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Fission, fusion and reactor control solutions

A power-system study for a polar research station

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 44 marks

Specification points covered

6.4.4(g): induced nuclear fission and chain reactions.

6.4.4(h): functions of the components of a nuclear fission reactor.

6.4.4(i): environmental effects associated with nuclear waste.

6.4.4(j): nuclear fusion, fusion reactions and temperature.

6.4.4(k): balancing nuclear transformation equations.

Supporting 6.4.4(a), (b), (d), (e): mass–energy and binding-energy reasoning; earlier power and efficiency skills.

Use $c = 2.998 \times 10^{8}$ m s^{-1}, 1 MeV = 1.602×10^{-13} J and $k = 1.38 \times 10^{-23}$ J K^{-1}. One day = 86 400 s. All power and fuel figures describe supplied models, not current commercial reactor specifications.

1 Identify the nuclear process

A polar research station compares a controlled-fission power model with a future fusion concept. Use only the stated physical and engineering information to judge the proposals.

Figure 1 shows component roles in a simplified thermal-neutron reactor model. The external heat exchanger and generator are not drawn; the coolant transfers heat to that external system.

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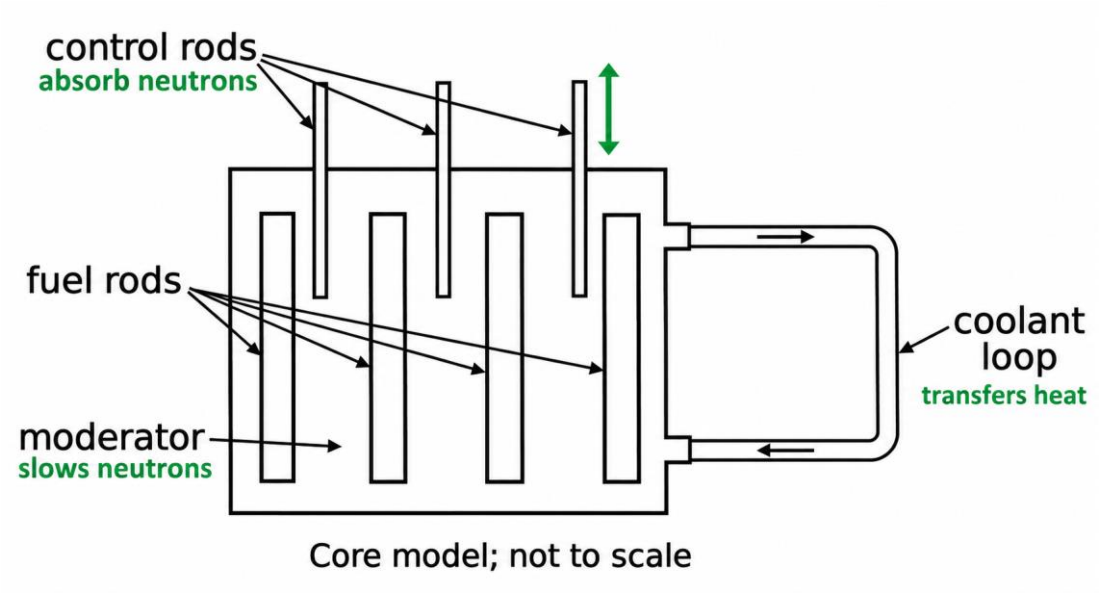


Figure 1 The moderator slows neutrons; control rods absorb neutrons.

1(a) Explain what induced fission means, distinguishing it from fusion. **[1 mark]**

Induced fission is the splitting of a heavy nucleus after an incident particle, commonly a neutron, is absorbed. Fusion combines light nuclei to form a heavier nucleus.

Marking guidance 1: triggered heavy-nucleus splitting correctly contrasted with light-nucleus combination.

1(b) In the model, uranium-235 absorbs a neutron, then forms barium-141, krypton-92 and free neutrons. Use Z(U) = 92, Z(Ba) = 56 and Z(Kr) = 36 to write the complete balanced equation. **[2 marks]**

$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\ {}^{1}_{0}\mathrm{n}.$

A: 235 + 1 = 236 and 141 + 92 + 3 = 236. Z: 92 = 56 + 36. There are three emitted neutrons in this model channel.

Marking guidance 1: correct fragments and three neutrons. 1: full balanced A/Z notation.

2 Control a chain reaction

2(a) Explain how emitted neutrons can make the fission process a chain reaction. **[2 marks]**

Some neutrons emitted in one fission are absorbed by other suitable heavy nuclei and induce further fissions. Those fissions emit more neutrons that can continue the process.

Not every emitted neutron must cause another fission; some escape or are absorbed without causing fission.

Marking guidance 1: emitted neutron induces another fission. 1: further neutrons continue the linked sequence.

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2(b) For steady reactor power, what must happen on average to the number of further fissions caused by each fission? Explain why “all three emitted neutrons must cause fission” is wrong. **[2 marks]**

On average each fission must cause one further fission for a steady chain reaction. If every one of three neutrons caused another fission, the number of fissions would increase rapidly from generation to generation.

Absorption and escape reduce the number that actually cause fission. Steady operation is not a requirement to remove every neutron.

Marking guidance 1: one further fission on average. 1: three further fissions would cause growth rather than steady power.

2(c) The measured fission rate begins to rise. State how control rods should be moved and explain the neutron process that reduces the rate. **[2 marks]**

Insert the control rods farther into the core. They absorb more neutrons, leaving fewer available to induce subsequent fissions.

Their primary control function is absorption, not merely slowing the neutrons.

Marking guidance 1: insert rods farther. 1: greater neutron absorption reduces subsequent fissions.

2(d) Explain the different roles of the moderator and coolant in this reactor model. Why is “the moderator absorbs all the neutrons” an unsuitable description? **[2 marks]**

The moderator slows fast neutrons by collisions so they are more likely to induce fission in the stated thermal-neutron fuel. It should not remove all neutrons; a chain reaction needs some to reach fuel nuclei.

The coolant transfers thermal energy from the core to the external heat-transfer system. Moderator and coolant are functional roles; a particular reactor may use a material for more than one role, but the processes are different.

Marking guidance 1: moderator slows, rather than absorbs all, neutrons for further fission. 1: coolant removes/transfers thermal energy.

3 Turn a mass difference into a reaction rate

3(a) For one complete model fission event, the total initial rest mass is 3.91810×10^{-25} kg and the total final rest mass is 3.91480×10^{-25} kg, including every product neutron. Calculate the rest-mass decrease. **[1 mark]**

$\Delta m = M_{initial} - M_{final} = (3.91810 - 3.91480) \times 10^{-25} = 3.30 \times 10^{-28}$ kg.

The difference concerns all initial and final particles, not just the two heavy fragments.

Marking guidance 1: 3.30×10^{-28} kg.

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3(b) Calculate the energy release per event in joules and MeV. Retain the unrounded joule value for later calculations. **[2 marks]**

$Q = \Delta mc^2 = (3.30 \times 10^{-28})(2.998 \times 10^{8})^2 = 2.96604132 \times 10^{-11}$ J $\approx 2.97 \times 10^{-11}$ J.

$Q = (2.96604132 \times 10^{-11})/(1.602 \times 10^{-13}) = 185.146$ MeV ≈ 185 MeV. The initial rest energy is larger, so energy is released.

Marking guidance 1: about 2.97×10^{-11} J. 1: about 185 MeV.

3(c) The station's model reactor supplies 45.0 MW of thermal power entirely from these fissions. Calculate the fission rate. **[2 marks]**

Step 1 Convert power: 45.0 MW = 4.50×10^{7} J s^{-1}.

Step 2 Divide energy per second by energy per event:

$R = P_{thermal}/Q = (4.50 \times 10^{7})/(2.96604132 \times 10^{-11}) = 1.51717 \times 10^{18}$ $s^{-1} \approx 1.52 \times 10^{18}$ fissions s^{-1}.

Marking guidance 1: correct thermal-power/energy-per-event relationship. 1: 1.52×10^{18} s^{-1}.

3(d) Calculate the number of fissions in one day and the mass of uranium-235 nuclei fissioned. Use 3.90×10^{-25} kg for the mass of one uranium-235 nucleus. **[2 marks]**

Number per day $= (1.51717 \times 10^{18})(86\,400) = 1.31083 \times 10^{23}$.

Mass fissioned $= (1.31083 \times 10^{23})(3.90 \times 10^{-25}) = 0.0511224$ kg ≈ 0.0511 kg, or 51.1 g.

This is the mass of nuclei that undergo fission, not the much smaller mass converted to released energy.

Marking guidance 1: approximately 1.31×10^{23} events. 1: approximately 0.0511 kg fissioned.

4 Keep the system boundary clear

4(a) The thermal-to-electrical efficiency is 32.0%. Calculate the electrical output and the rate at which energy must be transferred to the surroundings, for 45.0 MW thermal input. **[2 marks]**

Electrical output $= 0.320 \times 45.0 = 14.4$ MW.

Energy not delivered electrically $= 45.0 - 14.4 = 30.6$ MW. In steady operation this must be transferred to the surroundings, rather than accumulate without limit in the plant.

Marking guidance 1: 14.4 MW electrical. 1: 30.6 MW to surroundings.

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4(b) A pupil divides 45.0 MW by the fission energy and then multiplies that fission rate by 0.320, calling it the actual rate needed by the reactor. Explain the error. **[2 marks]**

The stated 45.0 MW is already thermal power produced by fissions, so $P_{thermal}/Q$ is the fission rate. Multiplying by efficiency would undercount the events needed to generate that thermal input.

Efficiency converts thermal power to electrical output. If electrical power were given instead, first divide by efficiency to reconstruct the thermal input.

Marking guidance 1: recognises 45.0 MW is thermal input. 1: correct direction/role of efficiency conversion.

4(c) A model fuel capsule contains 0.100 kg of uranium-235, but only 20.0% of those nuclei may fission before the capsule is replaced. Estimate how long it could support the 45.0 MW thermal model. Use the uranium nucleus mass above. **[3 marks]**

Step 1 The usable fissioned mass is 0.200 × 0.100 = 0.0200 kg.

Step 2 Available events = $0.0200/(3.90 \times 10^{-25}) = 5.12821 \times 10^{22}$.

Step 3 Time = available events / rate = $(5.12821 \times 10^{22})/(1.51717 \times 10^{18}) = 3.38012 \times 10^{4}$ s ≈ 9.39 h.

The calculation uses the permitted fraction, not the whole capsule, and is a simplified fuel-use estimate.

Marking guidance 1: permitted usable mass/number. 1: divides available events by fission rate. 1: about 3.38×10^4 s or 9.39 h.

4(d) Explain why energy release in fission does not mean that the two separated fragments need no careful containment after the chain reaction is stopped. **[1 mark]**

Some fission products are radioactive and continue to decay after the controlled chain reaction is stopped. They can still emit ionising radiation and release thermal energy, requiring containment and heat management.

Marking guidance 1: continuing radioactive-product decay linked to containment/heat.

5 Assess the fusion concept

5(a) The fusion concept uses deuterium and tritium to form helium-4 and one neutron. Write the balanced nuclear equation and explain the origin of its released energy in terms of binding. **[2 marks]**

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}.$$

For this reaction the final total binding energy is greater than the initial total binding energy. The products have lower combined rest energy, and the difference is released as kinetic energy/radiation. The free neutron must be included in the particle balance.

Marking guidance 1: balanced D–T equation. 1: greater product total binding/lower rest energy explains release.

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5(b) Explain why very high temperatures are needed for this fusion concept. Refer to both the electrical interaction and the range of the strong nuclear force. **[2 marks]**

Both nuclei have positive charge and repel electrically. Very high temperature gives a useful population of ions with enough kinetic energy to approach closely.

The nuclei must get sufficiently close for the short-range attractive strong nuclear interaction to act. Heating does not change electrostatic repulsion into attraction or make the strong force long-range.

Marking guidance 1: high kinetic energies needed against Coulomb repulsion. 1: close approach required for short-range strong attraction.

5(c) In a simple ion-energy model, the mean kinetic energy is 3kT/2. Calculate the temperature corresponding to mean energy 10.0 keV. This is an energy-scale estimate, not a prediction of a practical ignition temperature. **[3 marks]**

Step 1 Convert energy: 10.0 keV = 0.0100 MeV = 1.602×10^{-15} J.

Step 2 Rearrange E = 3kT/2 to T = 2E/(3k).

Step 3 $T = [2(1.602 \times 10^{-15})]/[3(1.38 \times 10^{-23})] = 7.73913 \times 10^{7}$ K ≈ 7.74×10^{7} K.

Real fusion rates depend on more than a mean ion energy; the question supplies only this simple energy model.

Marking guidance 1: energy conversion. 1: correct rearrangement. 1: about 7.74×10^{7} K.

5(d) The briefing states that fusion produces helium, but its energetic neutrons can make surrounding structural materials radioactive. Evaluate the claim “fusion would produce no radioactive material, so waste management is unnecessary”. **[2 marks]**

The helium product does not by itself justify the claim. According to the supplied briefing, neutrons can activate the structural material, creating radioactive nuclei that require management.

Fusion and fission can have different waste inventories and lifetimes, but zero radioactive material/no management does not follow. Compare the particular nuclides, activities and storage times, rather than make an absolute claim.

Marking guidance 1: supplied neutron activation contradicts the claim. 1: reasoned need to compare/manage actual radioactive inventory.

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6 Write a linked judgement, not a list of parts

6(a) A proposed waste store is near meltwater feeding a lake. Describe one possible environmental consequence of radioactive material leaking from the store. Explain why half-life alone cannot establish the activity of the leaked material, and identify the other quantity needed. **[2 marks]**

Leaked radioactive material could contaminate the lake water or enter organisms and food chains. Its ionising radiation could expose living organisms and damage cells; effective containment prevents that exposure route.

Activity is $A = \lambda N$, where $\lambda = \ln 2/t_{1/2}$. Half-life determines λ but does not state how many undecayed nuclei are present. The number N of radioactive nuclei is also needed to calculate activity.

Activity is one part of judging environmental impact; the radiation type/energy, exposure route and containment also matter. A longer half-life by itself does not prove greater activity.

Marking guidance 1: plausible environmental contamination/exposure consequence. 1: N of undecayed nuclei is also required, explained through $A = \lambda N$; no duplicate credit for naming and explaining the same requirement.

6(b) A research unit has fission rate 7.20×10^{17} s^{-1} and releases 3.00×10^{-11} J per fission. Identify the relationship needed to find its thermal power, and state what further measurement is needed to find its thermal-to-electrical efficiency. **[1 mark]**

Use $P_{thermal}$ = (fission rate) × (energy per fission). Measure useful electrical output power; efficiency is electrical output divided by thermal input.

Marking guidance 1: correct power relationship and electrical-output measurement.

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6 Write a linked judgement, not a list of parts Extended response

6(c) The research unit in 6(b) supplies 7.00 MW electrical output. Explain how its chain reaction can be kept steady, distinguish the moderator, control rods and coolant, and test a claim that the thermal-to-electrical efficiency is 30.0%. Present a linked answer with calculation and a conclusion. **[6 marks]**

One fission releases neutrons, some of which induce further fissions. Steady power requires one further fission per fission on average. In this thermal-neutron model the moderator slows neutrons by collisions, increasing the chance that they induce the intended fuel fission. It does not simply absorb them all.

The control rods absorb neutrons. If power begins to rise, inserting them farther reduces the number available for further fissions. The coolant transfers thermal energy out of the core to the external heat-transfer system; it has a different function from controlling the neutron population.

Step 1 Thermal power is the energy released per second: $P_{thermal} = (7.20 \times 10^{17})(3.00 \times 10^{-11}) = 2.16 \times 10^{7}$ W = 21.6 MW.

Step 2 Use the correct boundary: $\eta = P_{electrical}/P_{thermal} = 7.00/21.6 = 0.324074 = 32.4\%$.

The stated figures imply 32.4%, so the exact claim of 30.0% does not agree with them. A 30.0% efficiency would instead give 0.300 × 21.6 = 6.48 MW electrical output. No uncertainty is supplied to justify treating that difference as agreement.

Assessing 6(c) Best-fit marking guidance

Level 3 (5–6): a linked, correct explanation of a steady chain reaction and the distinct component roles AND a correct energy-per-event to thermal-power calculation and efficiency calculation with a justified numerical judgement The argument is clear, linked and scientifically sound.

Level 2 (3–4): a sound account of one strand with limited treatment of the other, or some relevant detail in both; links or evaluation are incomplete.

Level 1 (1–2): limited creditworthy method or analysis, presented as fragments with little connection. 0: no creditworthy response.

Use best fit, then the quality within the level. The exemplar is indicative, not a six-keyword checklist; accept other workable, justified approaches.

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