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ANSWER BOOK

Nuclear reactors and safety

Nuclear physics · Year 13

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18 questions · 55 marks

NAVY EDITION

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SECTION A · Warm-up

A1 Slows the fast neutrons released by fission to thermal speeds (1); thermal neutrons are much more likely to be absorbed by uranium-235 and cause further fission (1). [2]

A2 Absorb neutrons (1); they are raised or lowered to adjust the number of neutrons causing fission, controlling the rate of the chain reaction or shutting it down (1). [2]

A3 Transfers thermal energy from the core to a heat exchanger, where steam is raised to drive the turbines (1); it also prevents the core from overheating (1). [2]

A4 Moderator: water or graphite (1). Control rods: boron or cadmium (1). [2]

A5 It must transfer thermal energy effectively out of the core (1); it must absorb few neutrons (or: be stable and non-corrosive at the operating temperature) (1). [2]

SECTION B · Standard

B1 A neutron transfers the largest fraction of its kinetic energy when it collides with a particle of similar mass (1); light nuclei, such as hydrogen in water or carbon in graphite, have masses close to that of a neutron (1); so each collision removes a large fraction of the neutron's energy and few collisions are needed to reach thermal speeds (1). [3]

B2 The rods are adjusted so that, on average, exactly one neutron per fission causes a further fission (1); lowering the rods absorbs more neutrons and reduces the reaction rate (1); raising them absorbs fewer, increasing the rate, so the output is held steady (1). [3]

B3 Fission of the fuel releases fast neutrons and energy (1). The moderator slows the neutrons to thermal speeds so they can sustain the chain reaction (1). The control rods absorb surplus neutrons so that on average one neutron per fission causes another, keeping the rate steady (1). The coolant carries the thermal energy from the core to a heat exchanger to raise steam, preventing overheating (1). [4]

B4 The minimum mass of fuel for which the chain reaction is just self-sustaining (1); on average exactly one neutron per fission goes on to cause a further fission (1); below the critical mass too many neutrons escape and the reaction dies out (1). [3]

B5 For steady power, on average exactly one neutron per fission must go on to cause a further fission (1) [2]
So 2.5 - 1.0 = 1.5 neutrons per fission must be absorbed or otherwise lost (1)

B6 Fraction = $((9m - m)/(9m + m))^2 = (8/10)^2$ (1) [3]
Fraction = 0.64, so 36% of the kinetic energy is transferred in each head-on collision (1)
It must not absorb neutrons strongly (or: it must be chemically and thermally stable in the core) (1)

B7 The fuel contains fission fragments, which are neutron-rich and radioactive (1); radioactive decay is spontaneous, so it continues at a rate set by the fragments' half-lives and cannot be stopped by the control rods (1); the radiation emitted is absorbed in the fuel and its surroundings, so decay energy continues to heat the rods long after shutdown (1). [3]

SECTION C · Stretch

C1 In an elastic collision a neutron transfers the greatest share of its kinetic energy to a target of equal mass (1); it transfers very little to a much heavier nucleus, which recoils slowly (1). Hydrogen (in water) and carbon (in graphite) nuclei are comparable in mass to a neutron, so they slow neutrons in few collisions (1); with a heavy moderator, far more collisions would be needed to thermalise the neutrons (1). [4]

C2 The core is surrounded by thick steel and concrete shielding to absorb neutrons and gamma radiation (1); a sealed containment building encloses the reactor, and in an emergency all control rods drop in to shut the reaction down (1). High-level (spent fuel) waste is intensely radioactive and hot, so it is stored under water for years to cool and to provide shielding (1); it may then be encased in glass (vitrified) and stored securely in a deep, geologically stable repository (1). [4]

C3 Spent fuel contains highly radioactive fission products emitting intense, harmful radiation and generating heat (1); it is handled remotely behind shielding to protect workers from the radiation (1); many of the isotopes have long half-lives, so the activity takes many years to fall to a safe level (1). [3]

C4 Fraction = $((2m - m)/(2m + m))^2 = (m/3m)^2 = 1/9$ (1) [4]
After n collisions $E = 1.0\ \text{MeV} \times (1/9)^n$, and $1.0\ \text{eV}/1.0\ \text{MeV} = 10^{-6}$, so $(1/9)^n < 10^{-6}$ is required (1)
$n > \log(10^6)/\log 9 = 6.3$ (1)
So 7 collisions are needed (1)

C5 Reactor fuel contains only a few per cent uranium-235, far too dilute to support the runaway growth in fission rate that a weapon requires (1); the control rods and reactor design hold the chain reaction at one neutron per fission, and in an emergency the rods drop fully in and stop it (1); a mismanaged reactor can overheat, which is a serious accident, but a nuclear explosion is not possible, so the claim is unjustified (1). [3]

C6 Benefits: fission releases about a million times more energy per kilogram than burning coal, so a nuclear station needs very little fuel and delivers large amounts of reliable power (1); a reactor emits no carbon dioxide in operation, so unlike coal it does not add to the greenhouse effect while running (1); in normal operation the shielding and containment keep the dose to the public very low (1). Risks: accidents are rare, but a loss of cooling can release radioactive material with severe and long-lasting consequences (1); spent fuel contains long-lived isotopes and must be shielded, cooled and then stored securely for thousands of years (1). Conclusion: a reasoned judgement weighing a named benefit against a named risk, for example that the reliable low-carbon supply justifies building the stations provided the waste storage and safety systems are properly funded (1). [6]