Version GTP/4

EGT3 / EGT2
ENGINEERING TRIPOS PART IIB
ENGINEERING TRIPOS PART IIA

Friday 27 April 2018   2 to 3.40

Module 4M16

NUCLEAR POWER 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
Attachment: 4M16 data sheet (8 pages)
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

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

1 Transmutation of long-lived fission products into short-lived nuclides has been proposed as a solution to the problem of radioactive waste disposal. In one prototype transmutation system, fuel consisting of a mixture of fissionable material and fission products is irradiated with thermal neutrons produced using a particle accelerator.

One of the longest-lived fission products is caesium-135, which has a half-life of 2.315×10^6 years. $^{135}_{55}\text{Cs}$ decays by the emission of a low-energy β particle.

(a) Estimate the activity of 1 kg of $^{135}_{55}\text{Cs}$. The atomic mass of $^{135}_{55}\text{Cs}$ is 134.90598 u. [15%]

(b) By capturing a neutron in an (n,γ) reaction, $^{135}_{55}\text{Cs}$ can be transmuted into $^{136}_{55}\text{Cs}$. Calculate the energy released (in MeV) in this transmutation reaction. The atomic mass of $^{136}_{55}\text{Cs}$ is 135.90731 u. [10%]

(c) $^{136}_{55}\text{Cs}$ decays into $^{136}_{56}\text{Ba}$, which is stable. What sort of radioactive decay is this? [5%]

(d) The half-life of $^{136}_{55}\text{Cs}$ is 13.04 days. If 1 kg of $^{135}_{55}\text{Cs}$ is transmuted into $^{136}_{55}\text{Cs}$, how long will it take for the activity of the $^{136}_{55}\text{Cs}$ to fall below that of the original $^{135}_{55}\text{Cs}$? Comment on the significance of this result. For the purposes of this calculation, you can assume that the transmutation from $^{135}_{55}\text{Cs}$ to $^{136}_{55}\text{Cs}$ is instantaneous. [20%]

(e) In order to investigate the operation of the transmutation system experimentally, a physicist is using a fuel made from a mixture of $^{235}_{92}\text{U}$, $^{238}_{92}\text{U}$ and $^{135}_{55}\text{Cs}$. The $^{238}_{92}\text{U}$ atoms will have a number density of $4 \times 10^{28}\ \text{m}^{-3}$ and the $^{135}_{55}\text{Cs}$ atoms a number density of $1 \times 10^{27}\ \text{m}^{-3}$. For safety reasons it is important that the fuel is *non-multiplying*, i.e. that the average number of neutrons released per neutron absorbed in the fuel is less than 1. What is the highest number density of $^{235}_{92}\text{U}$ atoms that can be used in the fuel? Assume that the average number of neutrons released in fission reactions in $^{235}_{92}\text{U}$ is 2.43. [20%]

Data: σ_c of $^{235}_{92}\text{U}$: 107 b σ_c of $^{238}_{92}\text{U}$: 2.75 b σ_c of $^{135}_{55}\text{Cs}$: 8.3 b
σ_f of $^{235}_{92}\text{U}$: 580 b σ_f of $^{238}_{92}\text{U}$: 0 b

(f) By considering what you have learned from earlier parts of the question and ways in which $^{135}_{55}\text{Cs}$ can be produced in fission, discuss whether the proposed transmutation system seems to be a viable and appropriate means of dealing with $^{135}_{55}\text{Cs}$. [30%]

2 In a 'lumped' model of the kinetic behaviour of a source-free reactor, the equations for the neutron population n and the delayed neutron precursor population c can be written as

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \lambda c$$

$$\frac{dc}{dt} = \frac{\beta}{\Lambda} n - \lambda c$$

where all symbols have their usual meanings.

(a) Explain the physical significance of each term in these equations. (You do not have to explain the meaning of each symbol.) [15%]

(b) Show that, for this model, one version of the *in-hour equation*, relating the inverse periods p_i to the reactivity ρ, is

$$\rho = \Lambda p + \beta - \frac{\beta\lambda}{p + \lambda}$$ [40%]

(c) While in steady-state, critical, source-free operation, a Pressurized Water Reactor (PWR) is subject to a step increase in reactivity of 0.005. Find the ratio of precursors to neutrons in steady-state operation and the dominant time constant of the excursion resulting from the change in reactivity. Take $\beta = 0.0075$, $\lambda = 0.1\ \text{s}^{-1}$ and $\Lambda = 10^{-4}$ s. [20%]

(d) What would the dominant time constant be without the beneficial effect of delayed neutrons? [10%]

(e) If the same reactivity change was made in a Fast Breeder Reactor, discuss how the dominant time constant of the excursion would differ from that calculated for the PWR. [15%]

3 (a) The fuel of a nuclear reactor is subdivided into M batches of standard fuel assemblies that lose reactivity linearly with burn-up. The reactor is operated at constant power until the reactivity of the core as a whole reaches zero, whereupon one batch of fuel assemblies is replaced by a fresh batch, and so on, in cycles. Using the partial reactivity model, show that the length of the second such cycle will be $1/M$ times the first cycle length. [20%]

(b) A three-batch reloading scheme is chosen for such a reactor. The first cycle lasts 24 months. Derive a recurrence relationship governing the lengths of successive cycles, and hence find the lengths of the third, fourth and fifth cycles. What is the eventual steady-state cycle length? [30%]

(c) The availability of a reactor is defined as the fraction of time it spends at power. If the reactor is operating in steady state with an at-power cycle length of T_M and each refueling outage is of length Δ, explain why the availability will be maximized when Δ/T_M is minimized. [5%]

(d) For the reactor under consideration, Δ depends linearly on the number of fuel assemblies to be replaced as

$$\Delta = \alpha + \frac{\beta}{M}$$

If $\alpha = 1$ week, $\beta = 16$ weeks and the same fuel as that considered in (b) is used, show that a four-batch strategy (i.e. $M = 4$) maximizes availability. [25%]

(e) What is the total cycle length, including the refueling outage, for the four-batch case? From an economic and operational perspective is this cycle length optimal? If not, what changes would you recommend? [20%]

4 (a) List and distinguish (with appropriate quantitative detail) the three categories of nuclear waste as defined in the UK. [15%]

(b) Outline the methods currently used in the UK for handling and disposing of each category of nuclear waste. [30%]

(c) In civil Pressurized Water Reactors the Boron Recycle System is used to control the boron content of the coolant/moderator. The recycle stream is first passed through an ion exchange resin bed and then held up in decay tanks before being recycled to the reactor. One constituent of the recycle is ${}^{60}_{27}\mathrm{Co}$, which is a corrosion product of activated cobalt in the materials of construction.

Using the data below, calculate the specific activities of ${}^{60}_{27}\mathrm{Co}$ in the returned coolant leaving the ion exchange plant and leaving the hold-up/decay tank, and comment on the effectiveness of this method of treatment.

Recycle stream flow rate: $0.8208\ \mathrm{m^3\,hr^{-1}}$

Recycle stream density: $1000\ \mathrm{kg\,m^{-3}}$

Tank volume: $336\ \mathrm{m^3}$

Hold-up time: 312 hours

Specific activity of ${}^{60}_{27}\mathrm{Co}$ in the recycle stream: $20.7\ \mathrm{Bq\,g^{-1}}$

${}^{60}_{27}\mathrm{Co}$ decays into ${}^{60}_{28}\mathrm{Ni}$ with a half-life of 5.26 years. Take the decontamination factor for ${}^{60}_{27}\mathrm{Co}$ of the ion exchange plant to be 10. [55%]

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Answers

Q1 (a) 4.237×10^{10} Bq

(b) 6.837 MeV

(c) β^- decay

(d) 338 days

(e) $1.638 \times 10^{26}\ \mathrm{m}^{-3}$

Q2 (c) $c_0/n_0 = 750$; 5.0595 s

(d) 0.02 s

Q3 (b) $\tau_n = T_1 - \frac{2}{3}\tau_{n-1} - \frac{1}{3}\tau_{n-2}$;
$\tau_3 = 10\frac{2}{3}$ months; $\tau_4 = 14\frac{2}{9}$ months; $\tau_5 = 10\frac{26}{27}$ months; $T_3 = 12$ months

(e) 46.6 weeks

Q4 (c) $2.07\ \mathrm{Bq\,g^{-1}}$; $2.054\ \mathrm{Bq\,g^{-1}}$