higher. Why is this the case? [25%]

3 Nuclear fusion reactors could be fuelled with multiple materials, but a D-T mixture is the preferred fuel at present. The most common reaction produces a helium nucleus and a 14 MeV neutron. A fusion pulse at JET produces approximately 1×10^{18} neutrons/s, while ITER will produce 1×10^{20} neutrons/s.

(a) Name an alternative fuel mixture and provide two advantages of that fuel. Why is D-T the preferred fuel source? [25%]

(b) The geometry of a reactor plasma-facing wall can be approximated as a 'doughnut' torus with inner and outer radii R_I and R_O. For ITER, take these as 2.8 m and 8.0 m, respectively. Estimate the plasma-facing surface neutron flux during operation, take the surface area to be: [15%]

$$2\pi^2 R_I \times (R_O - R_I)$$

(c) The ^{16}O (n,p) reaction, with a threshold of 10.2 MeV, produces highly-radioactive ^{16}N which decays through high-energy gamma emission. The activation of water coolant poses a significant engineering challenge. The 14 MeV cross section for ^{16}O(n,p)^{16}N is approximately 1 mb. Given the flux from part (b), what is the reaction rate per second in 1 litre of water (of density $\rho = 1000$ kg/ m^3) under the surface neutron flux? Why do fission reactors not have this problem? [30%]

(d) Using your result from part (c), what is the ^{16}N activity per m^3 immediately after a 20 second ITER 'pulse'? What is the equilibrium activity (equivalent to an infinite irradiation)? The decay equation solution with a constant source *S*, and decay constant λ (λ = approximately 0.01 s^{-1} for ^{16}N) is: [30%]

$$N(t) = \frac{S}{\lambda}(1 - e^{-\lambda t})$$

4 In a D-T fusion reactor, the main fusion reaction is $^{2}H + ^{3}H \rightarrow ^{4}He + ^{0}n$. Approximately 80% of the energy is emitted with the outgoing neutron and 20% with the alpha particle.

(a) Where is this energy deposited by each of the products and how would it be used in a commercial power reactor? [20%]

(b) The neutrons pose serious engineering challenges for a commercial reactor, since they will travel and interact throughout the reactor. Identify one of the most serious consequences of neutron irradiation in a fusion reactor and explain how it will affect a specific system. [15%]

(c) The neutrons will also be used for the production of tritium in specially designed breeding blankets. What are the major tritium producing reactions and how do they differ? How do blanket concept designs incorporate these differences? [20%]

(d) Explain why a tritium breeding ratio (TBR) greater than one is required. Why are neutron multipliers such as Be or Pb included in all tritium breeding module designs in order to achieve a TBR > 1? [25%]

(e) What other well-known material/reaction could be used to produce significant neutron multiplication? Identify the principal advantage of fusion which would be jeopardised by the use of such material. [20%]

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