Physics Units 1 & 2

Chapter 4 — Nuclear energy

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Chapter 4 Nuclear energy — 4A Mass–energy conversion and the binding energy curve

Theory

Chapter 3 described what holds a nucleus together — the short-range strong nuclear force working against the long-range electrostatic repulsion between protons — and noted that nuclear decay releases energy, leaving open where that energy comes from. This section gives the answer: a small amount of mass is converted into energy. The same idea, applied through a graph called the **binding energy curve**, explains why two very different nuclear processes, fission and fusion, both release energy — and why those releases are so much larger than anything from a chemical reaction.

Mass and energy are equivalent. In 1905 Albert Einstein showed that mass and energy are not separate things: mass *is* a form of energy. An object of mass m has an amount of energy locked up in its mass given by

$$E = mc^2,$$

where $c = 3.00 \times 10^8\ \mathrm{m\ s^{-1}}$ is the speed of light in a vacuum. Because $c^2 = 9.00 \times 10^{16}\ \mathrm{m^2\,s^{-2}}$ is such a large number, even a tiny mass corresponds to an enormous amount of energy: the complete conversion of $1.0\ \mathrm{mg}$ of mass would release $9.0 \times 10^{10}\ \mathrm{J}$ — enough to keep a $100\ \mathrm{W}$ lamp burning for about 28 years.

The important consequence for nuclear energy is this: whenever a system releases energy, its mass decreases, and whenever it absorbs energy, its mass increases. The change in mass and the energy transferred are related by

$$\Delta E = \Delta m c^2.$$

The total amount of mass–energy is always conserved. Energy is not created from nothing in a nuclear reaction: the energy released comes from a measurable decrease in the mass of the nuclei involved. In everyday chemical reactions the mass change also happens, but it is so small that it can be ignored; in nuclear reactions it is large enough to measure and large enough to matter.

The mass defect. Measure the mass of a stable nucleus and compare it with the total mass of the protons and neutrons it contains, and the nucleus always comes out lighter. A helium-4 nucleus, for example, contains two protons and two neutrons, but its mass is about $5.0 \times 10^{-29}\ \mathrm{kg}$ less than the mass of those four nucleons standing apart. This missing mass is called the **mass defect**, Δm.

Nothing has been lost. When free nucleons come together to form a nucleus, the strong nuclear force pulls them into a bound state and energy is carried away. The bound nucleus has less energy than the separate nucleons did, and because energy has mass, it also has less mass. To split the nucleus back into separate nucleons, exactly that amount of energy has to be put back in.

Binding energy. The energy equivalent of the mass defect, $\Delta m c^2$, is called the **binding energy** of the nucleus. It has two interpretations, and this section uses both:

- the minimum energy needed to completely separate the nucleus into its individual protons and neutrons;
- the energy released when the nucleus is assembled from free nucleons.

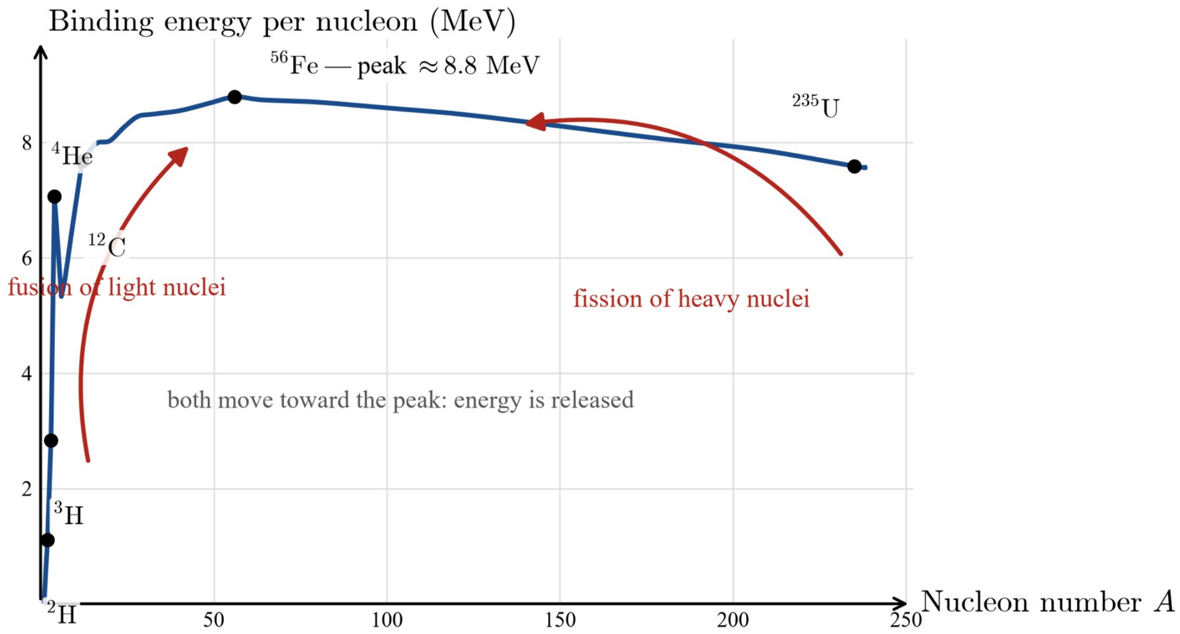
A nucleus with a larger binding energy is harder to break apart. Nuclear energies are of the order of $10^{-12}\ \mathrm{J}$, so nuclear physics uses a more convenient unit, the **megaelectronvolt**: $1\ \mathrm{MeV} = 1.60 \times 10^{-13}\ \mathrm{J}$.

Binding energy per nucleon. Heavier nuclei contain more nucleons, so their total binding energy is naturally larger. To compare how tightly different nuclei hold their nucleons, divide by the nucleon number A:

$$\text{binding energy per nucleon} = \frac{\text{binding energy}}{A}.$$

A nucleus with a larger binding energy per nucleon holds each of its nucleons more tightly and is the more stable nucleus.

The binding energy curve. The graph of binding energy per nucleon against nucleon number A is called the **binding energy curve**. It is one of the most useful graphs in nuclear physics.



The curve has three features worth remembering.

- It rises steeply for the light nuclei. The rise is not smooth: the light nuclei zig-zag, and helium-4, at 7.1 MeV per nucleon, stands well above its neighbours, which is why helium-4 is unusually tightly bound for such a light nucleus.
- It peaks near iron-56, at about 8.8 MeV per nucleon. Nuclei near the peak are the most tightly bound nuclei there are.
- It falls away slowly for the heavy nuclei: uranium-235 sits at about 7.6 MeV per nucleon.

Measured binding energies for selected nuclei are listed below; the worked examples and questions that follow use these values.

Nuclide	Binding energy	Binding energy per nucleon
$^{2}_{1}$H (deuterium)	2.2 MeV	1.1 MeV
$^{3}_{1}$H (tritium)	8.5 MeV	2.8 MeV
$^{4}_{2}$He	28.3 MeV	7.1 MeV
$^{12}_{6}$C	92 MeV	7.7 MeV
$^{56}_{26}$Fe	492 MeV	8.8 MeV
typical fission fragment	—	≈ 8.5 MeV
$^{235}_{92}$U	1790 MeV	7.6 MeV

Why fission releases energy. Nuclear fission is the splitting of a heavy nucleus into two medium-mass nuclei, called **fragments**, plus a small number of free neutrons. The binding energy curve explains why the process releases energy. A uranium-235 nucleus sits on the slow downward tail of the curve at about 7.6 MeV per nucleon. When it splits, the fragments land near the middle of the curve, where nuclei have about 8.5 MeV per nucleon. The nucleons have moved closer to the peak: the fragments are more tightly bound than the uranium nucleus they came from.

More tightly bound means less mass per nucleon. The total mass of the fragments and neutrons is therefore smaller than the mass of the original uranium nucleus, and by $\Delta E = \Delta m c^2$ that missing mass appears as released energy. Reading the gain from the curve — about 0.9 MeV per nucleon, times 235 nucleons — gives roughly 210 MeV per fission; the accepted value is about 200 MeV (3.2×10^{-11} J), because a few neutrons leave the reaction unbound. How one fission can trigger further fissions is examined in Section 4B.

Why fusion releases energy. Nuclear fusion is the joining of two light nuclei to form a heavier nucleus. The binding energy curve explains why fusion releases energy too. Light nuclei sit low on the steep rising part of the curve: deuterium, ${}^{2}_{1}H$, has only $1.1\,\text{MeV}$ per nucleon. When light nuclei fuse, the product lands much closer to the peak — helium-4, for example, has $7.1\,\text{MeV}$ per nucleon. The nucleons end up far more tightly bound, so the product nucleus has less mass than the nuclei that fused to make it, and the mass difference is released as energy.

Fusion is the process that powers the Sun and the other stars. The Sun radiates energy into space at a rate of $3.8 \times 10^{26}\,\text{W}$; Worked Example 3 uses this figure to find how much mass the Sun must be converting every second. Source: NASA, Sun Fact Sheet, retrieved 2026-08-18. There is one difficulty: nuclei are positively charged, so they repel one another. Fusion happens only when the nuclei are moving fast enough to get close enough for the short-range strong nuclear force to grab them — which is why fusion needs temperatures of millions of degrees.

Fission and fusion look very different — one splits heavy nuclei, the other joins light ones — but the binding energy curve shows that they release energy for the same reason: in both, the products are more tightly bound than the starting nuclei, so mass is converted into energy. Section 4B examines how fission is sustained as a chain reaction, and Section 4C compares the two processes.

Units 3 & 4 preview. This section teaches mass–energy conversion and the binding energy curve from the ground up. At Units 3 & 4 they are assumed knowledge: Unit 4 applies $E_0 = mc^2$ to nuclear transformations and uses the mass defect and the binding energy curve without re-teaching them. Nothing in this preview is assessed in this chapter's topic test.

Worked examples

Example 1 — scaffolded

Using the data below, find the mass defect, the binding energy (in joules and in MeV) and the binding energy per nucleon of the helium-4 nucleus, ${}^{4}_{2}He$.

$m_p = 1.6726 \times 10^{-27}\,\text{kg}$; $m_n = 1.6749 \times 10^{-27}\,\text{kg}$; mass of ${}^{4}_{2}He$ nucleus $= 6.6447 \times 10^{-27}\,\text{kg}$; $c = 3.00 \times 10^{8}\,\text{m s}^{-1}$; $1\,\text{MeV} = 1.60 \times 10^{-13}\,\text{J}$.

Working	Comment
${}^{4}_{2}He$ has $Z = 2$ protons and $N = 4 - 2 = 2$ neutrons.	Read Z and A from the nuclide notation.
Mass of separate nucleons: $2 \times 1.6726 \times 10^{-27} + 2 \times 1.6749 \times 10^{-27} = 6.6950 \times 10^{-27}$.	Add the masses of the two free protons and two free neutrons.
$\Delta m = 6.6950 \times 10^{-27} - 6.6447 \times 10^{-27} = 5.03 \times 10^{-29}\,\text{kg}$.	The bound nucleus is lighter than its separate nucleons: this is the mass defect.
$E = \Delta m c^2 = 5.03 \times 10^{-29} \times (3.00 \times 10^{8})^2 = 4.53 \times 10^{-12}\,\text{J}$.	Convert the missing mass into energy.
$\dfrac{4.53 \times 10^{-12}}{1.60 \times 10^{-13}} = 28.3\,\text{MeV}$.	Convert joules to MeV: this is the binding energy.
$\dfrac{28.3}{4} = 7.1\,\text{MeV per nucleon}$ (2 s.f.)	Divide the binding energy by $A = 4$ nucleons.

Example 2 — scaffolded

Use the binding energy curve (in the theory above) to estimate the energy released when one ${}^{235}_{92}U$ nucleus undergoes fission into two medium-mass fragments.

Working	Comment
At $A = 235$ the curve gives about $7.6\,\text{MeV}$ per nucleon.	Read the binding energy per nucleon of ${}^{235}_{92}U$ from the curve.

Working	Comment
The fragments ($A \approx 90–140$) sit nearer the peak, at about $8.5\,\text{MeV}$ per nucleon.	Fission products land near the middle of the curve.
Gain per nucleon: $8.5-7.6=0.9\,\text{MeV}$.	Each nucleon ends up this much more tightly bound.
Total: $0.9\times 235\approx 210\,\text{MeV}$.	Multiply by the number of nucleons.
Accepted value: about $200\,\text{MeV}=3.2\times 10^{-11}\,\text{J}$.	A few neutrons leave the reaction unbound, so the measured release is a little below the curve estimate.

Example 3 — unscaffolded

The Sun radiates energy into space at a rate of $3.8\times 10^{26}\,\text{W}$ (Source: NASA, Sun Fact Sheet, retrieved 2026-08-18). Assuming that all of this energy comes from the conversion of mass, calculate the mass the Sun converts into energy every second.

A power of $3.8\times 10^{26}\,\text{W}$ means the Sun releases $3.8\times 10^{26}\,\text{J}$ of energy every second. Using $\Delta E=\Delta m c^2$ with $c=3.00\times 10^{8}\,\text{m s}^{-1}$:

$$\Delta m=\frac{\Delta E}{c^2}=\frac{3.8\times 10^{26}}{(3.00\times 10^{8})^2}=\frac{3.8\times 10^{26}}{9.00\times 10^{16}}=4.2\times 10^{9}\,\text{kg}.$$

∴ The Sun converts about $4.2\times 10^{9}\,\text{kg}$ — 4.2 million tonnes — of mass into energy every second. That sounds enormous, but it is only a tiny fraction of the Sun's total mass of $2.0\times 10^{30}\,\text{kg}$, as Question 5 explores.

Example 4 — unscaffolded

One possible fusion reaction joins two deuterium nuclei, ${}^{2}_{1}\text{H}$, to form a single helium-4 nucleus, ${}^{4}_{2}\text{He}$. Using the data below, calculate the energy released by this reaction in MeV.

$m({}^{2}_{1}\text{H})=3.3436\times 10^{-27}\,\text{kg}$; $m({}^{4}_{2}\text{He})=6.6447\times 10^{-27}\,\text{kg}$; $c=3.00\times 10^{8}\,\text{m s}^{-1}$; $1\,\text{MeV}=1.60\times 10^{-13}\,\text{J}$.

The total mass before the reaction is the mass of two deuterium nuclei, $2\times 3.3436\times 10^{-27}=6.6872\times 10^{-27}\,\text{kg}$. The mass after the reaction is $6.6447\times 10^{-27}\,\text{kg}$, so the mass defect is

$$\Delta m=6.6872\times 10^{-27}-6.6447\times 10^{-27}=4.25\times 10^{-29}\,\text{kg}.$$

The energy released is

$$E=\Delta m c^2=4.25\times 10^{-29}\times (3.00\times 10^{8})^2=3.83\times 10^{-12}\,\text{J},$$

which in MeV is

$$\frac{3.83\times 10^{-12}}{1.60\times 10^{-13}}=23.9\,\text{MeV}.$$

∴ The reaction releases about $24\,\text{MeV}$. As a check, read the curve: the gain from deuterium ($1.1\,\text{MeV}$ per nucleon) to helium-4 ($7.1\,\text{MeV}$ per nucleon) is about $6.0\,\text{MeV}$ per nucleon, and with four nucleons involved that gives $6.0\times 4=24\,\text{MeV}$. The mass calculation and the curve agree.

Practice questions

Question 1 If $1.0\,\text{mg}$ of mass were completely converted into energy: (a) Convert $1.0\,\text{mg}$ to kilograms. (b) Calculate the energy released. (c) Convert your answer to kilowatt-hours ($1\,\text{kW h}=3.6\times 10^{6}\,\text{J}$).

Question 2 A carbon-12 nucleus, ${}^{12}_{6}\text{C}$, contains 6 protons and 6 neutrons. Use the data below to find: (a) the total mass of the 6 separate protons and 6 separate neutrons; (b) the mass defect of the carbon-12 nucleus; (c) the binding energy of carbon-12, in joules and in MeV; (d) the binding energy per nucleon.

$m_p = 1.6726 \times 10^{-27}$ kg; $m_n = 1.6749 \times 10^{-27}$ kg; mass of ${}^{12}_{6}C$ nucleus $= 1.9921 \times 10^{-26}$ kg; $c = 3.00 \times 10^{8}$ m s^{-1}; 1 MeV $= 1.60 \times 10^{-13}$ J.

Question 3 Use the binding energy curve in the theory section. (a) Read the binding energy per nucleon of ${}^{4}_{2}He$, ${}^{56}_{26}Fe$ and ${}^{235}_{92}U$. (b) Which of these three nuclei is the most tightly bound? How does the curve show this?

Question 4 Burning one carbon atom in oxygen releases about 6.6×10^{-19} J. One fission of a ${}^{235}_{92}U$ nucleus releases about 3.2×10^{-11} J. (a) Calculate how many carbon atoms must burn to release 1.0 MJ of energy. (b) Calculate how many uranium-235 fissions release 1.0 MJ of energy. (c) Compare your two answers and comment on what the comparison says about nuclear and chemical energy.

Question 5 Worked Example 3 found that the Sun converts 4.2×10^{9} kg of mass into energy every second. The Sun's total mass is 2.0×10^{30} kg (Source: NASA, Sun Fact Sheet, retrieved 2026-08-18), and 1 year $\approx 3.2 \times 10^{7}$ s. (a) Calculate the mass the Sun converts into energy in one year. (b) Calculate this as a fraction of the Sun's total mass. (c) The Sun has been shining for about 5×10^{9} years. Estimate the total fraction of its mass the Sun has converted into energy so far, and comment on your answer.

Question 6 Use the binding energy curve in the theory section. (a) Read the binding energy per nucleon of ${}^{2}_{1}H$ and ${}^{4}_{2}He$. (b) Calculate the gain in binding energy per nucleon if nucleons go from being bound as in deuterium to being bound as in helium-4. (c) When two deuterium nuclei fuse to form helium-4, four nucleons are involved. Use your answer to (b) to estimate the energy released. (d) Compare your estimate with the answer to Worked Example 4.

Question 7 A uranium-235 nucleus, ${}^{235}_{92}U$, contains 92 protons and 143 neutrons. Using the data below, calculate its binding energy per nucleon in MeV, and check your answer against the binding energy curve.

$m_p = 1.6726 \times 10^{-27}$ kg; $m_n = 1.6749 \times 10^{-27}$ kg; mass of ${}^{235}_{92}U$ nucleus $= 3.9021 \times 10^{-25}$ kg; $c = 3.00 \times 10^{8}$ m s^{-1}; 1 MeV $= 1.60 \times 10^{-13}$ J.

Question 8 A ${}^{12}_{6}C$ nucleus has less mass than six free protons and six free neutrons. Explain why the masses are different, and state what the missing mass represents.

Question 9 Suppose 1.0 g of mass were completely converted into energy. Use 1 year $\approx 3.2 \times 10^{7}$ s and 1 kW h $= 3.6 \times 10^{6}$ J. (a) Calculate the energy released, in joules. (b) Convert your answer to kilowatt-hours. (c) For how many years could this energy run a 100 W lamp?

Question 10 Use the binding energy curve to explain why the fission of ${}^{235}_{92}U$ releases energy.

Question 11 Fusion only happens when nuclei are travelling extremely fast, which means temperatures of millions of degrees. Use the forces between nuclei to explain why fusion needs such high temperatures.

Question 12 A nuclear power station produces thermal energy at a rate of 3.0 GW (3.0×10^{9} W). Assuming all of this energy comes from the conversion of mass: (a) calculate the mass converted into energy every second; (b) calculate the mass converted into energy in one year (1 year $\approx 3.2 \times 10^{7}$ s).

Question 13 The binding energy curve peaks near ${}^{56}_{26}Fe$ and falls away on both sides. Use the curve to explain why *both* the fusion of light nuclei *and* the fission of heavy nuclei release energy.

Question 14 One fission of a ${}^{235}_{92}U$ nucleus releases about 3.2×10^{-11} J, and the mass of one ${}^{235}_{92}U$ nucleus is about 3.9×10^{-25} kg. (a) Calculate the number of ${}^{235}_{92}U$ nuclei in 1.0 kg of uranium-235. (b) Calculate the total energy released if every one of these nuclei undergoes fission. (c) Convert your answer to kilowatt-hours (1 kW h $= 3.6 \times 10^{6}$ J).

Question 15 Burning petrol in a car engine converts a tiny amount of mass into energy, just as fission does in a reactor. Suggest why the mass change is ignored in chemical reactions but matters in nuclear reactions.

Question 16 A student writes: *"In a nuclear reaction, some of the mass is destroyed and replaced by energy, so the total amount of stuff decreases."* Correct the student's statement using the idea of mass–energy conservation.

Question 17 Deuterium, ${}^{2}_{1}H$, contains one proton and one neutron. Using the data below, calculate the binding energy of deuterium in MeV and its binding energy per nucleon.

$m_p = 1.6726 \times 10^{-27}$ kg; $m_n = 1.6749 \times 10^{-27}$ kg; mass of ${}^{2}_{1}H$ nucleus $= 3.3436 \times 10^{-27}$ kg; $c = 3.00 \times 10^{8}$ m s^{-1}; $1\,\text{MeV} = 1.60 \times 10^{-13}$ J.

Question 18 Fusion research uses light nuclei, such as isotopes of hydrogen, as fuel. Use the binding energy curve to justify this choice, and explain why a heavy nucleus such as uranium could not be used as fusion fuel.

Question 19 In one fusion reaction, 5.0×10^{-29} kg of mass is converted into energy. (a) Calculate the energy released, in joules. (b) Convert your answer to MeV ($1\,\text{MeV} = 1.60 \times 10^{-13}$ J). (c) Calculate how many such reactions are needed to release $1.0\,\text{kW h}$ of energy ($1\,\text{kW h} = 3.6 \times 10^{6}$ J).

Answers

Question 1 (a) $1.0\times10^{-6}\,\mathrm{kg}$; (b) $9.0\times10^{10}\,\mathrm{J}$; (c) $2.5\times10^{4}\,\mathrm{kW\,h}$. **Question 2** (a) $2.0085\times10^{-26}\,\mathrm{kg}$; (b) $1.64\times10^{-28}\,\mathrm{kg}$; (c) $1.48\times10^{-11}\,\mathrm{J}=92\,\mathrm{MeV}$; (d) $7.7\,\mathrm{MeV}$ per nucleon. **Question 3** (a) $^{4}_{2}$He: $\approx7.1\,\mathrm{MeV}$; $^{56}_{26}$Fe: $\approx8.8\,\mathrm{MeV}$; $^{235}_{92}$U: $\approx7.6\,\mathrm{MeV}$ per nucleon; (b) $^{56}_{26}$Fe — see solution. **Question 4** (a) 1.5×10^{24} atoms; (b) 3.1×10^{16} fissions; (c) see solution — about 50 million times fewer events. **Question 5** (a) $1.3\times10^{17}\,\mathrm{kg}$; (b) 6.7×10^{-14}; (c) $\approx3\times10^{-4}$ — see solution. **Question 6** (a) $\approx1.1\,\mathrm{MeV}$ and $\approx7.1\,\mathrm{MeV}$ per nucleon; (b) $\approx6.0\,\mathrm{MeV}$; (c) $\approx24\,\mathrm{MeV}$; (d) agrees — see solution. **Question 7** $\approx7.6\,\mathrm{MeV}$ per nucleon; matches the curve value. **Question 8** See solution — energy carried away when the nucleus formed; the missing mass $\times\,c^2$ is the binding energy. **Question 9** (a) $9.0\times10^{13}\,\mathrm{J}$; (b) $2.5\times10^{7}\,\mathrm{kW\,h}$; (c) 2.8×10^{4} years. **Question 10** See solution — fragments are more tightly bound than uranium; mass decreases and is released as energy. **Question 11** See solution — nuclei must reach close enough for the short-range strong force despite electrostatic repulsion. **Question 12** (a) $3.3\times10^{-8}\,\mathrm{kg\,s^{-1}}$; (b) $\approx1.1\,\mathrm{kg}$. **Question 13** See solution — both processes move nucleons toward the peak of the curve. **Question 14** (a) 2.6×10^{24} nuclei; (b) $8.2\times10^{13}\,\mathrm{J}$; (c) $2.3\times10^{7}\,\mathrm{kW\,h}$. **Question 15** See solution — chemical mass changes are roughly 50 million times smaller per event and far too small to measure. **Question 16** See solution — mass is a form of energy; total mass–energy is conserved. **Question 17** $2.2\,\mathrm{MeV}$; $1.1\,\mathrm{MeV}$ per nucleon. **Question 18** See solution — light nuclei gain binding energy per nucleon when they fuse; fusing uranium would lose it. **Question 19** (a) $4.5\times10^{-12}\,\mathrm{J}$; (b) $28\,\mathrm{MeV}$; (c) 8.0×10^{17} reactions.

Fully-worked solutions

Question 1 (a) $1\,\mathrm{mg}=10^{-3}\,\mathrm{g}=10^{-6}\,\mathrm{kg}$, so $1.0\,\mathrm{mg}=1.0\times10^{-6}\,\mathrm{kg}$. (b) $E=mc^2=1.0\times10^{-6}\times(3.00\times10^{8})^2=1.0\times10^{-6}\times9.00\times10^{16}=9.0\times10^{10}\,\mathrm{J}$ (2 s.f.). (c) $\dfrac{9.0\times10^{10}}{3.6\times10^{6}}=2.5\times10^{4}\,\mathrm{kW\,h}$. One milligram — a speck of dust — contains this much energy. The reason we never notice it is that ordinary processes convert only a tiny fraction of a system's mass.

Question 2 (a) Six protons and six neutrons: $6\times1.6726\times10^{-27}+6\times1.6749\times10^{-27}=6\times(1.6726+1.6749)\times10^{-27}=20.085\times10^{-27}=2.0085\times10^{-26}\,\mathrm{kg}$. (b) $\Delta m=2.0085\times10^{-26}-1.9921\times10^{-26}=0.0164\times10^{-26}=1.64\times10^{-28}\,\mathrm{kg}$. (c) $E=\Delta m c^2=1.64\times10^{-28}\times(3.00\times10^{8})^2=1.64\times10^{-28}\times9.00\times10^{16}=1.48\times10^{-11}\,\mathrm{J}$. In MeV: $\dfrac{1.48\times10^{-11}}{1.60\times10^{-13}}=92\,\mathrm{MeV}$ (2 s.f.). (d) $\dfrac{92}{12}=7.7\,\mathrm{MeV\ per\ nucleon}$, matching the theory table.

Question 3 (a) Reading the curve: $^{4}_{2}$He $\approx7.1\,\mathrm{MeV}$ per nucleon; $^{56}_{26}$Fe $\approx8.8\,\mathrm{MeV}$ per nucleon; $^{235}_{92}$U $\approx7.6\,\mathrm{MeV}$ per nucleon. (Readings to about $\pm0.2\,\mathrm{MeV}$ are acceptable.) (b) $^{56}_{26}$Fe is the most tightly bound of the three. It sits at the peak of the curve, meaning it has the largest binding energy per nucleon: more energy is needed to remove each nucleon than for any nucleus below it.

Question 4 (a) $\dfrac{1.0\times10^{6}}{6.6\times10^{-19}}=1.5\times10^{24}$ carbon atoms (2 s.f.). (b) $\dfrac{1.0\times10^{6}}{3.2\times10^{-11}}=3.1\times10^{16}$ fissions (2 s.f.). (c) The same energy needs about $\dfrac{1.5\times10^{24}}{3.1\times10^{16}}\approx5\times10^{7}$ — about 50 million — times as many chemical events as nuclear events. Each nuclear event releases tens of millions of times more energy than each chemical event, because nuclear forces and nuclear mass changes are so much larger than the rearrangements of electrons behind chemical reactions.

Question 5 (a) $4.2\times10^{9}\times3.2\times10^{7}=1.3\times10^{17}\,\mathrm{kg}$ (2 s.f.). (b) $\dfrac{1.3\times10^{17}}{2.0\times10^{30}}=6.7\times10^{-14}$ of the Sun's mass per year. (c) Over 5×10^{9} years: $6.7\times10^{-14}\times5\times10^{9}=3.4\times10^{-4}$, or about $0.03\,\%$ of the Sun's mass. Even after billions of years of shining, the Sun has converted only a tiny fraction of its mass into energy, which is why it is nowhere near running out.

Question 6 (a) ${}^{2}_{1}$H: $\approx 1.1\,\text{MeV}$ per nucleon; ${}^{4}_{2}$He: $\approx 7.1\,\text{MeV}$ per nucleon. (b) Gain: $7.1-1.1=6.0\,\text{MeV}$ per nucleon. (c) Four nucleons are involved, so the release is about $6.0\times 4=24\,\text{MeV}$. (d) Worked Example 4 got $24\,\text{MeV}$ (23.9 MeV) from the masses directly. The two methods agree: the curve is just a graph of the same mass-defect information.

Question 7 Separate nucleons: 92 protons and 143 neutrons give $92\times 1.6726\times 10^{-27}+143\times 1.6749\times 10^{-27}=(153.9+239.5)\times 10^{-27}=3.9339\times 10^{-25}\,\text{kg}$. Mass defect: $\Delta m=3.9339\times 10^{-25}-3.9021\times 10^{-25}=0.0318\times 10^{-25}=3.18\times 10^{-27}\,\text{kg}$. Binding energy: $E=3.18\times 10^{-27}\times (3.00\times 10^{8})^{2}=3.18\times 10^{-27}\times 9.00\times 10^{16}=2.86\times 10^{-10}\,\text{J}$, which is $\dfrac{2.86\times 10^{-10}}{1.60\times 10^{-13}}=1790\,\text{MeV}$. Per nucleon: $\dfrac{1790}{235}=7.6\,\text{MeV per nucleon}$. This matches the curve, which shows ${}^{235}_{92}$U at about $7.6\,\text{MeV}$ per nucleon.

Question 8 Model answer: when the free nucleons join to form the nucleus, the strong nuclear force pulls them into a bound state and energy is carried away, so the bound nucleus has less energy than the separate nucleons. By $E=mc^2$, less energy means less mass: that is why the nucleus is lighter. The missing mass Δm is the mass defect, and Δmc^2 is the binding energy — the energy that would have to be supplied to separate the nucleus back into free nucleons. Mass has not been lost or destroyed; it left with the energy that was released.

Question 9 (a) $1.0\,\text{g}=1.0\times 10^{-3}\,\text{kg}$, so $E=mc^2=1.0\times 10^{-3}\times 9.00\times 10^{16}=9.0\times 10^{13}$ J (2 s.f.). (b) $\dfrac{9.0\times 10^{13}}{3.6\times 10^{6}}=2.5\times 10^{7}\,\text{kW h}$. (c) At $100\,\text{W}$ the energy lasts $\dfrac{9.0\times 10^{13}}{100}=9.0\times 10^{11}\,\text{s}$, which is $\dfrac{9.0\times 10^{11}}{3.2\times 10^{7}}=2.8\times 10^{4}$ years (2 s.f.) — about $28\,000$ years from a single gram of mass.

Question 10 Model answer: on the binding energy curve, ${}^{235}_{92}$U sits on the heavy-nucleus tail at about $7.6\,\text{MeV}$ per nucleon. In fission it splits into two medium-mass fragments, which sit nearer the peak of the curve at about $8.5\,\text{MeV}$ per nucleon. The fragments are more tightly bound than the uranium nucleus, so the products have less total mass than the original nucleus. By $\Delta E=\Delta mc^2$, that missing mass is released as energy — about $200\,\text{MeV}$ per fission.

Question 11 Model answer: every nucleus is positively charged, so two approaching nuclei repel each other through the long-range electrostatic force. The force that could bind them — the strong nuclear force — only acts once the nucleons are within about 1–3 fm of one another. The nuclei therefore have to approach close enough against the electrostatic repulsion for the strong force to take over, and that takes a large amount of kinetic energy. Temperature is a measure of the average kinetic energy of particles, so getting nuclei to fuse requires temperatures of millions of degrees.

Question 12 (a) A rate of $3.0\times 10^{9}\,\text{W}$ means 3.0×10^{9} J every second. $\Delta m=\dfrac{\Delta E}{c^2}=\dfrac{3.0\times 10^{9}}{9.00\times 10^{16}}=3.3\times 10^{-8}\,\text{kg}$ every second (2 s.f.). (b) In one year: $3.3\times 10^{-8}\times 3.2\times 10^{7}=1.1\,\text{kg}$ (2 s.f.). Note that this is the mass actually *converted* into energy. The mass of uranium fuel used up is larger, because each fission converts only about one part in a thousand of the nucleus's mass into energy.

Question 13 Model answer: energy is released when the products of a reaction are more tightly bound than the starting nuclei, because more tightly bound means less mass per nucleon, and the lost mass is released as energy by $\Delta E=\Delta mc^2$. On the binding energy curve, "more tightly bound" means closer to the peak near ${}^{56}_{26}$Fe. Light nuclei sit on the steep rising side of the peak, so when they fuse the product moves up the curve toward the peak and energy is released. Heavy nuclei sit on the slowly falling side, so when one splits, the fragments move back toward the peak and energy is released. Both processes release energy for the same reason — the nucleons end up closer to the peak — which is also why nuclei already near iron release energy neither by fusing nor by splitting: they are already at the most tightly bound point.

Question 14 (a) $\frac{1.0}{3.9\times10^{-25}}=2.6\times10^{24}$ nuclei (2 s.f.). (b) $2.6\times10^{24}\times3.2\times10^{-11}=8.2\times10^{13}$ J (2 s.f.). (c) $\frac{8.2\times10^{13}}{3.6\times10^{6}}=2.3\times10^{7}\,\mathrm{kW\,h}$ (2 s.f.). A single kilogram of uranium-235 releases as much energy as tens of millions of kilowatt-hours — the scale difference behind nuclear power.

Question 15 Model answer: the energy released per event in a chemical reaction is about 6.6×10^{-19} J, roughly 50 million times smaller than the 3.2×10^{-11} J from one nuclear fission (Question 4). Since $\Delta m=\Delta E/c^2$, the mass converted in a chemical reaction is smaller by the same factor — of order one part in 10^9 of the reacting mass, far too small ever to be measured on a balance. In nuclear reactions the converted fraction is about a million times larger still and the total release is enormous, so the mass change is measurable and cannot be ignored.

Question 16 Model answer: the student's statement is not quite right. Mass is not "destroyed" and energy is not "created": mass itself is a form of energy ($E=mc^2$), and the total mass–energy is conserved. In a reaction that releases energy, the products alone have less mass than the starting nucleus, but the released energy carries the equivalent mass away with it. Starting nucleus = products + released energy, with the same total mass–energy on both sides. Nothing disappears; some of the mass simply leaves as energy.

Question 17 Mass of the separate nucleons: $1.6726\times10^{-27}+1.6749\times10^{-27}=3.3475\times10^{-27}$ kg. Mass defect: $\Delta m=3.3475\times10^{-27}-3.3436\times10^{-27}=3.9\times10^{-30}$ kg (2 s.f.). Binding energy: $E=3.9\times10^{-30}\times9.00\times10^{16}=3.5\times10^{-13}$ J, which is $\frac{3.5\times10^{-13}}{1.60\times10^{-13}}=2.2\,\mathrm{MeV}$. Per nucleon: $\frac{2.2}{2}=1.1\,\mathrm{MeV}$ per nucleon — the lowest value on the binding energy curve after a single proton, which is why fusing deuterium releases so much energy per nucleon.

Question 18 Model answer: light nuclei such as hydrogen's isotopes sit low on the steep rising part of the binding energy curve (deuterium at only $1.1\,\mathrm{MeV}$ per nucleon). When they fuse, the products land much closer to the peak, so the binding energy per nucleon increases by several MeV — a large release of energy per nucleon. That is what makes light nuclei good fusion fuel. Uranium sits on the falling tail of the curve at about $7.6\,\mathrm{MeV}$ per nucleon. Fusing two uranium nuclei would make one even heavier nucleus farther to the right of the peak, where the binding energy per nucleon is *lower*. The product would be less tightly bound than the nuclei that formed it, so the reaction would need energy put in rather than releasing it. Uranium can release energy by splitting (fission), never by joining.

Question 19 (a) $E=mc^2=5.0\times10^{-29}\times(3.00\times10^{8})^2=5.0\times10^{-29}\times9.00\times10^{16}=4.5\times10^{-12}$ J (2 s.f.). (b) $\frac{4.5\times10^{-12}}{1.60\times10^{-13}}=28\,\mathrm{MeV}$ (2 s.f.). (c) $\frac{3.6\times10^{6}}{4.5\times10^{-12}}=8.0\times10^{17}$ reactions (2 s.f.).

Theory

Section 4A explained why fission releases energy: the total mass of the products of a fission is slightly less than the total mass of the original nucleus and neutron, and that missing mass is converted to energy. This section is about how individual fissions link together into a **chain reaction**, and what determines whether that chain reaction dies out, runs steadily, or grows.

Fission, recalled. Nuclear fission is the splitting of a large nucleus into two smaller nuclei. In the reaction used in most reactors, a uranium-235 nucleus absorbs a slow neutron, briefly forms an unstable ^{236}U nucleus, and almost immediately splits into two lighter nuclei called the **fission fragments**, releasing on average two to three neutrons and about 3.2×10^{-11} J of energy. One of the many possible fission events is

$$^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3\ {}^{1}_{0}n + \text{energy}$$

Check the accounting: the nucleon numbers balance ($1+235=144+89+3=236$) and the charges balance ($0+92=56+36+0=92$), as they must in every nuclear equation (Section 3B). The fragments are different in almost every fission — hundreds of fragment pairs are possible — and they are neutron-rich and radioactive; their subsequent decay is treated in Sections 3B–3E. A nuclide such as ^{235}U that can undergo fission after absorbing a slow neutron is described as **fissile**. The energy from a single fission is tiny, so any useful release of energy requires an enormous number of fissions (Example 4).

The chain reaction. Each fission releases two to three neutrons. Those neutrons can travel on, be absorbed by other fissile nuclei, and cause further fissions — each of which releases more neutrons, which can cause more fissions again. A self-sustaining sequence of this kind is a **fission chain reaction**, and each round of fissions is called a **generation**.

For the reaction to keep going, at least one neutron from each fission must, on average, go on to cause another fission. This gives three regimes:

- **Subcritical** — fewer than one neutron per fission causes a further fission. Each generation is smaller than the one before it, and the reaction dies out.
- **Critical** — exactly one neutron per fission causes a further fission, on average. Each generation equals the last, and the reaction proceeds at a steady rate. This is the operating state of a nuclear reactor.
- **Supercritical** — more than one neutron per fission causes a further fission, on average. Each generation is larger than the one before it, so the reaction rate grows faster and faster. An uncontrolled supercritical reaction releases its energy in a violently short time; a controlled, deliberately managed approach to criticality is how a reactor is started up.

The first human-made self-sustaining chain reaction was achieved on 2 December 1942 in **Chicago Pile-1**, a reactor built by Enrico Fermi's team under the stands of a sports stadium at the University of Chicago. It used graphite as its moderator and cadmium control rods, and it ran at a power far too small to boil a kettle — the point of the experiment was to prove that a chain reaction could be held exactly critical.

Source: Wikipedia, *Chicago Pile-1*, retrieved 2026-08-18.

Where the neutrons go. Only some of the neutrons released by fission actually cause the next fission. Each neutron has three possible fates:

1. it causes a further fission in a fissile nucleus — this is the useful fate;
2. it is **absorbed** by a nucleus without causing fission — in a control rod, in a structural material, in the coolant, in a fission product, or in a non-fissile nucleus of the fuel itself;
3. it **escapes** through the surface of the material into the surroundings.

Criticality is decided entirely by the balance between these fates. The rest of this section looks at the four handles that control the balance: the mass and the shape of the fissile material (which set how many neutrons escape), neutron absorbers (which set how many are captured), and the moderator (which sets how likely a surviving neutron is to cause a fission).

The effect of mass on criticality. Neutrons escape through the *surface* of a lump of fissile material, while the fissions that produce them happen throughout its *volume*. A small lump has a large surface compared with its volume, so a large fraction of its neutrons escape before ever reaching a fissile nucleus — the lump is subcritical no matter how long you wait. As the amount of material increases, the volume (and the number of fissile nuclei in it) grows faster than the surface does, so the fraction of neutrons that escape steadily falls. Eventually the amount of material is large enough that production balances losses, and a self-sustaining chain reaction becomes possible. The **critical mass** is the minimum amount of a fissile material needed to sustain a chain reaction. The critical mass is not a single universal number: it depends on the material (what fraction of its nuclei are fissile), on the shape of the sample, and on what surrounds it.

The effect of shape on criticality. Two samples with the *same mass* can have very *different surface areas*, and the one with the larger surface leaks more neutrons. For any given volume, a sphere has the smallest surface area of any shape, so a spherical sample loses the fewest neutrons and has the smallest critical mass. The same mass of material pressed into a thin sheet has a much larger surface: many more neutrons escape, and a sample that would be critical as a sphere can be deeply subcritical as a sheet. This is used directly in criticality safety — fissile materials are stored and handled in flat or slender containers whose shape keeps them subcritical, a strategy called **geometry control** (Example 2).

Neutron absorption. The second loss route is absorption without fission. In a reactor this is put to work: **control rods** made of materials that absorb neutrons strongly — boron, cadmium and hafnium are common choices — are the main handle by which operators control the chain reaction.

- Pushing the rods further into the core increases absorption: fewer neutrons survive to cause fissions, and the reaction rate falls.
- Pulling the rods out reduces absorption: more neutrons survive, and the reaction rate rises.
- Driving the rods fully in makes the core subcritical, and the chain reaction stops.

Absorption also happens where it is not wanted — in structural materials, in fission products, and in non-fissile fuel nuclei such as ^{238}U. The particular case of neutron absorption in ^{238}U, and what it produces, is treated in Section 10D (Option 2.2).

Moderation. The neutrons released by fission are fast, travelling at roughly $10^7\ \mathrm{m\ s^{-1}}$. Slow neutrons are far more likely to be absorbed by ^{235}U nuclei and to cause fission, so most reactors slow their neutrons down deliberately. A **moderator** is a material that slows neutrons by repeated collisions without absorbing them.

The slowing works best when the moderator nuclei are light. In a collision, a neutron transfers the largest share of its kinetic energy to a nucleus with a mass close to its own — much as one billiard ball nearly stops when it strikes another of equal mass. A neutron colliding with a very heavy nucleus, by contrast, bounces off with almost all of its speed, as a ball bounces off a wall. Good moderators are therefore materials built from light nuclei: ordinary water ($\mathrm{H_2O}$, whose hydrogen nuclei are almost the neutron's mass), heavy water ($\mathrm{D_2O}$), and graphite (carbon). Chicago Pile-1 used graphite; OPAL, Australia's research reactor, uses ordinary water. Ordinary water also absorbs some neutrons, which is one reason reactors moderated with it use fuel that is slightly **enriched** — that is, fuel in which the fraction of ^{235}U has been increased above the 0.7% found in natural uranium.

A chain reaction in nature: Oklo. About 1.7 billion years ago, self-sustaining chain reactions ran naturally in a rich deposit of uranium ore at Oklo in Gabon, in central Africa. They were discovered in 1972, when measurements of the ore's isotope ratios came back wrong. At that time natural uranium contained about 3% ^{235}U — considerably more than today, because ^{235}U has a much shorter half-life than ^{238}U and has decayed further — so the ore was effectively a low-grade reactor fuel. Groundwater seeping through the deposit acted as the moderator. The reactions ran in cycles: critical while the water was present, then the heat boiled the water away, the moderator was lost, the reaction became subcritical and stopped, and the cycle began again once the water returned. The Oklo reactors operated on and off for roughly $500\,000$ years.

Source: Wikipedia, *Natural nuclear fission reactor*, retrieved 2026-08-18. Source: World Nuclear Association, *Radioactive Waste Management*, retrieved 2026-08-18.

Putting it together. A working reactor combines all four handles: enough fissile material in a geometry that does not leak too many neutrons, a moderator to make the surviving neutrons effective, and movable absorbers that trim the balance until exactly one neutron per fission, on average, causes the next one. Section 4C compares fission with the other energy-releasing nuclear process, fusion, and Section 4D examines the place of nuclear energy in Australia. Students undertaking Option 2.2 will meet the specific fission reactions of ^{235}U and ^{239}Pu again, in more detail, in Section 10D.

Worked examples

Example 1 — scaffolded

This question uses a deliberately simplified model of the neutron balance in a research reactor such as OPAL; the numbers are chosen for the model and are not measurements. In the model, each fission releases an average of 2.5 neutrons, and of every 100 neutrons produced, 40 go on to cause further fissions, 35 are absorbed without causing fission, and 25 escape the core.

(a) Calculate how many neutrons, on average, each fission contributes to the next generation.
(b) Classify the state of the chain reaction, and describe what happens to the reaction rate.
(c) The control rods are pushed further in, so that 55 of every 100 neutrons are absorbed while the number escaping stays at 25. Repeat the calculation and classify the new state.

Working	Comment
40 of every 100 neutrons cause fissions, so the fraction that do is $\frac{40}{100} = 0.40$.	Find the fraction of neutrons with the useful fate.
Neutrons per fission causing the next fission $= 2.5 \times 0.40 = 1.0$.	Each fission releases 2.5 neutrons; multiply by the useful fraction.
(b) Exactly 1 neutron per fission replaces the fission, so the reactor is **critical**: the generations are equal and the rate is steady.	The definition of critical.
(c) Neutrons causing fissions: $100 - 55 - 25 = 20$ of every 100, so $2.5 \times 0.20 = 0.5$ per fission.	Absorption has risen; escape is unchanged.
$0.5 < 1$, so the reactor is now **subcritical** and the reaction dies away.	Fewer than one replacement neutron per fission.

Example 2 — scaffolded

Criticality-safety engineers must keep stored fissile material subcritical, and one tool is geometry control: choosing container shapes that let neutrons escape. Two samples of the same fissile material each have a volume of $1000\,\text{cm}^3$. Sample A is a sphere and sample B is a cube.

(a) Show that the spherical sample has a radius of about $6.2\,\text{cm}$ and a surface area of about $484\,\text{cm}^2$.
(b) Calculate the surface-area-to-volume ratio for each sample.
(c) State which shape keeps the material further from criticality, and why.

Working	Comment
(a) $V = \frac{4}{3}\pi r^3 = 1000$, so $r^3 = \frac{3 \times 1000}{4\pi} = 238.7$ and $r = 6.20\,\text{cm}$.	Rearrange the sphere volume formula.
Surface area $= 4\pi r^2 = 4\pi \times 6.20^2 = 484\,\text{cm}^2$.	Sphere surface area formula.
(b) Sphere: $\frac{484}{1000} = 0.48\,\text{cm}^{-1}$.	Surface area ÷ volume.
Cube: side $= 10.0\,\text{cm}$, surface area	Same volume, larger surface.

Working	Comment
$=6\times 10.0^2=600\,\text{cm}^2$, ratio $=\dfrac{600}{1000}=0.60\,\text{cm}^{-1}$.	
(c) The cube, because it has the larger surface-area-to-volume ratio, so a larger fraction of its neutrons reach the surface and escape.	More leakage means further from criticality.

Example 3 — unscaffolded

In a simplified model of a supercritical chain reaction, the number of fissions doubles every generation: generation 0 is a single fission, and every fission in any generation leads to two fissions in the next. Each fission releases 3.2×10^{-11} J. Show that the total energy released first reaches 1 J by the end of generation 34.

The number of fissions in generation n is 2^n, so the total number of fissions up to and including generation g is

$$1+2+4+\ldots+2^g=2^{g+1}-1.$$

The number of fissions needed to release 1 J is

$$N=\frac{1.0}{3.2\times 10^{-11}}=3.1\times 10^{10}.$$

Testing powers of two: $2^{34}-1=1.7\times 10^{10}$ fissions is not quite enough, but

$$2^{35}-1\approx 3.4\times 10^{10}\,\text{fissions}$$

is, and 2^{35} corresponds to $g+1=35$, that is, $g=34$. By the end of generation 34 the total energy released is about $\left(3.4\times 10^{10}\right)\times\left(3.2\times 10^{-11}\right)\approx 1.1$ J.

∴ the energy first reaches 1 J by the end of generation 34. Notice how little this is on the human scale: a truly supercritical chain reaction passes through 35 generations in a tiny fraction of a second, which is why uncontrolled chain reactions release their energy so violently.

Example 4 — unscaffolded

OPAL, at ANSTO's Lucas Heights campus in Sydney, is Australia's only nuclear reactor. It is a $20\,\text{MW}$ research reactor — it does not generate electricity; among other work it produces radioisotopes for medicine (Section 3F). A power of $20\,\text{MW}$ means the reactor releases 2.0×10^7 J of energy every second. Taking the energy released per fission as 3.2×10^{-11} J,

(a) calculate the number of fissions occurring each second;
(b) calculate the number of neutrons released each second, taking 2.5 neutrons per fission on average;
(c) state what must be true, on average, about the neutrons released in each fission if the reactor is to hold a steady power.

Source: ANSTO, *OPAL reactor*, ansto.gov.au, retrieved 2026-08-18.

(a) Each fission releases 3.2×10^{-11} J, so the number of fissions per second is

$$\frac{2.0\times 10^7}{3.2\times 10^{-11}}=6.25\times 10^{17}\approx 6.3\times 10^{17}.$$

(b) Each fission releases 2.5 neutrons on average, so the number of neutrons produced per second is

$$2.5\times 6.25\times 10^{17}=1.56\times 10^{18}\approx 1.6\times 10^{18}.$$

(c) If the power is steady the reactor is critical, so of the 2.5 neutrons released by each fission, exactly one, on average, must go on to cause the next fission. The remaining 1.5 per fission are absorbed — chiefly by the control rods and the water — or escape.

∴ about 6.3×10^{17} fissions and about 1.6×10^{18} neutrons each second, with exactly one neutron per fission on average sustaining the chain reaction.

Practice questions

Question 1 (a) State what is meant by nuclear fission. (b) State how many neutrons are typically released in one fission of ^{235}U, and explain why that number matters for a chain reaction. (c) State what is meant by a fission chain reaction.

Question 2 A ^{235}U nucleus absorbs a neutron and splits into ^{144}Ba, one other fragment $^{A}_{Z}X$, and three neutrons: $^{1}_{0}$n + $^{235}_{92}$U → $^{144}_{56}$Ba + $^{A}_{Z}X + 3\ ^{1}_{0}\text{n} + \text{energy}$ (a) Calculate the values of A and Z, and identify the element X. (b) Show that both nucleon number and charge are conserved in this reaction. (c) Apart from the two fragments and the three neutrons, state what else this reaction produces.

Question 3 In three separate assemblies, the average number of neutrons from each fission that go on to cause a further fission are: (i) 0.7; (ii) 1.0; (iii) 1.3. (a) Classify each assembly as subcritical, critical or supercritical. (b) Describe what happens to the reaction rate over time in each case. (c) State which condition is the target for steady reactor operation.

Question 4 (a) Define the critical mass of a fissile material. (b) Explain why a lump of fissile material smaller than the critical mass cannot sustain a chain reaction. (c) Explain how increasing the mass of the lump helps a chain reaction to become self-sustaining.

Question 5 (a) State the purpose of the control rods in a nuclear reactor. (b) State one material used for control rods, and the property that makes it suitable. (c) Explain, in terms of neutrons, how pushing the control rods further into the core reduces the reactor's power. (d) State how operators shut the chain reaction down completely, and name the resulting condition of the core.

Question 6 (a) Explain why the fast neutrons released by fission are deliberately slowed in a reactor fuelled with ^{235}U. (b) Explain why the nuclei of a good moderator need to be light. (c) Name two materials used as moderators.

Question 7 In a simplified model of a reactor core, each fission releases an average of 2.5 neutrons, and of every 200 neutrons produced, 90 go on to cause further fissions, 70 are absorbed without causing fission, and the rest escape. (a) Calculate the fraction of neutrons that escape. (b) Calculate how many neutrons, on average, each fission contributes to the next generation. (c) Classify the state of the chain reaction.

Question 8 Research reactors such as OPAL are normally held exactly critical, but in a deliberate test the chain reaction is briefly taken slightly supercritical, producing a pulse of 5.0×10^{16} fissions. Taking the energy released per fission as 3.2×10^{-11} J, calculate the total energy released in the pulse.

Question 9 Explain why the critical mass of a fissile material shaped as a sphere is smaller than the critical mass of the same material shaped as a thin sheet.

Question 10 Two spheres are made of the same fissile material. Sphere A has radius r and sphere B has radius $2r$. (a) Show that sphere B has eight times the mass of sphere A. (b) Show that the surface-area-to-volume ratio of sphere B is half that of sphere A. (c) State which sphere is closer to criticality, and why.

Question 11 Explain how a moderator slows neutrons down, referring to what happens in the collisions between neutrons and moderator nuclei.

Question 12 OPAL uses ordinary (light) water as its moderator. (a) Explain, in terms of collisions, why hydrogen nuclei are effective at slowing neutrons. (b) State one other role the water plays in the reactor.

Question 13 In a simplified model of a supercritical chain reaction, every fission leads on average to 1.3 fissions in the next generation. Generation 0 consists of 1000 fissions. (a) Calculate the number of fissions in generation 4. (b) Explain why this growth cannot continue indefinitely in any real mass of fuel.

Question 14 About 1.7 billion years ago, self-sustaining chain reactions ran naturally in uranium ore at Oklo in Gabon; they were discovered in 1972. The ore then contained about $3\,\%$ ^{235}U, and groundwater seeping through it acted as the moderator. The reactions ran in cycles, stopping and starting, for roughly $500\,000$ years. (a) Explain the role of the groundwater in sustaining the chain reactions. (b) Explain why a reaction stopped when its heat boiled the water away, and started again once the water returned. (c) The fraction of ^{235}U in natural uranium today is about $0.7\,\%$. Explain, in terms of half-life, why the fraction was larger 1.7 billion years ago.

Question 15 Distinguish between a controlled and an uncontrolled chain reaction, referring to the average number of neutrons per fission that cause further fissions in each case.

Question 16 OPAL operates steadily at $20\,\text{MW}$. Calculate the number of fissions that occur in one hour of operation, taking the energy released per fission as $3.2 \times 10^{-11}\,\text{J}$.

Question 17 Instruments show that the chain reaction in a reactor is growing too quickly. Explain, in terms of neutrons, what driving the control rods fully into the core does to the chain reaction, and state the resulting condition of the core.

Question 18 A spherical sample of fissile material has a radius of $6.0\,\text{cm}$. (a) Calculate its surface-area-to-volume ratio. (b) The same mass of material is divided into eight equal smaller spheres. Calculate the radius of each smaller sphere, and show that the total surface area of the eight spheres is twice the surface area of the original sphere. (c) Explain the consequence of this subdivision for neutron leakage and criticality.

Question 19 Identify two ways in which a neutron released by fission can fail to cause a further fission, and for each way state one thing reactor designers do to manage it.

Answers

Question 1 (a) the splitting of a large nucleus into two smaller nuclei; (b) two to three; the reaction is self-sustaining only if at least one of them, on average, causes a further fission; (c) a self-sustaining sequence in which neutrons released by fissions cause further fissions. **Question 2** (a) $A=89$, $Z=36$, krypton (Kr); (b) nucleon number: $1+235=236$ and $144+89+3=236$; charge: $0+92=92$ and $56+36+0=92$; (c) energy. **Question 3** (a) (i) subcritical, (ii) critical, (iii) supercritical; (b) (i) dies away, (ii) constant, (iii) grows; (c) 1.0 (critical). **Question 4** (a) the minimum amount of a fissile material needed to sustain a chain reaction; (b) too many neutrons escape through the surface — losses exceed production; (c) the volume grows faster than the surface, so the fraction of neutrons escaping falls until production balances losses. **Question 5** (a) to control the rate of the chain reaction by absorbing neutrons; (b) e.g. boron (or cadmium, hafnium): it absorbs neutrons strongly without fissioning; (c) more neutrons are absorbed in the rods, fewer survive to cause fissions, and the reaction rate falls; (d) drive the rods fully in; subcritical. **Question 6** (a) slow neutrons are far more likely to be absorbed by ^{235}U and cause fission; (b) a neutron transfers the largest share of its kinetic energy to a nucleus of similar (small) mass; (c) any two of: ordinary water, heavy water, graphite. **Question 7** (a) $20\,\%$; (b) 1.1; (c) supercritical. **Question 8** $1.6\times10^{6}\,\mathrm{J}$. **Question 9** A sphere has the smallest surface area for a given mass, so the fewest neutrons escape; a sheet has a much larger surface and loses many more neutrons, so more mass is needed for production to balance losses. **Question 10** (a) mass $\propto$ volume $\propto r^3$, and $(2r)^3=8r^3$; (b) $\frac{\text{surface area}}{\text{volume}}=\frac{4\pi r^2}{\frac{4}{3}\pi r^3}=\frac{3}{r}$, which halves when r doubles; (c) sphere B — its larger mass loses a smaller fraction of its neutrons. **Question 11** By repeated collisions with light nuclei; in each collision the neutron gives up part of its kinetic energy, most when the nucleus has a mass close to the neutron's, until the neutron is slow. **Question 12** (a) a hydrogen nucleus has almost the same mass as a neutron, so each collision transfers a large share of the neutron's kinetic energy; (b) it also acts as a coolant, carrying thermal energy away from the fuel. **Question 13** (a) about 2900 fissions; (b) e.g. the fuel is gradually used up, fission products that absorb neutrons accumulate, and the heating changes (or destroys) the geometry of the mass. **Question 14** (a) it moderated (slowed) the neutrons, making them far more likely to cause fission of ^{235}U; (b) without water the neutrons stayed fast and too few caused fission — the reaction became subcritical and stopped; when the water returned, moderation was restored and the reaction became critical again; (c) ^{235}U has a much shorter half-life than ^{238}U, so a larger fraction of the original ^{235}U has since decayed away. **Question 15** Controlled: the average is held at exactly one (critical), so the rate is steady and adjustable with absorbers; uncontrolled: the average exceeds one (supercritical), so the rate grows rapidly and the energy is released violently. **Question 16** 2.3×10^{21} fissions. **Question 17** The rods absorb neutrons, so fewer than one neutron per fission on average causes a further fission; the core becomes subcritical and the chain reaction dies away. **Question 18** (a) $0.50\,\mathrm{cm}^{-1}$; (b) $3.0\,\mathrm{cm}$; total surface area $905\,\mathrm{cm}^2$, twice the original $452\,\mathrm{cm}^2$; (c) more surface means more neutron leakage, so each piece is further from criticality. **Question 19** Escaping through the surface — use enough mass in a compact geometry; being absorbed without causing fission — choose low-absorbing materials for structures and coolant, and use strong absorbers (control rods) deliberately to trim the balance.

Fully-worked solutions

Question 1 Model answer. (a) Nuclear fission is the splitting of a large nucleus into two smaller nuclei (the fission fragments), typically after the large nucleus absorbs a neutron. (b) A fission of ^{235}U releases two to three neutrons on average. This number matters because the chain reaction survives only if at least one of those neutrons, on average, goes on to cause a further fission: if fewer than one does, the reaction dies out, and if more than one does, the reaction grows. (c) A fission chain reaction is a self-sustaining sequence of fissions in which the neutrons released by one generation of fissions cause the next generation.

Question 2 (a) Conservation of nucleon number: $1+235=144+A+3$, so $A=236-147=89$. Conservation of charge: $0+92=56+Z+0$, so $Z=36$. Element 36 is krypton: $^{89}_{36}$Kr. (b) Nucleon number: left side $1+235=236$; right side $144+89+3\times1=236$. Charge: left side $0+92=92$; right side $56+36+0=92$. Both are conserved. (c) Energy (released mainly as kinetic energy of the fragments, with some gamma radiation).

Question 3 The state is set by the average number of neutrons per fission that cause the next fission. (a) (i) $0.7<1$: subcritical. (ii) $1.0=1$: critical. (iii) $1.3>1$: supercritical. (b) (i) Each generation is smaller than the last, so the reaction rate falls to zero. (ii) Each generation equals the last, so the rate stays constant. (iii) Each generation is larger than the last, so the rate grows — faster and faster as the generations pass. (c) The critical condition, 1.0 neutron per fission, is the target for steady operation.

Question 4 (a) The critical mass is the minimum amount of a fissile material needed to sustain a chain reaction. (b) In a small lump the surface area is large compared with the volume, so a large fraction of the neutrons escape through the surface before they can cause fissions. With fewer than one neutron per fission causing a further fission, each generation is smaller than the one before and the reaction dies out. (c) As the mass increases, the volume — and the number of fissile nuclei — grows faster than the surface area. The fraction of neutrons that escape therefore falls, and at the critical mass the production of neutrons by fission just balances the losses by escape and absorption.

Question 5 (a) The control rods control the rate of the chain reaction by absorbing neutrons. (b) Boron (cadmium and hafnium are also used). The required property is that the material absorbs neutrons strongly without itself fissioning. (c) Pushing the rods further into the core places more absorbing material among the fuel. More of the neutrons released by fission are captured in the rods, so fewer survive to cause further fissions; the average number of next-generation fissions per fission falls, and the reaction rate — and hence the power — decreases. (d) The rods are driven fully into the core. Absorption then removes enough neutrons that fewer than one per fission causes a further fission: the core is subcritical and the chain reaction stops.

Question 6 (a) The neutrons released by fission are fast, and slow neutrons are far more likely to be absorbed by ^{235}U nuclei and to cause fission. Slowing the neutrons therefore increases the fraction that causes fissions, which makes a self-sustaining chain reaction possible with less fuel. (b) In a collision, a neutron transfers the largest share of its kinetic energy to a nucleus whose mass is close to its own. Light moderator nuclei therefore slow the neutrons efficiently, while very heavy nuclei would barely slow them at all. (c) Any two of: ordinary (light) water, heavy water, graphite.

Question 7 (a) Escaping neutrons: $200-90-70=40$ of every 200, so the fraction escaping is $\frac{40}{200}=0.20$, i.e. 20%. (b) The fraction causing fissions is $\frac{90}{200}=0.45$, so each fission contributes $2.5\times0.45=1.125\approx1.1$ neutrons to the next generation. (c) More than one neutron per fission causes a further fission, so the core is **supercritical** and the reaction rate is growing.

Question 8 $N=5.0\times10^{16}$ fissions, 3.2×10^{-11} J each:

$$E=N\times3.2\times10^{-11}=5.0\times10^{16}\times3.2\times10^{-11}=1.6\times10^{6}\,\text{J}.$$

Question 9 Model answer. Neutrons escape through the surface, so neutron losses are set by how much surface a given mass of material has. A sphere has the smallest possible surface area for a given volume, so a spherical sample loses the fewest neutrons: production balances losses at the smallest mass. The same material shaped as a thin sheet has a far larger surface area, so a far larger fraction of its neutrons escape, and a greater mass is needed before production can balance the losses — the critical mass for the sheet geometry is therefore larger than for the sphere.

Question 10 (a) Both spheres are made of the same material, so mass is proportional to volume. The volume of a sphere is $\frac{4}{3}\pi r^3$, so doubling the radius multiplies the volume by $2^3=8$: sphere B has eight times the volume, and hence eight times the mass, of sphere A. (b) For any sphere,

$$\frac{\text{surface area}}{\text{volume}}=\frac{4\pi r^2}{\frac{4}{3}\pi r^3}=\frac{3}{r}.$$

Sphere A has ratio $\frac{3}{r}$; sphere B has ratio $\frac{3}{2r}$ — exactly half. (c) Sphere B. It has the larger mass and the smaller surface-area-to-volume ratio, so a smaller fraction of its neutrons escape; it is therefore closer to (or past) criticality.

Question 11 Model answer. The moderator surrounds the fuel, and the fast neutrons released by fission collide repeatedly with the moderator's nuclei. In each collision the neutron gives up part of its kinetic energy to the nucleus it strikes; the transfer is largest when the struck nucleus has a mass close to the neutron's own. After many such collisions the neutron has lost most of its kinetic energy and is moving slowly. A good moderator does all this while absorbing very few neutrons, so that the slowed neutrons survive to cause further fissions.

Question 12 (a) A hydrogen nucleus is almost exactly the neutron's mass. In a collision between two objects of equal mass, the moving object can transfer a very large share of its kinetic energy — as one billiard ball can stop almost dead when it strikes another — so each collision slows the neutron efficiently. (b) The water also acts as a coolant, carrying thermal energy away from the fuel so that the reactor does not overheat. (The energy transfers that put this thermal energy to work are treated in Section 4D.)

Question 13 (a) Each generation is 1.3 times the one before: generation 1: $1000 \times 1.3 = 1300$; generation 2: $1300 \times 1.3 = 1690$; generation 3: $1690 \times 1.3 = 2197$; generation 4: $2197 \times 1.3 = 2856$, i.e. about 2900 fissions (equivalently $1000 \times 1.3^4 = 2856$). (b) Model answer. The growth cannot continue indefinitely because the assumptions of the model break down in a real mass of fuel: the fissile nuclei are gradually used up; fission products accumulate, and many of them absorb neutrons strongly; and the energy released heats the material, changing its shape, density and geometry — in an uncontrolled case the mass melts and comes apart, which increases neutron leakage and stops the growth. In a reactor, operators simply push in the control rods once the desired power is reached.

Question 14 (a) Model answer. The groundwater acted as a moderator: its hydrogen nuclei slowed the fast neutrons released by fission through repeated collisions. Slow neutrons are far more likely to be absorbed by ^{235}U and to cause fission, so the water made a self-sustaining chain reaction possible in the ore. (b) Model answer. When the heat of the reaction boiled the water away, the moderator was lost. The neutrons then stayed fast, far fewer of them caused fissions, losses (escape and absorption) exceeded production, and the reaction became subcritical and stopped. Once groundwater seeped back into the deposit, moderation was restored, the balance returned to critical, and the reaction started again — hence the on–off cycling. (c) ^{235}U has a much shorter half-life (about 700 million years) than ^{238}U (about 4.5 billion years). Over the last 1.7 billion years a much larger fraction of the original ^{235}U has therefore decayed away, so the proportion of ^{235}U in natural uranium was larger in the past than it is today.

Question 15 Model answer. In a controlled chain reaction the average number of neutrons per fission that cause a further fission is held at exactly one — the reaction is critical — so each generation equals the last, the rate is steady, and operators can raise, lower or stop the reaction at will by moving neutron absorbers (the control rods). In an uncontrolled chain reaction that average exceeds one — the reaction is supercritical — so each generation is larger than the one before, the reaction rate grows extremely quickly, and the energy is released violently rather than steadily.

Question 16 In one hour the reactor releases

$$E = P\,t = 2.0 \times 10^7 \times 3600 = 7.2 \times 10^{10}\ \mathrm{J}$$

(a power of $20\,\mathrm{MW}$ means 2.0×10^7 J each second). The number of fissions is

$$N = \frac{7.2 \times 10^{10}}{3.2 \times 10^{-11}} = 2.25 \times 10^{21} \approx 2.3 \times 10^{21}.$$

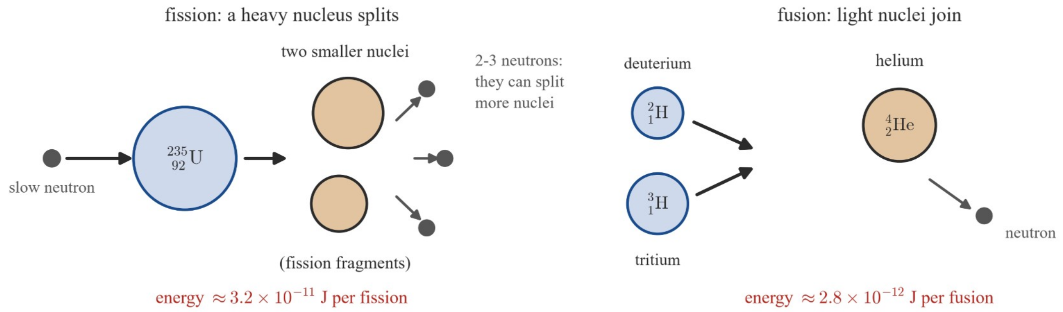
Question 17 Model answer. The control rods are strong neutron absorbers. Driving them fully into the core greatly increases the fraction of neutrons captured without causing fission, so fewer than one neutron per fission, on average, goes on to cause a further fission. The core becomes **subcritical**, each generation of fissions is smaller than the one before, and the chain reaction dies away rapidly.

Question 18 (a) For a sphere, $\dfrac{\text{surface area}}{\text{volume}} = \dfrac{3}{r}$, so with $r = 6.0\,\mathrm{cm}$ the ratio is $\dfrac{3}{6.0} = 0.50\,\mathrm{cm}^{-1}$. (Equivalently: surface area $= 4\pi r^2 = 4\pi \times 6.0^2 = 452\,\mathrm{cm}^2$ and volume $= \dfrac{4}{3}\pi r^3 = 905\,\mathrm{cm}^3$, giving $452/905 = 0.50\,\mathrm{cm}^{-1}$.) (b) Dividing the volume into eight equal parts divides each linear dimension by $\sqrt[3]{8} = 2$, so each smaller sphere has radius $3.0\,\mathrm{cm}$. The surface area of each is $4\pi \times 3.0^2 = 113.1\,\mathrm{cm}^2$, and the total is $8 \times 113.1 = 905\,\mathrm{cm}^2$, while the original sphere's surface area was $452\,\mathrm{cm}^2$ — twice as much, exactly, since halving the radius and taking eight pieces multiplies the total surface area by $8\times\left(\frac{1}{2}\right)^2=2$. (c) Model answer. The subdivision has doubled the surface area through which neutrons can escape, so the fraction of neutrons leaking out is much larger. Each small sphere is therefore further from criticality than the original lump. Dividing fissile material into separated smaller pieces is a standard criticality-safety measure; the pieces must also be kept apart, so that neutrons escaping one piece do not simply enter another.

Question 19 Model answer. - **Escape through the surface.** Designers use enough fissile material, arranged in a compact geometry with a small surface-area-to-volume ratio, so that only a small fraction of neutrons reach the surface and leave. - **Absorption without fission.** Designers choose materials with low neutron absorption for the structures and coolant around the fuel, and they deliberately place strong absorbers — the control rods — in the core so that the unavoidable absorption can be adjusted to hold the reactor exactly critical. (The moderator addresses the same balance from the other side: by slowing the neutrons, it makes each surviving neutron far more likely to cause a fission before it is lost.)

Theory

The nuclei of some atoms can release energy in two different ways. **Fission** splits a heavy nucleus apart. **Fusion** joins light nuclei together. Both processes release energy because the total mass of the products is slightly less than the total mass of the reactants: the missing mass is converted into energy, as explained in 4A. This subtopic compares the two processes side by side.



per kilogram of fuel, fusion releases about four times the energy of fission

Fission — recap. In 4B you saw that when a nucleus of uranium-235 (^{235}U) absorbs a neutron, it splits into two smaller nuclei, called **fission fragments**, and releases two or three neutrons and energy. Each fission of a ^{235}U nucleus releases about 3.2×10^{-11} J.

Source: World Nuclear Association, Nuclear Fusion Power, retrieved 2026-08-18.

Because the neutron carries no electric charge, it is not repelled by the positive nucleus, so fission can be started at ordinary temperatures. The neutrons released by one fission can then split further nuclei: this is the chain reaction of 4B, whose rate is controlled by absorbing neutrons.

Fusion. In fusion, two light nuclei combine to form one heavier nucleus, and energy is released. The reaction pursued by most current fusion experiments combines two isotopes of hydrogen, **deuterium** and **tritium** (isotopes of an element have nuclei with the same number of protons but different numbers of neutrons). Each such fusion event releases about 2.8×10^{-12} J.

Source: World Nuclear Association, Nuclear Fusion Power, retrieved 2026-08-18.

The difficulty with fusion is getting the nuclei close enough to stick. Every nucleus is positively charged, so two nuclei repel each other electrostatically. The **strong nuclear force** (3A) can bind them only when they are extremely close together, within about 10^{-15} m. To reach that distance, the nuclei must collide at enormous speeds, which means the fuel must be at an enormous temperature: tens to hundreds of millions of kelvin. At such temperatures the electrons are stripped from the atoms, and the fuel becomes a **plasma** — a hot mixture of bare positive nuclei and free electrons. A plasma cannot touch any solid container, because it would cool at once and damage the container, so it must be held in place, or **confined**, without touching the walls.

Achieving fusion — stars and machines. In the Sun and other stars, gravity squeezes the plasma to an enormous density and holds it in place, so fusion proceeds steadily even though the Sun's core is at about 1.5×10^{7} K.

Source: NASA Science, Sun facts, retrieved 2026-08-18.

On Earth, two methods are used to confine the fuel:

- **Magnetic confinement.** A doughnut-shaped machine called a **tokamak** uses magnetic fields to hold the plasma away from the walls. ITER, an international experiment under construction in southern France, is designed to confine a plasma at about 1.5×10^{8} K — about ten times the temperature at the core of the Sun —

and to release 500×10^6 J of fusion energy every second while 50×10^6 J per second is supplied to heat the plasma.

Source: ITER Organization, https://www.iter.org, retrieved 2026-08-18.

- **Laser confinement.** Powerful laser beams squeeze and heat a tiny pellet of fuel. In December 2022, the National Ignition Facility in the United States delivered 2.05 MJ of laser energy to such a pellet, and the fusion reactions that followed released 3.15 MJ — the first experiment in which the fuel released more energy than the energy delivered to it.

  Source: United States Department of Energy, National Ignition Facility achieves fusion ignition, 13 December 2022, retrieved 2026-08-18.

Control: chain reaction versus steady burning. A fission chain reaction is self-sustaining: once it is started, the neutrons released by each fission go on to trigger the next one, and the rate is adjusted by absorbing neutrons (4B). A fusion reaction has no chain reaction — each fusion event consumes its two nuclei, and nothing released by the event triggers the next one. The fuel fuses only for as long as the temperature and the confinement are maintained. If the plasma cools, or if it escapes, the fusion stops at once. A fusion machine therefore cannot run away in the way an uncontrolled fission chain reaction can.

Energy released: per event versus per kilogram. A single fission event (3.2×10^{-11} J) releases about 11 times as much energy as a single fusion event (2.8×10^{-12} J). Per kilogram of fuel, however, the comparison reverses:

- 1 kg of fusion fuel (a deuterium–tritium mixture) releases about 3.4×10^{14} J;
- 1 kg of ^{235}U releases about 8.2×10^{13} J.

Fusion releases about 4 times as much energy per kilogram of fuel, because 1 kg of light fuel contains many more nuclei than 1 kg of heavy fuel, so many more reactions are available. Both figures are millions of times larger than for chemical fuels: burning 1 kg of coal releases about 3×10^7 J.

Source: World Nuclear Association, Nuclear Fusion Power, retrieved 2026-08-18.

Why does energy come out in both directions? As 4A showed with the binding energy curve, both splitting a very heavy nucleus and joining very light nuclei produce nuclei that are more tightly bound, with less total mass. The lost mass is converted into energy.

Fuels. Fission reactors use heavy nuclei, mainly ^{235}U, which is mined from ore: a finite mineral resource. Fusion uses light nuclei. Deuterium occurs naturally in seawater, and tritium — which is almost absent in nature — can be produced inside a fusion reactor from lithium, an element that is plentiful in the Earth's crust. The specific reactions are studied in Option 2.2 (10D); whether nuclear energy could become an energy source for Australia is investigated in 4D.

Source: World Nuclear Association, Nuclear Fusion Power, retrieved 2026-08-18.

Products and waste. The two fission fragments are radioactive, and many have long half-lives (3C), so fission produces long-lived radioactive waste that must be stored behind shielding. The neutrons released also make the reactor's own materials radioactive over time. The direct product of deuterium–tritium fusion is helium — a stable, non-radioactive gas — so fusion produces no long-lived, fission-fragment-style waste. However, the neutrons released by fusion also activate the reactor walls (that is, they make the wall materials radioactive), producing short- to medium-lived waste. The long-term hazard of fusion waste is far lower than that of fission waste.

Source: World Nuclear Association, Nuclear Fusion Power, retrieved 2026-08-18.

Status today. Fission is an established source of electricity: 441 power reactors operable in 31 countries supply about 9% of the world's electricity.

Source: World Nuclear Association, Nuclear Power in the World Today, updated 2026-08-17, retrieved 2026-08-18.

Fusion is not yet used to generate electricity; it remains at the research stage, with engineering challenges still unsolved. Australia's only nuclear reactor is OPAL, a 20-megawatt research reactor at Lucas Heights in New South Wales, which makes radioisotopes for medicine (3F) rather than electricity.

Source: Australian Nuclear Science and Technology Organisation, OPAL reactor, retrieved 2026-08-18.

The comparison is summarised below.

Feature	Fission	Fusion
What happens in the nucleus	A heavy nucleus splits into two smaller nuclei	Two light nuclei join to form one heavier nucleus
How the reaction is started	A heavy nucleus absorbs a neutron	Two light nuclei must collide at enormous speed
Conditions needed	Can proceed at ordinary temperatures	Fuel must be heated to tens of millions of kelvin and confined
Chain reaction	Yes — released neutrons split further nuclei (4B)	No — the conditions must be maintained continuously
Energy released per reaction	about 3.2×10^{-11} J	about 2.8×10^{-12} J
Energy released per kilogram of fuel	about 8.2×10^{13} J	about 3.4×10^{14} J, roughly 4 times fission
Fuel	Heavy nuclei, e.g. ^{235}U	Light nuclei, e.g. deuterium and tritium
Main products	Two radioactive fission fragments and neutrons	Helium and neutrons
Long-lived radioactive waste	Yes	No; activated reactor materials are short- to medium-lived
Used for electricity today	Yes — 441 reactors, about 9% of the world's electricity	No — research stage (ITER, National Ignition Facility)
Where it occurs naturally	Rarely on Earth	In stars, including the Sun

Answering a "compare" question. The command word *compare* asks for both similarities and differences, and a strong answer names the feature being compared in each sentence. For example: "Both fission and fusion release energy because their products have less total mass than their reactants; however, fission splits a heavy nucleus while fusion joins light nuclei."

Worked examples

Example 1 — scaffolded

Each fission of a ^{235}U nucleus in a power station releases about 3.2×10^{-11} J. Each deuterium–tritium fusion event releases about 2.8×10^{-12} J. (a) Calculate how many fusion events are needed to release the same energy as one fission event. (b) In a reactor core, 6.0×10^{19} fissions occur each second. Calculate the energy released by fission each second. (c) Calculate how many fusion events per second would be needed to release that same energy each second.

Working	Comment
(a) Number of fusion events $= \dfrac{3.2 \times 10^{-11}}{2.8 \times 10^{-12}} = 11.4$.	Divide the energy of one fission by the energy of one fusion event.
About 11 fusion events are needed to match one fission event.	Round to the same two significant figures as the data.
(b) Energy each second $= 6.0 \times 10^{19} \times 3.2 \times 10^{-11} = 1.9 \times 10^{9}$ J.	Multiply the number of fissions per second by the energy per fission.

Working	Comment
(c) Number of fusion events $= \dfrac{1.92 \times 10^{9}}{2.8 \times 10^{-12}} = 6.9 \times 10^{20}$.	Divide the energy per second by the energy per fusion event.

Example 2 — scaffolded

When $1\,\text{kg}$ of deuterium–tritium fusion fuel reacts completely, it releases about $3.4 \times 10^{14}\,\text{J}$. When $1\,\text{kg}$ of ^{235}U undergoes complete fission, it releases about $8.2 \times 10^{13}\,\text{J}$. (a) Calculate how many times as much energy fusion fuel releases per kilogram compared with fission fuel. (b) Calculate the mass of fusion fuel needed to release $1.0 \times 10^{14}\,\text{J}$. (c) Explain why fusion releases more energy per kilogram of fuel even though one fusion event releases less energy than one fission event.

Working	Comment
(a) Ratio $= \dfrac{3.4 \times 10^{14}}{8.2 \times 10^{13}} = 4.1$.	Divide the energy per kilogram of fusion fuel by that of fission fuel.
Fusion releases about 4 times as much energy per kilogram.	
(b) $m = \dfrac{1.0 \times 10^{14}}{3.4 \times 10^{14}} = 0.29\,\text{kg}$.	Mass = required energy ÷ energy per kilogram.
(c) Fusion nuclei are much lighter, so $1\,\text{kg}$ of fusion fuel contains many more nuclei — and so many more possible reactions — than $1\,\text{kg}$ of fission fuel.	Per kilogram, the larger number of reactions more than makes up for the smaller energy per event.

Example 3 — unscaffolded

Burning $1\,\text{kg}$ of coal releases about $3.0 \times 10^{7}\,\text{J}$. (a) Calculate the energy released by burning 5.0 tonnes of coal. (b) Calculate the mass of ^{235}U that would release the same energy by complete fission. (c) Calculate the mass of deuterium–tritium fusion fuel that would release the same energy.

The energy released by the coal is

$$E = 5.0 \times 10^{3}\,\text{kg} \times 3.0 \times 10^{7}\,\text{J kg}^{-1} = 1.5 \times 10^{11}\,\text{J}.$$

For the same energy from fission, using $8.2 \times 10^{13}\,\text{J}$ per kilogram,

$$m = \frac{1.5 \times 10^{11}}{8.2 \times 10^{13}} = 1.8 \times 10^{-3}\,\text{kg},$$

and for fusion fuel, using $3.4 \times 10^{14}\,\text{J}$ per kilogram,

$$m = \frac{1.5 \times 10^{11}}{3.4 \times 10^{14}} = 4.4 \times 10^{-4}\,\text{kg}.$$

∴ burning 5.0 tonnes of coal releases $1.5 \times 10^{11}\,\text{J}$, which could instead come from about $1.8\,\text{g}$ of ^{235}U or about $0.44\,\text{g}$ of fusion fuel. This is why nuclear fuels are described as energy-dense: millions of times more energy comes from each kilogram than from a chemical fuel.

Example 4 — unscaffolded

The core of the Sun is at about $1.5 \times 10^{7}\,\text{K}$. The plasma in the ITER experiment is designed to reach about $1.5 \times 10^{8}\,\text{K}$ — ten times hotter. (a) Explain why nuclei do not fuse at ordinary temperatures. (b) Suggest why the Sun can sustain fusion at a temperature ten times lower than ITER's design temperature. (c) Explain why a fusion machine on Earth cannot use the Sun's method.

(a) Every nucleus is positively charged, so two nuclei repel each other electrostatically. The strong nuclear force can bind them only when they are within about 10^{-15} m of each other. At ordinary temperatures the nuclei move far too slowly to get that close; only at tens of millions of kelvin do they collide hard enough to fuse.

(b) The Sun's enormous gravity squeezes its core to a far greater density than any machine can achieve, and the Sun holds this dense fuel in place for billions of years. With so many nuclei packed so closely together for so long, fusion can proceed steadily even at the lower temperature.

(c) The Earth's gravity is far too weak to squeeze a plasma to the Sun's core density, and no container can hold the fuel by gravity alone. Machines on Earth must make up for the lower density with higher temperatures, holding the plasma with magnetic fields or squeezing tiny pellets with laser beams.

Practice questions

Question 1 Copy the table below into your logbook and complete each row for fission and fusion.

Feature	Fission	Fusion
(a) What happens to the nuclei		
(b) How the reaction is started		
(c) One fuel		
(d) One product		

Question 2 Each fission of a ^{235}U nucleus releases about 3.2×10^{-11} J, and each deuterium–tritium fusion event releases about 2.8×10^{-12} J. (a) Calculate how many fusion events release the same energy as one fission event. (b) A reactor core releases 4.8×10^{9} J of energy each second by fission. Calculate the number of fissions occurring each second.

Question 3 Complete fission of 1 kg of ^{235}U releases about 8.2×10^{13} J; complete reaction of 1 kg of deuterium–tritium fuel releases about 3.4×10^{14} J. (a) Calculate the energy released by the complete fission of 2.0 kg of ^{235}U. (b) Calculate the mass of deuterium–tritium fuel that would release the same energy. (c) State how many times as much energy 1 kg of fusion fuel releases compared with 1 kg of fission fuel.

Question 4 Fusion fuel must be heated until it becomes a plasma. (a) Explain why two light nuclei repel each other when they approach. (b) Define the term *plasma*. (c) State two methods used on Earth to confine a plasma without letting it touch the walls of a container.

Question 5 Compare the waste produced by fission and by deuterium–tritium fusion. (a) State the main direct product of deuterium–tritium fusion and say whether it is radioactive. (b) Explain why a fusion machine still produces some radioactive waste. (c) Compare how long the waste from fusion and the waste from fission remain hazardous.

Question 6 (a) State where fusion occurs naturally. (b) Use the idea of a chain reaction to explain why a fission reactor can keep going once started, while a fusion machine needs a continuous supply of energy to maintain its conditions. (c) State one piece of evidence from this subtopic that fusion research is making progress.

Question 7 In the December 2022 National Ignition Facility experiment, 2.05 MJ of laser energy was delivered to the fuel and the fusion reactions released 3.15 MJ. (a) Calculate the ratio of energy released to energy delivered. (b) A future experiment delivers 12.0 MJ to the fuel and achieves the same ratio. Calculate the energy released by fusion. (c) The ratio in (a) compares the fusion energy with the energy delivered to the fuel only. Suggest why this does not yet mean that a fusion power station could supply electricity to homes.

Question 8 Assume a household uses 2.0×10^{10} J of energy in a year. Calculate the mass of deuterium–tritium fuel that would supply this energy, and comment on your answer. Use 3.4×10^{14} J per kilogram.

Question 9 A student says: "One fission event releases more energy than one fusion event, so fission fuel must release more energy per kilogram." Use the energy-per-event and energy-per-kilogram figures from the theory table to show by calculation that the second statement does not follow from the first.

Question 10 A small town uses 2.0×10^{12} J of energy in a year. Burning $1\,\text{kg}$ of coal releases about 3.0×10^{7} J. (a) Calculate the mass of coal needed, in tonnes. (b) Calculate the mass of ^{235}U that would supply the same energy by complete fission. (c) Calculate the mass of deuterium–tritium fuel that would supply the same energy.

Question 11 The core of the Sun is at about $1.5 \times 10^{7}\,\text{K}$; the plasma in ITER is designed to reach about $1.5 \times 10^{8}\,\text{K}$. (a) Calculate how many times hotter than the Sun's core the ITER design temperature is. (b) Convert both temperatures to degrees Celsius, and comment on the size of the 273 offset at these temperatures.

Question 12 The ITER design goal is for the fusion reactions to release 10 times the energy supplied to heat the plasma. (a) In a test, the heating system supplies 2.5×10^{9} J. Calculate the fusion energy the design goal would predict. (b) In another test, 1.8×10^{9} J of heating energy results in 9.0×10^{9} J of fusion energy. Calculate how many times the heating energy this is.

Question 13 Explain why fission can be started at ordinary temperatures, while fusion requires tens of millions of kelvin. In your answer refer to the electric charge of the particle that starts each reaction.

Question 14 Explain why a drop in temperature, or a loss of confinement, stops a fusion reaction at once, while a fission chain reaction does not necessarily stop when its heating is removed.

Question 15 A media article claims that fusion machines "produce no radioactive waste at all". Evaluate this claim using the physics of this subtopic.

Question 16 Fusion is often proposed as the energy source of the future, while fission already supplies about 9% of the world's electricity. (a) Construct one argument, using physics from this subtopic, in favour of investing in fusion research. (b) Construct one argument, using physics from this subtopic, in favour of continuing to use fission now. (c) State one limitation of each argument.

Question 17 Use the forces in the nucleus (3A) to explain why energy must be supplied to start a fusion reaction, and use the conversion of mass (4A) to explain where the much larger released energy comes from.

Question 18 Tritium is almost absent in nature, yet fusion fuel supplies are considered very large. Explain why, referring to where deuterium is found and how tritium can be produced.

Question 19 A reactor core undergoes 2.5×10^{19} fissions each second, each releasing 3.2×10^{-11} J. Calculate the total energy released in one full day of operation.

Question 20 A news report states that ITER "will show that fusion can produce ten times more energy than is put in". (a) State precisely what "ten times more energy than is put in" refers to in the ITER design. (b) Explain why demonstrating this would not mean a fusion power station is ready to be built.

Question 21 The Sun cannot be switched off, but a fission reactor can be shut down by inserting control rods that absorb neutrons. Explain both facts in terms of the conditions each process needs to continue.

Answers

Question 1 (a) Fission: a heavy nucleus splits into two smaller nuclei; fusion: two light nuclei join to form one heavier nucleus. (b) Fission: a heavy nucleus absorbs a neutron; fusion: two light nuclei collide at enormous speed. (c) Fission: ^{235}U; fusion: deuterium and tritium. (d) Fission: fission fragments (and neutrons); fusion: helium (and neutrons). **Question 2** (a) About 11; (b) 1.5×10^{20} fissions per second. **Question 3** (a) 1.6×10^{14} J; (b) 0.48 kg; (c) about 4.1 times. **Question 4** (a) Both nuclei are positively charged, so they repel electrostatically; (b) a gas heated until electrons are stripped from the atoms, leaving bare nuclei and free electrons; (c) magnetic fields in a tokamak; laser beams squeezing a fuel pellet. **Question 5** (a) Helium; it is not radioactive; (b) neutrons released by fusion activate the reactor walls; (c) fusion waste is short- to medium-lived; fission waste includes fragments with long half-lives and remains hazardous far longer. **Question 6** (a) In stars, including the Sun; (b) fission releases neutrons that trigger further fissions (a chain reaction), while fusion releases nothing that triggers further fusion, so its conditions must be maintained continuously; (c) the National Ignition Facility released more energy from the fuel than the laser energy delivered to it (December 2022), or ITER is being built to release 10 times the heating energy. **Question 7** (a) 1.5; (b) 18.4 MJ; (c) the ratio does not include the energy needed to run the whole machine, and no fusion machine yet generates electricity continuously. **Question 8** 5.9×10^{-5} kg, about 0.06 g — a year's household energy from a fraction of a gram of fuel. **Question 9** Per event, fission releases $3.2 \times 10^{-11} / 2.8 \times 10^{-12} \approx 11$ times as much as fusion; per kilogram, fusion releases $3.4 \times 10^{14} / 8.2 \times 10^{13} \approx 4.1$ times as much as fission. The lighter fuel has many more nuclei per kilogram, so the per-kilogram comparison reverses. **Question 10** (a) About 67 tonnes; (b) 2.4×10^{-2} kg (24 g); (c) 5.9×10^{-3} kg (5.9 g). **Question 11** (a) 10; (b) about 1.5×10^{7} °C and about 1.5×10^{8} °C — at tens of millions of kelvin, the 273 offset is negligible. **Question 12** (a) 2.5×10^{10} J; (b) 5.0 times. **Question 13** Fission is started by a neutron, which has no electric charge and is not repelled by the nucleus, so even a slow neutron can be absorbed. Fusion needs two positive nuclei to get close together, and enormous speeds (tens of millions of kelvin) are needed to overcome their electrostatic repulsion. **Question 14** Fusion only continues while the fuel is kept hot and confined; if either is lost, the nuclei slow down or escape and the reaction stops. A fission chain reaction is self-sustaining: the neutrons released keep triggering further fissions without any heating, and it stops only when the neutrons are absorbed. **Question 15** The claim is exaggerated. The direct product, helium, is not radioactive and there are no long-lived fission fragments, but the neutrons released by fusion activate the reactor walls, producing short- to medium-lived radioactive waste. **Question 16** Model points in the solution; award the reasoning, not the conclusion. **Question 17** Energy must be supplied to push the positive nuclei together against their electrostatic repulsion, until the strong nuclear force can bind them. The released energy comes from the conversion of mass: the products have less total mass than the reactants. **Question 18** Deuterium occurs naturally in seawater, and tritium can be produced inside a fusion reactor from lithium, which is plentiful in the Earth's crust. **Question 19** 6.9×10^{13} J. **Question 20** (a) The fusion reactions would release 10 times the energy supplied to heat the plasma; (b) it is a research result about the plasma only — continuous operation, electricity generation and the engineering challenges remain unsolved. **Question 21** The Sun's own gravity maintains the temperature, density and confinement of its fuel indefinitely, so its fusion cannot be switched off. In a fission reactor the chain reaction needs free neutrons; control rods absorb the neutrons and the reaction stops.

Fully-worked solutions

Question 1 (a) Fission: a heavy nucleus splits into two smaller nuclei. Fusion: two light nuclei join to form one heavier nucleus. (b) Fission: a heavy nucleus absorbs a neutron. Fusion: two light nuclei collide at enormous speed (tens of millions of kelvin). (c) Fission: ^{235}U (a heavy nucleus). Fusion: deuterium and tritium (light hydrogen isotopes). (d) Fission: two fission fragments and neutrons. Fusion: helium and neutrons.

Question 2 Energy per fission $= 3.2 \times 10^{-11}$ J; energy per fusion $= 2.8 \times 10^{-12}$ J. (a) Number of fusion events $= \dfrac{3.2 \times 10^{-11}}{2.8 \times 10^{-12}} = 11.4$, so about **11** fusion events. (b) Number of fissions each second $= \dfrac{4.8 \times 10^{9}}{3.2 \times 10^{-11}} = 1.5 \times 10^{20}$.

Question 3 (a) $E = 2.0 \times 8.2 \times 10^{13} = 1.64 \times 10^{14}\,\text{J} \approx 1.6 \times 10^{14}$ J. (b) $m = \dfrac{1.64 \times 10^{14}}{3.4 \times 10^{14}} = 0.48$ kg. (c) $\dfrac{3.4 \times 10^{14}}{8.2 \times 10^{13}} = 4.1$, so about **4.1 times** as much.

Question 4 (a) Both nuclei are positively charged. Like charges repel, so the two nuclei repel each other electrostatically as they approach. (b) A **plasma** is a gas heated to such a high temperature that the electrons are stripped from the atoms, leaving a mixture of bare positive nuclei and free electrons. (c) 1. Magnetic fields in a doughnut-shaped machine (a tokamak) hold the plasma away from the walls. 2. Powerful laser beams squeeze and heat a tiny fuel pellet.

Question 5 (a) The main direct product of deuterium–tritium fusion is helium, which is stable and not radioactive. (b) The neutrons released by the fusion reactions are absorbed by the reactor walls and activate them — that is, they make the wall materials radioactive. (c) Fusion waste (the activated wall materials) is short- to medium-lived. Fission waste includes fission fragments with long half-lives, so it remains hazardous for far longer and must be stored behind shielding.

Question 6 (a) In stars, including the Sun. (b) Each fission releases neutrons that can split further nuclei, so once started the chain reaction sustains itself. Fusion releases nothing that triggers further fusion: each event consumes its two nuclei, so the fuel fuses only while the temperature and confinement are maintained by a continuous supply of energy. (c) In December 2022 the National Ignition Facility released $3.15\,\mathrm{MJ}$ from fusion after $2.05\,\mathrm{MJ}$ of laser energy was delivered to the fuel — the first time the fuel released more energy than was delivered to it. (Alternatively: ITER is under construction with the design goal of releasing 10 times the heating energy.)

Question 7 (a) Ratio $=\dfrac{3.15}{2.05}=1.5$ (to two significant figures). (b) Energy released $=12.0\times1.537=18.4\,\mathrm{MJ}$. (c) The ratio compares the fusion energy with the energy delivered to the fuel only. It does not include the energy needed to run the lasers or magnets and the rest of the machine, and no fusion machine yet operates continuously or generates electricity. A power station must produce more usable energy overall than it consumes.

Question 8 Energy per year $=2.0\times10^{10}\,\mathrm{J}$; energy per kilogram $=3.4\times10^{14}\,\mathrm{J}$.

$$m=\frac{2.0\times10^{10}}{3.4\times10^{14}}=5.9\times10^{-5}\,\mathrm{kg}.$$

This is about $0.06\,\mathrm{g}$ — a whole year of household energy from less than a tenth of a gram of fusion fuel, showing how energy-dense fusion fuel is.

Question 9 Per event:

$$\frac{\text{fission}}{\text{fusion}}=\frac{3.2\times10^{-11}}{2.8\times10^{-12}}\approx11,$$

so one fission event releases about 11 times as much energy as one fusion event — the student is right about this. Per kilogram:

$$\frac{\text{fusion}}{\text{fission}}=\frac{3.4\times10^{14}}{8.2\times10^{13}}\approx4.1,$$

so $1\,\mathrm{kg}$ of fusion fuel releases about 4 times as much energy as $1\,\mathrm{kg}$ of fission fuel. The second statement does not follow from the first because the fuels have very different nuclear masses: $1\,\mathrm{kg}$ of the lighter fusion fuel contains many more nuclei, so many more reactions are available per kilogram. The larger number of reactions per kilogram more than makes up for the smaller energy per event.

Question 10 Energy needed $=2.0\times10^{12}\,\mathrm{J}$. (a) $m=\dfrac{2.0\times10^{12}}{3.0\times10^{7}}=6.7\times10^{4}\,\mathrm{kg}$, about **67 tonnes** of coal. (b) $m=\dfrac{2.0\times10^{12}}{8.2\times10^{13}}=2.4\times10^{-2}\,\mathrm{kg}$, about **24 g** of ^{235}U. (c) $m=\dfrac{2.0\times10^{12}}{3.4\times10^{14}}=5.9\times10^{-3}\,\mathrm{kg}$, about **5.9 g** of fusion fuel.

Question 11 (a) $\dfrac{1.5\times10^{8}}{1.5\times10^{7}}=10$ times hotter. (b) $T(°\mathrm{C})=T(\mathrm{K})-273$. For the Sun's core: $1.5\times10^{7}-273=14\,999\,727\,°\mathrm{C}\approx1.5\times10^{7}\,°\mathrm{C}$. For ITER: $1.5\times10^{8}-273=149\,999\,727\,°\mathrm{C}\approx1.5\times10^{8}\,°\mathrm{C}$. At tens of millions of kelvin the offset of 273 is far smaller than the uncertainty in the values themselves, so the Celsius and kelvin figures are numerically the same to two significant figures.

Question 12 (a) Fusion energy $= 10 \times 2.5 \times 10^{9} = 2.5 \times 10^{10}$ J. (b) Ratio $= \dfrac{9.0 \times 10^{9}}{1.8 \times 10^{9}} = 5.0$ times the heating energy.

Question 13 Fission is started when a nucleus absorbs a neutron. The neutron has no electric charge, so it is not repelled by the positive nucleus and can be absorbed even when it is moving slowly — no high temperature is needed. Fusion needs two light nuclei, both positively charged, to come close enough for the strong nuclear force to bind them. Their electrostatic repulsion pushes them apart, so they must approach at enormous speeds, which means the fuel must be at tens of millions of kelvin.

Question 14 Fusion continues only while the fuel is hot enough and confined. If the temperature drops, the nuclei slow down and can no longer overcome their electrostatic repulsion; if the confinement fails, the plasma escapes and cools. Either way the reaction stops at once, because fusion releases nothing that keeps itself going. A fission chain reaction is different: each fission releases neutrons that trigger further fissions, so the reaction is self-sustaining and needs no heating at all. It stops only when the neutrons are removed, for example by absorbing them with control rods (4B).

Question 15 The claim is exaggerated. Points for a full evaluation: - True part: the direct product of deuterium–tritium fusion is helium, which is not radioactive, and fusion produces no long-lived fission fragments. - False part: the neutrons released by the fusion reactions are absorbed by the reactor walls and activate them, making the wall materials radioactive. - Conclusion: fusion machines do produce radioactive waste, but it is short- to medium-lived, and its long-term hazard is far lower than that of fission waste.

Question 16 Award the reasoning, not the conclusion reached. Model points: (a) For investing in fusion research: fusion fuel releases about 4 times as much energy per kilogram as fission fuel; its fuels (deuterium from seawater, lithium for making tritium) are very large in supply; it produces no long-lived radioactive waste; and it cannot run away, because the reaction stops at once if the conditions are lost. (b) For continuing with fission now: fission is a proven technology that already works at scale, supplying about 9% of the world's electricity through 441 reactors, while fusion still has unsolved engineering challenges and is not yet used to generate electricity at all; fission fuel is already millions of times more energy-dense than chemical fuels. (c) Limitations: the fusion argument assumes the unsolved engineering challenges will eventually be overcome, which is not guaranteed; the fission argument accepts long-lived radioactive waste and a finite fuel supply as the price of a technology that works today.

Question 17 To start fusion, the two positive nuclei must be pushed together against their electrostatic repulsion until they are within about 10^{-15} m, where the strong nuclear force can bind them. Overcoming the repulsion requires energy — supplied as the enormous kinetic energy of nuclei at tens of millions of kelvin. Once the nuclei fuse, the released energy comes from the conversion of mass (4A): the total mass of the products is slightly less than the total mass of the reactants, and the lost mass is converted into energy, far more than was needed to start the reaction.

Question 18 Deuterium occurs naturally in seawater, so the oceans hold a very large supply of it. Tritium is almost absent in nature, but it can be produced inside a fusion reactor from lithium, and lithium is plentiful in the Earth's crust. Because one half of the fuel pair comes from seawater and the other half can be made from a plentiful element, the overall fuel supply is considered very large.

Question 19 Energy per second:

$$2.5 \times 10^{19} \times 3.2 \times 10^{-11} = 8.0 \times 10^{8}\ \text{J per second}.$$

One day is $24 \times 60 \times 60 = 86\,400$ s, so the energy released in one day is

$$8.0 \times 10^{8} \times 86\,400 = 6.9 \times 10^{13}\ \text{J}.$$

Question 20 (a) It means the fusion reactions would release 10 times the energy supplied to heat the plasma — ITER's design goal of 500×10^{6} J of fusion energy each second from 50×10^{6} J per second of heating. (b) The ratio describes the plasma only. It does not include the energy needed to run the whole machine, the experiment does not operate continuously, and no fusion machine yet converts the released energy into electricity. The engineering challenges of a power station — continuous operation, extracting the heat, and generating electricity — remain unsolved, so a research result is not a ready power station.

Question 21 Fusion continues only while the fuel is hot, dense and confined. The Sun's own gravity supplies all three: it squeezes the core to enormous density and holds the fuel in place, and it cannot be switched off, so the Sun's fusion continues. In a fission reactor the chain reaction needs a supply of free neutrons to keep splitting nuclei. Inserting control rods absorbs the neutrons, so no neutrons remain to trigger further fissions and the reaction stops.

Theory

In 4A you saw that nuclear reactions release energy because a small amount of mass is converted into energy. In 4B you saw how a fission chain reaction can be controlled, and in 4C you compared fission with fusion. This subtopic applies those ideas to a real, ongoing national question: should nuclear fission supply some of Australia's energy? The study design asks you to *investigate the viability of nuclear energy as an energy source for Australia* — that is, to gather evidence, examine the arguments on each side, and reach a reasoned conclusion of your own. Fusion (4C) does not yet generate electricity commercially anywhere in the world, so this debate is about **fission**.

What *viable* means here. *Viability* is not a measurable quantity like mass or wavelength. It is a **contested term**: competing definitions exist, and the definition you choose changes the conclusion you reach. Someone who defines *viable* as "physically able to generate electricity" will answer yes immediately — fission reactors plainly work. Someone who defines it as "the cheapest way to generate electricity in Australia" will answer no. Neither is cheating; they are using different frames.

> The VCE Physics Study Design uses the term *viable* but does not define it. This subtopic therefore treats it as: **able to supply a significant share of Australia's electricity at an acceptable cost, within a reasonable time, with safety and environmental effects no worse than the alternatives it would replace.** Every question in this section is answerable on that definition alone. Other definitions exist and are not interchangeable with this one — if you use a different definition in your own investigation, state it.

A question like *"Is nuclear energy viable for Australia?"* also carries hidden assumptions: it assumes that a single yes-or-no answer makes sense, that "Australia" is the right frame (rather than one state, or the whole world), and that today's technologies, costs and laws are the ones to judge. Part of a good investigation is to surface those assumptions before answering.

From fission to the grid. In a nuclear power station, the fission of uranium-235 nuclei is sustained as a controlled chain reaction in a reactor core (4B). The energy released appears first as thermal energy of the fuel and the surrounding material. That heat is used to produce steam, which spins a turbine connected to an electrical generator, so the energy chain is *nuclear → thermal → kinetic → electrical*. This second half of the plant — steam, turbine, generator — is the same in a nuclear station as in a coal-fired one; the difference is what makes the heat. Like all thermal power stations, a nuclear station converts only about one third of the thermal energy into electrical energy; the rest is transferred to the surroundings as waste heat. The energy transfers and transformations of these conversion systems are treated in detail in 10D.

The energy in a kilogram of uranium. Each fission of a uranium-235 nucleus releases about $200\ \text{MeV}$, or 3.2×10^{-11} J. One kilogram of uranium-235 contains about 2.6×10^{24} atoms, so the complete fission of $1\ \text{kg}$ of uranium-235 releases

$$E \approx 8.2 \times 10^{13}\ \text{J}.$$

This enormous figure is the mass–energy conversion of 4A made concrete: about $0.1\ \%$ of the fuel's mass is converted into energy. By comparison, burning $1\ \text{kg}$ of coal releases of the order of 10^7 J. One kilogram of uranium-235 therefore holds as much energy as roughly **eight million kilograms of brown coal**. Power-station fuel is uranium that has been **enriched** — its fraction of uranium-235 raised from the $0.7\ \%$ found in natural uranium to about $3–5\ \%$ — yet even so, a single fuel pellet of a few grams holds as much energy as about a tonne of black coal.

Australia's nuclear situation today. No nuclear power station has ever operated in Australia. The country's only operating nuclear reactor is **OPAL**, a $20\ \text{MW}$ research reactor run by ANSTO at Lucas Heights in New South Wales. OPAL produces radioisotopes for medicine (3F), industry and research — not electricity.

Source: ANSTO, OPAL reactor, retrieved 2026-08-18.

Commonwealth law prohibits nuclear power stations: section 140A of the *Environment Protection and Biodiversity Conservation Act 1999* provides that the Minister must not approve the construction or operation of a nuclear power station in Australia. Victoria's *Nuclear Activities (Prohibitions) Act 1983* prohibits specified nuclear activities, including uranium mining and the construction of nuclear reactors, within the state, and other states have restrictions of their own. Radiation and nuclear safety in Australia are regulated by ARPANSA. A 2019 inquiry of the federal House of Representatives Standing Committee on the Environment and Energy recommended that the prohibition be lifted, but only for advanced reactor designs (Generation III+ and Generation IV, including small modular reactors), and only after a technology assessment and community consent; the report carried dissenting reports. As at 2026 the prohibition remains in force, and changing it would require an Act of Parliament.

Source: Australian Government, Environment Protection and Biodiversity Conservation Act 1999 (Cth) s 140A, retrieved 2026-08-18. Source: Parliament of Victoria, Nuclear Activities (Prohibitions) Act 1983 (Vic.), retrieved 2026-08-18. Source: ARPANSA, Regulation of nuclear and radiation safety, retrieved 2026-08-18. Source: House of Representatives Standing Committee on the Environment and Energy, Not without your approval: a way forward for nuclear technology in Australia, 2019, retrieved 2026-08-18.

Australia nonetheless holds the **world's largest identified uranium resources** — the Olympic Dam deposit in South Australia is the largest known uranium resource on Earth — and Australian mines produce uranium for export. None of it is burnt at home: Australia has never used uranium to generate electricity.

Source: Geoscience Australia, Australia's uranium resources, retrieved 2026-08-18. Source: World Nuclear Association, Nuclear power in Australia, retrieved 2026-08-18.

Australia's electricity, and why the question is asked. Australia generates about $260\,\mathrm{TW\,h}$ of electrical energy each year. In recent years a little under half has come from coal, more than a third from renewable sources (wind, solar and hydroelectricity) and most of the rest from gas. Electricity generation is Australia's largest single source of greenhouse gas emissions — about one third of the national total — and the *Climate Change Act 2022* commits Australia to reducing emissions to $43\,\%$ below 2005 levels by 2030 and to net zero by 2050. Any source that might supply a large share of Australia's electricity is therefore judged by its emissions, its cost, its reliability and the time it takes to build. Around the world, about 440 fission power reactors in roughly 32 countries supply about one tenth of the world's electricity, so the technology itself is mature and proven.

Source: Department of Climate Change, Energy, the Environment and Water, Australian Energy Statistics, retrieved 2026-08-18. Source: Department of Climate Change, Energy, the Environment and Water, Quarterly Update of Australia's National Greenhouse Gas Inventory, retrieved 2026-08-18. Source: Australian Government, Climate Change Act 2022 (Cth), retrieved 2026-08-18. Source: World Nuclear Association, Nuclear power in Australia, retrieved 2026-08-18.

The physical measures in the debate. Four physical ideas keep appearing in the evidence.

Power and capacity factor. Power is the rate of transfer of energy, measured in watts ($1\,\mathrm{W} = 1\,\mathrm{J\,s^{-1}}$); the power rating of a station is the maximum rate at which it can deliver electrical energy. The **capacity factor** of a station is the fraction of a year's energy it actually delivers compared with running at full power for the whole year. Nuclear stations in the best-performing fleets run with capacity factors above $90\,\%$: they generate close to full power almost continuously, regardless of weather or time of day, which makes them **dispatchable** — available on demand. Wind and solar stations have lower capacity factors (typically well under half) because they depend on the weather and the time of day.

Source: U.S. Energy Information Administration, nuclear capacity factors, retrieved 2026-08-18.

Build time. A nuclear power station typically takes of the order of a decade from decision to first electricity, and several recent constructions in Europe and the United States have finished years late and far over budget. A solar or wind farm of similar capacity takes far less time to build.

Source: World Nuclear Association, The Economics of Nuclear Power, retrieved 2026-08-24.

Cost. The CSIRO–AEMO GenCost studies, which compare the cost of building new electricity generation in Australia, have consistently estimated that new nuclear energy would cost more than new wind or solar generation together with the storage needed to make it dependable.

Source: CSIRO and AEMO, GenCost 2023-24, retrieved 2026-08-18.

Waste. The fission fragments produced in a reactor are unstable nuclei, so spent fuel is radioactive (Chapters 3A–3C). Some of the material decays with half-lives of decades; some remains hazardous for many thousands of years. High-level waste must therefore be isolated from the biosphere on geological timescales, and no country yet operates a permanent deep repository for power-reactor waste, though several are building them.

Source: Posiva Oy, ONKALO trial operations and STUK safety assessment, retrieved 2026-08-24.

The strongest case on each side. A fair investigation presents each position in the strongest form its own advocates would recognise, then tests both with the same tools.

The case for. Proponents argue that fission releases millions of times more energy per kilogram than any chemical fuel, so a station needs only tonnes of fuel per year, delivered by a handful of trucks. Its lifecycle greenhouse emissions — emissions counted over the whole fuel cycle, from mining and construction to operation and waste management — are low, comparable with wind and far below coal. It is dispatchable, with capacity factors above $90\,\%$, so it can supply power day and night and complement variable wind and solar. Australia holds the world's largest identified uranium resources, so the fuel is secure. Once built, a station operates for decades.

The case against. Opponents argue that new nuclear energy is the most expensive new generation option in Australian cost studies, and recent Western builds show a pattern of cost and time overruns. A decade or more of construction means the first electricity arrives too late to help meet the 2030 emissions target. The legal prohibitions, and the absence of any Australian nuclear power industry, workforce or waste repository, mean much of that decade would be spent before construction even begins. The waste remains hazardous for timescales far longer than any institution has existed. And because Australia has world-class wind and solar resources, a cheaper low-emissions pathway is available here that is not available in every country.

Notice that the two cases must be tested **symmetrically**. Each side is tempted to choose its own most favourable capacity factors, cost figures and build times. Whenever a number is used in your investigation, say what it measures, where it comes from and when it was retrieved.

Conducting your investigation. A strong response to *"Is nuclear energy viable for Australia?"* will: (1) define *viable* and state the frame being used; (2) surface the assumptions built into the question; (3) collect secondary data from named sources with retrieval dates; (4) compare nuclear with the actual alternatives — coal, gas, and renewables with storage — rather than with an idealised version of them; (5) test the strongest case on each side; and (6) acknowledge the limitations and uncertainties of the evidence before drawing a conclusion. Assessment rewards the quality of the reasoning, not the conclusion reached: a well-argued *yes* and a well-argued *no* can both be excellent responses. The risks and benefits of nuclear energy as a power source are examined further in 10D.

Worked examples

Example 1 — scaffolded

Fuel for a light-water power reactor is uranium enriched in uranium-235. Taking the energy released per fission of uranium-235 as $200\,\text{MeV}$, calculate the total energy released by the complete fission of $1.0\,\text{kg}$ of uranium-235.

Working	Comment
$E = 200 \times 10^{6} \times 1.602 \times 10^{-19} = 3.20 \times 10^{-11}$ J per fission.	Convert $200\,\text{MeV}$ to joules using $1\,\text{eV} = 1.602 \times 10^{-19}\,\text{J}$.
$N = \dfrac{6.022 \times 10^{23}}{0.235} = 2.56 \times 10^{24}$ atoms.	Number of uranium-235 atoms in $1.0\,\text{kg}$: Avogadro's number per $235\,\text{g}$, scaled to $1000\,\text{g}$.
$E_{\text{total}} = N \times 3.20 \times 10^{-11} = 2.56 \times 10^{24} \times 3.20 \times 10^{-11} = 8.$: .	Multiply the energy per fission by the number of atoms.

$\therefore$ the complete fission of $1.0\,\text{kg}$ of uranium-235 releases about $8.2 \times 10^{13}\,\text{J}$.

Example 2 — scaffolded

The Loy Yang power stations in Victoria's Latrobe Valley burn brown coal with a typical energy content of about $10\,\text{MJ kg}^{-1}$ (given). Calculate the mass of brown coal that must be burnt to release the same energy as the complete fission of $1.0\,\text{kg}$ of uranium-235 ($8.2\times10^{13}\,\text{J}$), and comment on the result.

Working	Comment
Energy per kilogram of brown coal $=10\times10^{6}\,\text{J}=1.0\times10^{7}\,\text{J kg}^{-1}$.	Convert MJ to J.
$m=\dfrac{8.2\times10^{13}}{1.0\times10^{7}}=8.2\times10^{6}\,\text{kg}$.	Divide the total energy required by the energy each kilogram of coal releases.
$m=8.2\times10^{3}\,\text{t}=8200\,\text{t}$.	$1\,\text{t}=1000\,\text{kg}$.

∴ about $8200\,\text{t}$ of brown coal — the load of more than eighty 100-tonne rail wagons — releases the same energy as $1.0\,\text{kg}$ of uranium-235. This is why a nuclear station needs only a small mass of fuel, while a brown-coal station of the same output consumes millions of tonnes each year.

Example 3 — unscaffolded

A proposed nuclear power station for Australia is rated at $1.0\,\text{GW}$ of electrical power — a little larger than the biggest generating units on Australia's current grid. Like all thermal stations, it converts about $33\,\%$ of its thermal energy into electrical energy. Calculate the mass of uranium-235 the station would fission in one year of continuous operation, and the mass of brown coal ($10\,\text{MJ kg}^{-1}$) a coal-fired station of the same electrical output and efficiency would burn in the same year.

The electrical energy delivered in one year is $E=Pt$, with $P=1.0\times10^{9}\,\text{W}$ and $t=365\times24\times3600=3.1536\times10^{7}\,\text{s}$. Since only $33\,\%$ of the thermal energy becomes electrical energy, the thermal energy needed is

$$E_{\text{thermal}}=\frac{Pt}{0.33}=\frac{1.0\times10^{9}\times3.1536\times10^{7}}{0.33}=9.6\times10^{16}\,\text{J}.$$

Using the energy released per kilogram of uranium-235 from Example 1,

$$m_{\text{U}}=\frac{9.6\times10^{16}}{8.2\times10^{13}}\approx1.2\times10^{3}\,\text{kg}.$$

For brown coal releasing $1.0\times10^{7}\,\text{J kg}^{-1}$,

$$m_{\text{coal}}=\frac{9.6\times10^{16}}{1.0\times10^{7}}=9.6\times10^{9}\,\text{kg}=9.6\,\text{million tonnes}.$$

∴ the nuclear station fissions about $1.2\,\text{t}$ of uranium-235 per year, while a brown-coal station of the same output burns about 9.6 million tonnes of coal — a ratio of almost eight million, exactly the energy-density ratio found in Example 2.

Example 4 — unscaffolded

Compare the annual carbon dioxide emissions of the $1.0\,\text{GW}$ station of Example 3 if it is (a) a brown-coal station emitting $1.1\,\text{t}$ of carbon dioxide per MW h generated (given), or (b) a nuclear station, using the lifecycle emission figure of $12\,\text{g}$ of carbon dioxide equivalent per kW h (an IPCC median covering mining, construction, fuel processing, operation and waste). Comment on the comparison.

The electrical energy delivered in one year is

$$E=Pt=1.0\times10^{6}\,\text{kW}\times8760\,\text{h}=8.76\times10^{9}\,\text{kW h}.$$

For the brown-coal station, at $1.1\,\text{t}$ per $\text{MW h}=1.1\,\text{kg}$ per kW h,

$$m_{CO_2} = 8.76 \times 10^9 \times 1.1 = 9.6 \times 10^9\,\text{kg} = 9.6\,\text{million tonnes}.$$

For the nuclear station, at $12\,\text{g} = 0.012\,\text{kg}$ per kW h,

$$m_{CO_2} = 8.76 \times 10^9 \times 0.012 = 1.1 \times 10^8\,\text{kg} \approx 0.11\,\text{million tonnes}.$$

∴ the coal station emits about 9.6 million tonnes of carbon dioxide each year, while the nuclear station's entire fuel cycle accounts for about 0.11 million tonnes — a ratio of about 90. The nuclear station emits no carbon dioxide from the reactor itself; its small lifecycle figure comes from mining, enrichment, construction and waste management, which is why the comparison is made on a lifecycle basis.

Source: IPCC, Fifth Assessment Report, Working Group III, Annex III, retrieved 2026-08-18.

Practice questions

Question 1 The energy released in a single fission of a uranium-235 nucleus is about $200\,\text{MeV}$. (a) Convert this energy to joules. (b) Calculate the number of uranium-235 atoms in $1.0\,\text{kg}$ of uranium-235. (The molar mass of uranium-235 is $235\,\text{g mol}^{-1}$ and Avogadro's number is $6.022 \times 10^{23}\,\text{mol}^{-1}$.) (c) Hence calculate the total energy released by the complete fission of $1.0\,\text{kg}$ of uranium-235.

Question 2 Brown coal from Victoria's Latrobe Valley has a typical energy content of about $10\,\text{MJ kg}^{-1}$ (given). (a) Calculate the mass of brown coal that must be burnt to release the same energy as the complete fission of $1.0\,\text{kg}$ of uranium-235 ($8.2 \times 10^{13}\,\text{J}$). (b) Comment on what your answer implies about the amount of fuel a nuclear power station needs compared with a brown-coal station of the same output.

Question 3 The kilowatt-hour is a unit of energy: $1\,\text{kW h} = 3.6 \times 10^6\,\text{J}$. Assume an Australian household uses $4500\,\text{kW h}$ of electrical energy per year. (a) Express $1\,\text{kW h}$ in joules. (b) Express the household's annual electrical energy use in joules. (c) Using the result of Question 1, calculate how many such households could be supplied for one year by the complete fission of $1.0\,\text{kg}$ of uranium-235, if the conversion of thermal energy to electrical energy is $33\,\%$ efficient.

Question 4 The study design asks you to investigate the *viability* of nuclear energy as an energy source for Australia, but does not define the word *viable*. (a) Identify what kind of term *viable* is, and explain why two students using different definitions of it could honestly reach opposite conclusions. (b) State the definition of *viable* used in this subtopic. (c) Identify one assumption built into the question *"Is nuclear energy viable for Australia?"*

Question 5 (a) Name Australia's only operating nuclear reactor, and state its location, its power rating and its purpose. (b) Identify the Commonwealth legislation that prohibits nuclear power stations in Australia, and state what it prohibits. (c) Australia exports uranium but generates no nuclear electricity. Explain why the existence of a large uranium mining industry does not, by itself, tell you whether nuclear electricity is viable in Australia.

Question 6 Some fission products in spent nuclear fuel have half-lives of decades. Consider caesium-137, with a half-life of 30 years. (a) Calculate the fraction of a sample of caesium-137 remaining after 10 half-lives. (b) Calculate the time this corresponds to for caesium-137. (c) Explain why some nuclear waste must still be isolated for thousands of years, even though ten half-lives reduces the activity of caesium-137 to less than one part in a thousand.

Question 7 A nuclear power station is rated at $1.0\,\text{GW}$ of electrical power and converts $33\,\%$ of its thermal energy into electrical energy. Take one year as $3.1536 \times 10^7\,\text{s}$ and the energy released per kilogram of uranium-235 as $8.2 \times 10^{13}\,\text{J kg}^{-1}$. (a) Calculate the thermal power of the reactor. (b) Calculate the thermal energy the reactor must produce in one year of continuous operation. (c) Calculate the mass of uranium-235 fissioned in that year. (d) Calculate the mass of brown coal ($10\,\text{MJ kg}^{-1}$) a coal-fired station of the same electrical output and efficiency would burn in the same year.

Question 8 The capacity factor of a power station is the fraction of a year's energy it actually delivers compared with running at full power for the whole year. (a) Calculate the electrical energy, in kW h, that a $1.0\,\text{GW}$ station would deliver in one year if it ran at full power the whole time. (b) Nuclear stations in the best-performing fleets achieve capacity factors above $90\,\%$. Calculate the energy actually delivered in one year at a capacity factor of $90\,\%$. (c) Estimate the number of households, each using $4500\,\mathrm{kW\ h}$ per year, that this energy could supply.

Question 9 The energy released in one fission of uranium-235 is $200\,\mathrm{MeV}$. (a) Use $E = \Delta m c^2$ to calculate the mass converted into energy in a single fission. (b) Express this mass in atomic mass units ($1\,\mathrm{u} = 1.66 \times 10^{-27}\,\mathrm{kg}$). (c) Calculate this mass as a fraction of the mass of a uranium-235 nucleus ($235\,\mathrm{u}$), and explain how the result connects with the energy release described in 4A.

Question 10 Natural uranium contains $0.7\,\%$ uranium-235. Assume that only the uranium-235 in natural uranium undergoes fission, and use $8.2 \times 10^{13}\,\mathrm{J}$ per kilogram of uranium-235. (a) Calculate the energy available from the complete fission of the uranium-235 contained in $1.0\,\mathrm{kg}$ of natural uranium. (b) Calculate the mass of natural uranium needed to supply the electrical energy used by one household in one year ($4500\,\mathrm{kW\ h}$), if the thermal-to-electrical conversion is $33\,\%$ efficient. (c) Uranium ore typically contains far less than $1\,\%$ uranium. Calculate the mass of ore graded $0.20\,\%$ uranium that must be processed to obtain the mass of natural uranium found in (b).

Question 11 A nuclear power station emits no carbon dioxide from its reactor, yet its lifecycle emissions are quoted as about $12\,\mathrm{g}$ of carbon dioxide equivalent per $\mathrm{kW\ h}$, while coal is quoted at about $820\,\mathrm{g}$ per $\mathrm{kW\ h}$. (a) Explain how a nuclear station can have lifecycle greenhouse emissions even though the fission reaction itself produces no carbon dioxide. (b) A media article claims that nuclear energy "produces zero greenhouse gases". Evaluate this claim using the figures given.

Question 12 A commentator argues: *"Australia has the world's largest identified uranium resources, so nuclear energy must be viable for Australia."* (a) Identify two assumptions built into this argument. (b) Explain why the size of Australia's uranium resources does not, by itself, determine whether nuclear energy is viable. (c) Apply a substitution test: would the same reasoning show that solar energy is viable for Australia because Australia has abundant sunshine? What does your answer reveal about the argument?

Question 13 Take the $1.0\,\mathrm{GW}$ station of Question 7 running at full power for one year, delivering $8.76 \times 10^{9}\,\mathrm{kW\ h}$. (a) Calculate the annual carbon dioxide emissions if the station is brown-coal fired, emitting $1.1\,\mathrm{t}$ of carbon dioxide per $\mathrm{MW\ h}$. (b) Calculate the annual lifecycle carbon dioxide emissions if the station is nuclear, at $12\,\mathrm{g}$ of carbon dioxide equivalent per $\mathrm{kW\ h}$. (c) Compare the two results as a ratio, and state which measure of the two stations this comparison is really testing.

Question 14 Nuclear stations are described as **dispatchable**; wind and solar stations are described as **variable**. (a) Explain the physical difference between a dispatchable source and a variable source. (b) State one advantage that nuclear energy's dispatchability gives an electricity grid. (c) State one advantage that wind and solar generation have over nuclear energy in the Australian context. (This section tests both sides by the same standard — give each a genuine strength.)

Question 15 Australia's legislated emissions target is a $43\,\%$ reduction on 2005 levels by 2030. A nuclear power station typically takes of the order of a decade from decision to first electricity. (a) Explain why the construction time of a generating technology matters for cumulative greenhouse emissions, not only for the date the station starts. (b) Give one counter-argument that uses the operating lifetime of a nuclear station (several decades) to answer part (a).

Question 16 Spent nuclear fuel contains fission fragments that are unstable nuclei. (a) Explain, with reference to the ideas of Chapter 3, why the fission fragments of uranium-235 are radioactive. (b) A proposal claims that spent fuel can simply "be stored until it is safe". Explain why this claim is incomplete unless it states a timescale, and how half-lives set that timescale. (c) Evaluate the claim: *"Storing spent fuel for 100 years makes it harmless."*

Question 17 A typical reactor fuel pellet contains $7.0\,\mathrm{g}$ of uranium enriched to $4.0\,\%$ uranium-235. (a) Calculate the energy released by the complete fission of the uranium-235 in one pellet. (b) Calculate the mass of black coal (energy content $25\,\mathrm{MJ\ kg^{-1}}$) that releases the same energy. (c) Comment on the result in one sentence.

Question 18 Using the evidence and arguments of this section, write a reasoned response to the statement: *"Nuclear energy is a viable energy source for Australia."* Take a position — for, against, or conditional — and support it. Your response should define *viable* in the sense you are using, use at least three quantitative pieces of evidence from this section, address the strongest argument on the other side, and acknowledge at least one limitation of your evidence.

Answers

Question 1 (a) 3.2×10^{-11} J; (b) 2.56×10^{24} atoms; (c) 8.2×10^{13} J. **Question 2** (a) 8.2×10^{6} kg (8200 t); (b) see solution — the fuel mass for a nuclear station is millions of times smaller. **Question 3** (a) 3.6×10^{6} J; (b) 1.62×10^{10} J; (c) about 1700 households. **Question 4** (a) a contested term — the definition chosen changes the conclusion; (b) able to supply a significant share of Australia's electricity at an acceptable cost, within a reasonable time, with safety and environmental effects no worse than the alternatives; (c) e.g. that a single yes-or-no answer exists. **Question 5** (a) OPAL, Lucas Heights (NSW), 20 MW, radioisotope production for medicine, industry and research; (b) *Environment Protection and Biodiversity Conservation Act 1999* s 140A — the Minister must not approve the construction or operation of a nuclear power station; (c) see solution — resources and viability are different questions. **Question 6** (a) $1/1024\approx0.098\,\%$; (b) 300 years; (c) see solution — other isotopes have far longer half-lives. **Question 7** (a) 3.0 GW; (b) 9.6×10^{16} J; (c) 1.2×10^{3} kg; (d) 9.6×10^{9} kg. **Question 8** (a) 8.76×10^{9} kW h; (b) 7.9×10^{9} kW h; (c) about 1.8 million households. **Question 9** (a) 3.6×10^{-28} kg; (b) 0.21 u; (c) about 0.09 % — the 0.1 % mass conversion of 4A. **Question 10** (a) 5.7×10^{11} J; (b) 0.085 kg (85 g); (c) 43 kg. **Question 11** (a) mining, enrichment, construction, transport and waste management all emit greenhouse gases; (b) see solution — the claim is not supported: 12 g per kW h is low, not zero. **Question 12** (a) e.g. that fuel availability alone determines viability, and that exporting raw uranium is equivalent to using it domestically; (b) cost, build time, law, waste and grid effects all matter too; (c) see solution — the substitution shows the argument form is too weak. **Question 13** (a) 9.6×10^{6} t; (b) 1.1×10^{5} t; (c) ratio about 90 — lifecycle greenhouse emissions. **Question 14** (a) dispatchable sources can deliver power on demand; variable sources depend on the weather and time of day; (b) supplies power continuously and on demand; (c) lower cost and far shorter build time in Australia. **Question 15** (a) while the station is being built, existing (higher-emitting) stations keep supplying, so emissions accumulate; (b) a nuclear station then operates for decades at low emissions, so the lifetime benefit can outweigh the slow start. **Question 16** (a) fission fragments are neutron-rich unstable nuclei that decay by emitting radiation; (b) "safe" depends on the half-lives of every isotope present; (c) false for long-lived isotopes — 100 years is far less than one half-life for some of them. **Question 17** (a) 2.3×10^{10} J; (b) 920 kg; (c) one pellet of uranium holds about the same energy as a tonne of black coal. **Question 18** Rubric-style model answer in the fully-worked solutions.

Fully-worked solutions

Question 1 (a) $200\text{ MeV}=200\times10^{6}\text{ eV}$, and $1\text{ eV}=1.602\times10^{-19}\text{ J}$, so

$$E=200\times10^{6}\times1.602\times10^{-19}=3.20\times10^{-11}\text{ J}.$$

(b) $1.0\text{ kg}=1000\text{ g}$ of uranium-235, of molar mass 235 g mol^{-1}:

$$N=\frac{1000}{235}\times6.022\times10^{23}=2.56\times10^{24}\text{ atoms}.$$

(c) $E_{\text{total}}=N\,E=2.56\times10^{24}\times3.20\times10^{-11}=8.2\times10^{13}\text{ J}$.

Question 2 (a) The energy per kilogram of brown coal is $1.0\times10^{7}\text{ J kg}^{-1}$, so

$$m=\frac{8.2\times10^{13}}{1.0\times10^{7}}=8.2\times10^{6}\text{ kg}=8200\text{ t}.$$

(b) The fission of one kilogram of uranium-235 releases the same energy as burning about 8200 tonnes of brown coal. A nuclear station therefore needs only tonnes of fuel per year — arriving in a few trucks — while a brown-coal station of the same output burns millions of tonnes a year, delivered continuously by train. The energy density of the fuel is one of the strongest physical arguments in favour of nuclear energy.

Question 3 (a) $1\text{ kW h}=3.6\times10^{6}\text{ J}$. (b) $E=4500\times3.6\times10^{6}=1.62\times10^{10}\text{ J}$. (c) Useful electrical energy from 1.0 kg of uranium-235 at 33 % efficiency:

$$E_{\text{useful}} = 0.33 \times 8.2 \times 10^{13} = 2.7 \times 10^{13}\,\text{J}\,.$$

Number of households:

$$n = \frac{2.7 \times 10^{13}}{1.62 \times 10^{10}} \approx 1700\,.$$

About 1700 households could be supplied for a year by the fission of one kilogram of uranium-235.

Question 4 A full response should: (a) Identify *viable* as a **contested term**: competing definitions exist, and the choice of definition changes the conclusion. For example, defining *viable* as "physically able to generate electricity" yields an immediate yes, while defining it as "the cheapest new generation in Australia" yields a no — both students can reason perfectly and disagree, because they are answering different questions. (b) State the frame used here: able to supply a significant share of Australia's electricity at an acceptable cost, within a reasonable time, with safety and environmental effects no worse than the alternatives it would replace. (c) Any one, clearly stated: that a single yes-or-no answer makes sense; that "Australia" (rather than one state, or the world) is the right frame; that present technologies, costs and laws are the ones to judge; that "energy source" means electricity rather than transport fuel.

Question 5 A full response should: (a) Name **OPAL**, the 20 MW research reactor operated by ANSTO at Lucas Heights in New South Wales. Its purpose is producing radioisotopes for medicine (3F), industry and research — it does not generate electricity for the grid. (b) Name section 140A of the *Environment Protection and Biodiversity Conservation Act 1999*, which provides that the Minister must not approve the construction or operation of a nuclear power station in Australia. (c) Distinguish the two questions. Uranium resources are a fact about what is in the ground; viability is a judgement about cost, construction time, law, waste, safety and the alternatives available for generating electricity. Australia has exported uranium for decades without building a power station, which shows directly that having the fuel does not settle the question.

Question 6 (a) After 10 half-lives the fraction remaining is

$$\left(\frac{1}{2}\right)^{10} = \frac{1}{1024} \approx 0.098\,\%\,.$$

(b) For caesium-137, $10 \times 30 = 300$ years. (c) Spent fuel is a mixture of many isotopes. Caesium-137 is only one of them; other fission products and the heavier nuclei formed in a reactor have half-lives of thousands of years or more. Ten half-lives of caesium-137 is 300 years, but for an isotope with a half-life of 24 000 years, ten half-lives is 240 000 years. The storage time must be set by the longest-lived significant isotopes present, not by the fastest-decaying ones.

Question 7 (a) At 33 % efficiency, electrical power = 0.33 × thermal power, so

$$P_{\text{thermal}} = \frac{1.0 \times 10^{9}}{0.33} = 3.0 \times 10^{9}\,\text{W} = 3.0\,\text{GW}\,.$$

(b) $E_{\text{thermal}} = P_{\text{thermal}}\, t = 3.03 \times 10^{9} \times 3.1536 \times 10^{7} = 9.6 \times 10^{16}\,\text{J}$. (c) $m_{\text{U}} = \dfrac{9.6 \times 10^{16}}{8.2 \times 10^{13}} \approx 1.2 \times 10^{3}\,\text{kg}$ — about 1.2 t per year. (d) $m_{\text{coal}} = \dfrac{9.6 \times 10^{16}}{1.0 \times 10^{7}} = 9.6 \times 10^{9}\,\text{kg}$ — about 9.6 million tonnes per year.

Question 8 (a) Running at full power for one year:

$$E = P\,t = 1.0 \times 10^{6}\,\text{kW} \times 8760\,\text{h} = 8.76 \times 10^{9}\,\text{kW h}\,.$$

(b) At a capacity factor of 90 %:

$$E = 0.90 \times 8.76 \times 10^{9} = 7.9 \times 10^{9}\,\text{kW h}\,.$$

(c) $n = \dfrac{7.9 \times 10^{9}}{4500} \approx 1.8 \times 10^{6}$ — about 1.8 million households.

Question 9 (a) $\Delta m = \frac{E}{c^2} = \frac{200 \times 10^6 \times 1.602 \times 10^{-19}}{(2.998 \times 10^8)^2} = 3.6 \times 10^{-28}\,\mathrm{kg}$. (b) In atomic mass units, carrying the unrounded mass from (a): $\frac{3.57 \times 10^{-28}}{1.66 \times 10^{-27}} = 0.21\,\mathrm{u}$. (c) As a fraction of the nucleus: $\frac{0.21}{235} \approx 9 \times 10^{-4}$, about $0.09\,\%$. This is the $0.1\,\%$ mass conversion described qualitatively in 4A: in fission, roughly one part in a thousand of the nucleus's mass is converted into energy, and it is this small fraction, multiplied by c^2, that makes the energy release per fission so large.

Question 10 (a) Only $0.7\,\%$ of natural uranium is uranium-235, so the energy available per kilogram of natural uranium is

$$E = 0.007 \times 8.2 \times 10^{13} = 5.7 \times 10^{11}\,\mathrm{J}.$$

(b) The household's electrical energy is $4500 \times 3.6 \times 10^6 = 1.62 \times 10^{10}\,\mathrm{J}$; at $33\,\%$ efficiency the thermal energy needed is

$$E_{\text{thermal}} = \frac{1.62 \times 10^{10}}{0.33} = 4.91 \times 10^{10}\,\mathrm{J},$$

requiring

$$m = \frac{4.91 \times 10^{10}}{5.74 \times 10^{11}} = 0.085\,\mathrm{kg}$$

of natural uranium — about $85\,\mathrm{g}$ per household per year. (c) At an ore grade of $0.20\,\%$, the ore mass is

$$m_{\text{ore}} = \frac{0.085}{0.0020} \approx 43\,\mathrm{kg}.$$

Even allowing for enrichment and ore grade, the mass of material handled is tiny compared with the millions of tonnes of coal supplying the same energy.

Question 11 A full response should: (a) Explain that the fission reaction itself produces no carbon dioxide, but the fuel cycle around it does: mining and milling uranium ore, converting and enriching it, building the station (concrete and steel), transporting fuel and waste, and eventually decommissioning the station all involve energy that, in practice, partly comes from fossil fuels. Adding these stages gives the lifecycle figure of about $12\,\mathrm{g}$ per $\mathrm{kW\,h}$. (b) Evaluate the claim against the data: "zero" is not supported. The correct statement is that nuclear energy's lifecycle emissions are very low — about $12\,\mathrm{g}$ per $\mathrm{kW\,h}$ compared with about $820\,\mathrm{g}$ per $\mathrm{kW\,h}$ for coal, roughly 70 times lower. The claim is wrong in fact but right in direction; a careful investigation reports the figure and its basis rather than the slogan.

Question 12 A full response should: (a) Identify at least two assumptions, for example: that the availability of a fuel resource alone determines the viability of the technology that uses it; that uranium in the ground is equivalent to uranium available cheaply for domestic use (much of it is exported); that no other factors — cost, construction time, law, waste, public acceptance, alternatives — need to be considered. (b) Explain that the size of the resource addresses only one factor in the definition of *viable* used here (fuel security). The other factors — the cost of building stations in Australia, the decade-long construction time, the present legal prohibitions, the absence of a waste repository, and the cost of the renewable alternatives — are not settled by how much uranium exists. A country could hold the world's largest uranium resources and still find nuclear energy unviable, just as a country can have abundant coal and choose not to burn it. (c) Substitute: *"Australia has abundant sunshine, so solar energy must be viable for Australia."* The substituted argument sounds plausible but proves too much — abundant sunshine does not by itself settle the cost of storage, grid design or manufacturing either. The substitution shows that the original argument's form (abundant resource $\Rightarrow$ viable technology) is too weak: resource abundance is relevant evidence but never sufficient on its own.

Question 13 (a) $8.76 \times 10^9\,\mathrm{kW\,h} = 8.76 \times 10^6\,\mathrm{MW\,h}$. At $1.1\,\mathrm{t}$ per $\mathrm{MW\,h}$,

$$m_{CO_2} = 8.76 \times 10^6 \times 1.1 = 9.6 \times 10^6\,\mathrm{t}.$$

(b) At $12\,g = 1.2 \times 10^{-5}\,t$ per kW h,

$$m_{CO_2} = 8.76 \times 10^9 \times 1.2 \times 10^{-5} = 1.1 \times 10^5\,t.$$

(c) The ratio is $\frac{9.6 \times 10^6}{1.1 \times 10^5} \approx 90$: the coal station emits about 90 times more carbon dioxide per year. The comparison is a test of the two stations' **lifecycle greenhouse emissions**, not of their power output (which is the same) or of direct smokestack emissions alone (the nuclear station has none).

Question 14 A full response should: (a) Explain that a **dispatchable** source can be turned up or down, and called on, whenever the grid needs it, because its fuel supply is under human control. A **variable** source depends on conditions humans do not control — the wind and the sunlight — so its output changes with the weather and the time of day and cannot be guaranteed at any particular moment. (b) Any one genuine advantage: nuclear output is available at night and during calm weather; capacity factors above 90 % mean one station supplies close to its full rating continuously, which helps balance the grid when wind and solar output falls. (c) Any one genuine advantage for wind and solar in Australia: lower estimated cost in Australian studies (GenCost); far shorter construction time; no long-lived radioactive waste; Australia's world-class sun and wind make the resource exceptional here. (Both sides earn their mark with a real strength — not a straw man.)

Question 15 A full response should: (a) Explain that emissions accumulate over time. During the decade a nuclear station is being planned and built, the electricity still has to come from existing stations, which in Australia are mostly coal- and gas-fired. A technology that takes longer to build therefore allows more emissions to accumulate before it can displace any fossil generation — what matters for the atmosphere is the total (cumulative) emissions over the period, not only the rate once the new station finally runs. (b) Give a genuine counter-argument: a nuclear station then operates for several decades at very low lifecycle emissions. Over a 60-year lifetime, the emissions avoided can be far larger than the extra emissions accumulated during the slow construction, so a slow start is not decisive if the station runs long enough. The strength of this counter-argument depends on the actual lifetime and on what the station displaces.

Question 16 A full response should: (a) Explain that the fission fragments are neutron-rich, unstable nuclei (3A): they lie away from the region of nuclear stability and reach it by radioactive decay — mostly β^- decay with accompanying γ radiation (3B). It is this decay of unstable nuclei that makes spent fuel radioactive. (b) Explain that "until it is safe" has no meaning without a timescale, because different isotopes decay at different rates. The half-life sets the timescale: after each half-life the amount of a given isotope halves, and after about ten half-lives less than one part in a thousand remains (3C). A safe-storage period must therefore be matched to the half-lives of the isotopes actually present. (c) Evaluate: the claim is false as stated. For caesium-137 (30-year half-life), 100 years is a little over three half-lives, leaving about one tenth of the original amount — not harmless — and for isotopes with half-lives of thousands of years, 100 years is far less than one half-life, so almost all of them remain. The claim would be true only for specific short-lived isotopes, which is why the timescale must be stated isotope by isotope.

Question 17 (a) Mass of uranium-235 in the pellet: $0.040 \times 7.0 = 0.28\,g = 2.8 \times 10^{-4}\,kg$.

$$E = 2.8 \times 10^{-4} \times 8.2 \times 10^{13} = 2.3 \times 10^{10}\,J.$$

(b) At $25\,MJ\,kg^{-1}$, the equivalent mass of black coal is

$$m = \frac{2.3 \times 10^{10}}{2.5 \times 10^7} = 9.2 \times 10^2\,kg.$$

(c) One small fuel pellet — a few grams of uranium — holds about the same energy as a tonne of black coal, which is the energy-density argument of this subtopic in a single object.

Question 18 This is a reasoning task. Marks are awarded for the quality of the reasoning, not the conclusion reached; a well-argued *for*, *against* or *conditional* position can all be excellent. A rubric-style model response (here arguing *against*, to show the form — the same structure serves the opposite conclusion):

Define the term and the frame. “I use *viable* to mean: able to supply a significant share of Australia’s electricity at an acceptable cost, within a reasonable time, with safety and environmental effects no worse than the alternatives.”

Evidence for the strongest case on the chosen side. “The case against rests on cost, time and the available alternatives. Australian cost studies (GenCost) consistently estimate new nuclear as the most expensive new generation option. Construction typically takes of the order of a decade, too late to contribute meaningfully to the 2030 target, and Commonwealth law (EPBC Act s 140A) currently prohibits nuclear power stations, so much of that decade would be spent changing law and building regulation, workforce and industry from nothing. Meanwhile Australia already generates more than a third of its electricity from renewables, and the physics of the fuel cycle shows the comparison is not about energy density — one kilogram of uranium-235 releases 8.2×10^{13} J, about eight million times the energy of a kilogram of brown coal — which is a strength nuclear energy does not need debated.”

Address the strongest argument on the other side. “The strongest argument for nuclear is its low lifecycle emissions ($12\,\mathrm{g}$ per $\mathrm{kW\,h}$ versus about $820\,\mathrm{g}$ for coal) combined with dispatchability and capacity factors above $90\,\%$. That argument is genuine, but it establishes only that nuclear is a low-emissions source — not that it is the cheapest or fastest low-emissions source available in Australia, where wind and solar resources are world-class.”

Acknowledge limitations. “My conclusion depends on cost estimates that change with time and method, on build-time figures taken largely from overseas experience, and on the present legal position, which Parliament could change. If construction costs fell sharply, or if storage for renewables proved far more expensive than current studies estimate, the balance could shift.”

Conclusion. “On the definition stated, and the evidence above, I judge nuclear energy not currently viable for Australia — not because the physics fails (it does not), but because cost, time, law and the available alternatives weigh against it.”

A response arguing *for* should use the same structure and the same quantitative evidence — energy density, lifecycle emissions, dispatchability, fuel security from the world’s largest identified uranium resources — while honestly addressing cost, construction time, waste and the legal prohibitions as the strongest counterpoints.

Topic 2 Test A — Radiation from the nucleus and nuclear energy (multiple choice)

Time allowed: 25 minutes · 20 marks · One scientific calculator permitted · The formula sheet may be used. Marks and timings are house conventions for school-based assessment.

Choose the response that is correct or that best answers the question. A correct answer scores 1 mark; an incorrect answer scores 0. Marks are not deducted for incorrect answers. No marks are given if more than one answer is completed for any question. The constant $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$ *is provided on the formula sheet.*

Question 1

Which one of the following statements about the strong nuclear force in a nucleus is correct?

A. It acts only between protons and neutrons, but not between two protons.

B. It is stronger than the electrostatic force at every distance.

C. It is attractive between all pairs of nucleons, but acts only over distances of about 1–3 fm.

D. It is the force responsible for changing a neutron into a proton in β^- decay.

Question 2

The number of neutrons in a nucleus of $^{235}_{92}U$ is

A. 92

B. 143

C. 235

D. 327

Question 3

Which one of the following lists α, β and γ radiation in order of increasing penetrating power?

A. γ, β, α

B. α, β, γ

C. β, α, γ

D. α, γ, β

Question 4

Plutonium-238 decays by emitting an alpha particle:

$^{238}_{94}Pu \rightarrow X + ^{4}_{2}He$

The daughter nucleus X is

A. $^{234}_{90}Th$

B. $^{242}_{96}Cm$

C. $^{238}_{92}U$

D. $^{234}_{92}U$

Question 5

During β^- decay, one neutron in a nucleus changes into a proton. Compared with the original nucleus, the daughter nucleus has

A. the same mass number and a proton number larger by 1.

B. a mass number smaller by 1 and the same proton number.

C. the same mass number and a proton number smaller by 1.

D. a mass number smaller by 4 and a proton number smaller by 2.

Question 6

A nucleus with mass number A and proton number Z is in an excited state. It emits a gamma ray as it returns to a lower-energy state. After the emission, the nucleus has

A. a mass number of $A - 4$ and a proton number of $Z - 2$.

B. the same mass number and a proton number of $Z + 1$.

C. the same mass number and the same proton number.

D. the same mass number and a proton number of $Z - 1$.

Question 7

A radioactive source has an activity of $960\,\mathrm{Bq}$ and a half-life of 15 minutes. The activity of the source after 45 minutes is closest to

A. $120\,\mathrm{Bq}$

B. $320\,\mathrm{Bq}$

C. $240\,\mathrm{Bq}$

D. $0\,\mathrm{Bq}$

Question 8

Which one of the following statements about radioactive decay is correct?

A. Heating a radioactive sample increases its rate of decay.

B. After two half-lives, all of the sample has decayed.

C. The half-life of a sample depends on the amount of the sample present.

D. The exact time at which any particular nucleus will decay cannot be predicted.

Question 9

On a decay series diagram, with proton number Z on the horizontal axis and nucleon number A on the vertical axis, a nucleus moves to a position 4 units lower and 2 units to the left. This step represents

A. α decay.

B. β^- decay.

C. β^+ decay.

D. γ decay.

Question 10

A $0.30\,\text{kg}$ region of tissue absorbs $1.5\times10^{-3}\,\text{J}$ of radiation energy. The absorbed dose is

A. $2.0\times10^{2}\,\text{Gy}$

B. $4.5\times10^{-4}\,\text{Gy}$

C. $5.0\times10^{-3}\,\text{Gy}$

D. $5.0\times10^{-3}\,\text{Sv}$

Question 11

A worker's tissue receives an absorbed dose of $2.0\,\text{mGy}$ from alpha radiation. For alpha radiation, $w_R=20$. The equivalent dose is

A. $0.10\,\text{mSv}$

B. $40\,\text{mSv}$

C. $2.0\,\text{mSv}$

D. $40\,\text{mGy}$

Question 12

A radiotherapist is selecting an isotope to seal inside a source and implant in a patient. The source should deliver its dose over several days. Which one of the following half-lives would be most suitable?

A. about 6 hours

B. about 6 days

C. about 5 years

D. about 5000 years

Question 13

If $2.0\times10^{-3}\,\text{kg}$ of mass were completely converted into energy, the energy released would be closest to

A. $6.0\times10^{5}\,\text{J}$

B. $1.8\times10^{17}\,\text{J}$

C. $2.2\times10^{-20}\,\text{J}$

D. $1.8\times10^{14}\,\text{J}$

Question 14

The binding energy per nucleon is greatest for nuclei near

A. hydrogen-2.

B. uranium-235.

C. iron-56.

D. helium-4.

Question 15

Each fission of a uranium-235 nucleus releases about 3.2×10^{-11} J. The number of fissions needed to release 1.0 J of energy is closest to

A. 3×10^{-11}

B. 3×10^{10}

C. 200

D. 6×10^{23}

Question 16

In a nuclear reactor, the purpose of the moderator is to

A. absorb neutrons so that the chain reaction can be controlled.

B. slow neutrons so that they are more likely to cause fission.

C. remove heat from the core in order to produce electricity.

D. convert uranium-238 into plutonium-239.

Question 17

A chain reaction in which, on average, exactly one neutron from each fission goes on to cause a further fission is described as

A. subcritical.

B. supercritical.

C. critical.

D. runaway.

Question 18

Which one of the following statements is correct?

A. Fusion joins light nuclei together; fission splits heavy nuclei apart.

B. Fusion splits heavy nuclei apart; fission joins light nuclei together.

C. Both fusion and fission require temperatures of millions of degrees to begin.

D. Fusion releases energy because the total mass of the products is greater than the total mass of the reactants.

Question 19

Which one of the following statements about nuclear energy in Australia is correct?

A. About one tenth of Australia's electricity is generated by nuclear fission.

B. The OPAL reactor at Lucas Heights supplies electricity to the Sydney grid.

C. Nuclear power stations are permitted in every Australian state.

D. Australia has no operating nuclear power stations.

Question 20

The critical mass of a fissile material is the minimum amount needed to

A. start a fusion reaction.

B. absorb all of the neutrons released.

C. sustain a chain reaction.

D. melt the fuel at operating temperature.

End of Topic 2 Test A

Topic 2 Test A — solutions

Question	Answer	Question	Answer
1	C	11	B
2	B	12	B
3	B	13	D
4	D	14	C
5	A	15	B
6	C	16	B
7	A	17	C
8	D	18	A
9	A	19	D
10	C	20	C

Question 1 — C. The strong nuclear force is attractive between all pairs of nucleons (proton–proton, neutron–neutron and proton–neutron) but has a very short range, about 1–3 fm; within that range it is far stronger than the electrostatic repulsion. **A** wrongly limits it to proton–neutron pairs; **B** is false because the strong force falls away rapidly beyond a few fm while the electrostatic repulsion is long-range (which is why very large nuclei can be unstable); **D** describes the weak force.

Question 2 — B. $N = A - Z = 235 - 92 = 143$. **A** gives the proton number; **C** the nucleon number; **D** adds $A + Z$.

Question 3 — B. α radiation is stopped by paper or the outer layer of skin, β by a few millimetres of aluminium, while γ is only reduced by thick lead or concrete: penetrating power increases $\alpha < \beta < \gamma$. **A** reverses the order; **C** and **D** misplace γ.

Question 4 — D. Conserve nucleon number: $238 = A + 4$, so $A = 234$; conserve proton number: $94 = Z + 2$, so $Z = 92$, uranium. **A** has the right mass number but subtracts 4 from the proton number (90 is thorium); **B** adds the alpha particle instead of removing it; **C** keeps the mass number at 238.

Question 5 — A. A neutron changes into a proton: the number of nucleons is unchanged (same mass number) while the proton number rises by 1. **B** describes a neutron leaving the nucleus; **C** describes β^+ decay; **D** describes α decay.

Question 6 — C. Gamma emission is the release of energy by an excited nucleus; no nucleon is lost or transformed, so both A and Z are unchanged. **A** describes α decay; **B** β^- decay; **D** β^+ decay.

Question 7 — A. 45 minutes is 3 half-lives: $960 \rightarrow 480 \rightarrow 240 \rightarrow 120\,\text{Bq}$. **B** treats the decay as linear (dividing by 3); **C** stops after only 2 half-lives; **D** assumes the sample is completely gone after a few half-lives.

Question 8 — D. Decay is random for a single nucleus — only the probability of decay in a given interval is fixed, so the exact moment cannot be predicted. **A** is false (ordinary heating does not change nuclear decay rates); **B** is false (a quarter of the sample remains after two half-lives); **C** is false (the half-life is a property of the nuclide and does not depend on the sample size).

Question 9 — A. Moving 4 units lower (A down by 4) and 2 units to the left (Z down by 2) matches the emission of an alpha particle, ${}^4_2\text{He}$. A β^- step is a short horizontal step to the right at the same height; β^+ is a short step to the left; γ produces no movement at all.

Question 10 — C. $D = \frac{E}{m} = \frac{1.5 \times 10^{-3}}{0.30} = 5.0 \times 10^{-3}\,\text{Gy}$. **A** inverts the ratio ($m / E = 200$); **B** multiplies E by m; **D** has the right number but the wrong unit — the sievert is the unit of equivalent dose, which also needs w_R.

Question 11 — B. $H = w_R \times D = 20 \times 2.0\,\text{mGy} = 40\,\text{mSv}$. **A** divides by w_R; **C** uses $w_R = 1$ (the gamma value); **D** keeps the wrong unit.

Question 12 — B. A source implanted for several days needs a half-life matched to the treatment: about 6 days lets the source deliver most of its dose over that time. **A** (about 6 hours) is far too short — the source would decay before the planned dose was delivered; **C** (about 5 years) and **D** (about 5000 years) leave the patient significantly radioactive long after the treatment is complete.

Question 13 — D. $E = mc^2 = 2.0 \times 10^{-3} \times (3.00 \times 10^8)^2 = 1.8 \times 10^{14}$ J. **A** multiplies by c only ($mc = 6.0 \times 10^5$); **B** uses 2.0 instead of 2.0×10^{-3} kg; **C** divides by c^2.

Question 14 — C. The binding energy curve peaks at about $8.8\,\text{MeV}$ per nucleon near iron-56. Hydrogen-2 ($1.1\,\text{MeV}$) and helium-4 ($7.1\,\text{MeV}$) sit on the steep rising part; uranium-235 ($7.6\,\text{MeV}$) sits on the slow falling part.

Question 15 — B. Number of fissions $= \dfrac{1.0}{3.2 \times 10^{-11}} = 3.1 \times 10^{10}$. **A** is the reciprocal (energy per fission); **C** confuses the $200\,\text{MeV}$ energy value with a number of fissions; **D** inserts Avogadro's number.

Question 16 — B. Slow neutrons are far more likely to be absorbed by uranium-235 and cause fission, so the moderator slows the fast fission neutrons through collisions with light nuclei. **A** describes the control rods; **C** describes the coolant; **D** describes breeding of plutonium.

Question 17 — C. With exactly one neutron per fission causing the next fission, the reaction rate is steady: critical. **A** (subcritical) has fewer than one, so the reaction dies out; **B** (supercritical) has more than one, so the reaction grows; **D** describes an uncontrolled supercritical reaction.

Question 18 — A. By definition, fusion joins light nuclei and fission splits heavy nuclei. **B** reverses the two; **C** is false — only fusion needs such temperatures (fission is started by neutron absorption); **D** reverses the mass change: energy is released only when the products have less total mass than the reactants.

Question 19 — D. Australia has no nuclear power stations. About 440 reactors in about 32 countries supply about one tenth of the world's electricity — not Australia's (**A**). The OPAL reactor at Lucas Heights is a research reactor that produces radioisotopes, not electricity (**B**). Federal law prohibits the construction of nuclear power stations, so **C** is false.

Question 20 — C. The critical mass is the smallest amount of fissile material for which enough neutrons go on to cause further fissions to keep the chain reaction going. **A** is unrelated (fusion does not use a critical mass); **B** would stop the reaction; **D** is unrelated.

Topic 2 Test B — Radiation from the nucleus and nuclear energy (written responses)

Time allowed: 50 minutes · 40 marks · One scientific calculator permitted · The formula sheet may be used. Marks and timings are house conventions for school-based assessment. In questions where more than one mark is available, appropriate working must be shown.

Answer all questions in the spaces provided. Where a final answer has a required unit, give your answer in that unit.

Question 1 (5 marks)

Strontium-90 ($^{90}_{38}Sr$) is a fission product formed in nuclear reactors. It decays by β^- emission to an isotope of yttrium (symbol Y, proton number 39), which is also radioactive.

a. Write the decay equation for the β^- decay of strontium-90. 1 mark

b. The yttrium daughter also decays by β^- emission to a stable isotope of zirconium (symbol Zr, proton number 40). Write the decay equation for this decay. 1 mark

c. State the change that takes place inside a nucleus when it undergoes β^- decay. 1 mark

d. Strontium-90 ingested in food can accumulate in bone. Explain why strontium-90 inside the body is hazardous, even though the same source held outside the body is far less of a hazard. 2 marks

Question 2 (5 marks)

A cobalt-60 source has a half-life of 5.27 years and an initial activity of $3.2 \times 10^{6}\,\text{Bq}$.

a. Define the half-life of a radioactive sample. 1 mark

b. Show that the activity of the source after 15.81 years is $4.0 \times 10^{5}\,\text{Bq}$. 2 marks

c. State the fraction of the original cobalt-60 nuclei that have decayed after 15.81 years. 1 mark

d. Each decay is random, yet the activity of the sample at any time can be predicted. Explain why. 1 mark

Question 3 (6 marks)

During the clean-up of a disused research site, a $0.50\,\text{kg}$ region of a worker's skin is contaminated with dust that emits alpha radiation. Before the dust is removed, it deposits $4.0 \times 10^{-3}\,\text{J}$ of energy in that region of skin. For alpha radiation, $w_R = 20$.

a. Define absorbed dose, and calculate the absorbed dose delivered to this region of skin. Give your answer in Gy. 2 marks

b. Calculate the equivalent dose delivered to the skin. Give your answer in Sv. 2 marks

c. If the same absorbed dose had been delivered by gamma radiation instead, the equivalent dose would have been $8.0 \times 10^{-3}\,\text{Sv}$. Explain why alpha and gamma radiation give different equivalent doses for the same absorbed dose. 1 mark

d. The worker also inhales some of the dust, which delivers an equivalent dose of $0.30\,\text{Sv}$ to the lungs. The tissue weighting factor for the lungs is $w_T = 0.12$. Calculate the contribution of the lungs to the worker's effective dose. Give your answer in Sv. 1 mark

Question 4 (5 marks)

In one fission event of uranium-235, the total mass of the products is $3.6 \times 10^{-28}\,\text{kg}$ less than the total mass before the fission.

a. Calculate the energy released in this fission event. Give your answer in J. 2 marks

b. The total binding energy of iron-56 ($^{56}_{26}Fe$) is about $492\,\text{MeV}$. Calculate the binding energy per nucleon for iron-56. Give your answer in MeV. 1 mark

c. The binding energy per nucleon is about $7.6\,\text{MeV}$ for uranium-235 and about $8.5\,\text{MeV}$ for typical fission fragments. Use these values to explain why the fission of uranium-235 releases energy. 2 marks

Question 5 (5 marks)

a. State the three possible fates of a neutron released in a fission event in a reactor. 2 marks

b. Explain why the neutrons released in fission are slowed before they cause further fissions, and explain how the nuclei of the moderator slow them down. 2 marks

c. State and explain the effect on the chain reaction of pushing the control rods further into the core. 1 mark

Question 6 (4 marks)

a. State two differences between nuclear fusion and nuclear fission as ways of releasing nuclear energy. 2 marks

b. Explain why the fusion of light nuclei requires temperatures of millions of degrees. 2 marks

Question 7 (4 marks)

a. Explain why alpha radiation cannot be used for external-beam radiotherapy, yet an alpha-emitting source placed inside the body next to a tumour can be very effective. 2 marks

b. Tumour cells divide more rapidly than most healthy cells. Explain why this makes radiotherapy effective against tumours while largely sparing the healthy tissue around them. 2 marks

Question 8 (6 marks)

A student investigates the decay of a short-lived radioactive sample. She places the sample in front of a detector connected to a counter and records the count rate every 60 s. She also measures the background count rate separately and finds it to be 20 counts per second. Her results are:

Time (s)	Count rate (counts per second)
0	660
60	340
120	180
180	100
240	60

a. State why the student measures the background count rate and subtracts it from her readings. 1 mark

b. Calculate the corrected count rate at $t = 60\,\text{s}$ and at $t = 120\,\text{s}$. 1 mark

c. Use the corrected data to determine the half-life of the sample. Give your answer in s. 2 marks

d. Identify the independent variable and the dependent variable in this investigation. 1 mark

e. Suggest one improvement to this method that would increase confidence in the value obtained for the half-life. 1 mark

End of Topic 2 Test B

Topic 2 Test B — solutions

Question 1

(a) $^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}e$ **(1 mark: equation balanced — mass number 90 conserved, proton numbers $38 = 39 + (-1)$, β⁻ particle shown.)**

(b) $^{90}_{39}Y \rightarrow {}^{90}_{40}Zr + {}^{0}_{-1}e$ **(1 mark: equation balanced with zirconium, proton number 40.)**

(c) A neutron in the nucleus changes into a proton (and an electron is emitted). The proton number rises by 1 while the nucleon number is unchanged. **(1 mark: neutron → proton, with Z up by 1 / A unchanged.)**

(d) Inside the body the source sits directly beside living cells — there is no dead outer skin layer to stop the radiation. The β radiation penetrates millimetres into the tissue around the bone, ionising atoms and damaging cells and DNA where the strontium-90 has accumulated. Outside the body, much of the β radiation is stopped by clothing and the dead outer layer of the skin, so far less reaches living tissue. (**1 mark** internal source irradiates living tissue directly / β absorbed in tissue near the bone; **1 mark** outside the body, β largely stopped by clothing/dead skin layer.)

Question 2

(a) The half-life is the time taken for the activity of a sample to fall to half its initial value (equivalently, for half of the radioactive nuclei in the sample to decay). **(1 mark: correct definition in terms of activity or undecayed nuclei.)**

(b) Number of half-lives: $n = \frac{15.81}{5.27} = 3.0$.

$$A = A_0\left(\frac{1}{2}\right)^n = 3.2 \times 10^6 \times \left(\frac{1}{2}\right)^3 = \frac{3.2 \times 10^6}{8} = 4.0 \times 10^5\,\text{Bq},$$

as required. (**1 mark** $n = 3$ half-lives identified; **1 mark** correct value $4.0 \times 10^5\,\text{Bq}$.)

(c) The fraction remaining is $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$, so the fraction that have decayed is $1 - \frac{1}{8} = \frac{7}{8}$. **(1 mark: 7/8 — the fraction decayed, not the fraction remaining.)**

(d) The sample contains an extremely large number of nuclei. Any single decay is random, but a fixed fraction of the nuclei decays in each interval, so the average behaviour of the whole sample — and therefore its activity — is predictable. **(1 mark: large number of nuclei / fixed fraction per interval makes the average predictable.)**

Question 3

(a) Absorbed dose is the energy absorbed per unit mass of tissue: $D = \frac{E}{m}$.

$$D = \frac{4.0 \times 10^{-3}}{0.50} = 8.0 \times 10^{-3}\,\text{Gy}.$$

(**1 mark** definition (energy absorbed per unit mass); **1 mark** correct value $8.0 \times 10^{-3}\,\text{Gy}$.)

(b) $H = w_R \times D = 20 \times 8.0 \times 10^{-3} = 0.16\,\text{Sv}$. (**1 mark** $H = w_R D$ used; **1 mark** correct value $0.16\,\text{Sv}$.)

(c) Alpha radiation is far more densely ionising than gamma radiation: it deposits its energy along a much shorter path, causing more biological damage per joule absorbed. It therefore carries a larger radiation weighting factor ($w_R = 20$ rather than 1), giving a larger equivalent dose for the same absorbed dose. **(1 mark: alpha more densely ionising / greater biological damage per joule ⇒ larger w_R.)**

(d) Contribution to the effective dose: $w_T \times H = 0.12 \times 0.30 = 0.036\,\text{Sv}$ ($= 36\,\text{mSv}$). **(1 mark: correct value $0.036\,\text{Sv}$.)**

Question 4

(a) $\Delta E = \Delta m c^2 = 3.6 \times 10^{-28} \times (3.00 \times 10^8)^2 = 3.6 \times 10^{-28} \times 9.00 \times 10^{16} = 3.2 \times 10^{-11}\,\text{J}$. **(1 mark** $\Delta E = \Delta m c^2$ with correct substitution; **1 mark** correct value $3.2 \times 10^{-11}\,\text{J}$. This is about $200\,\text{MeV}$, the accepted energy per fission.)

(b) Binding energy per nucleon $= \frac{492}{56} = 8.8\,\text{MeV}$. **(1 mark: correct value** $8.8\,\text{MeV}$ **per nucleon.)**

(c) The fission fragments ($8.5\,\text{MeV}$ per nucleon) are more tightly bound than the uranium-235 nucleus ($7.6\,\text{MeV}$ per nucleon), so the total binding energy of the products is greater and the total mass of the products is less than the mass before the fission. This lost mass is released as energy, $E = mc^2$. **(1 mark** fragments have greater binding energy per nucleon / are more tightly bound; **1 mark** mass decrease released as energy via $E = mc^2$.)

Question 5

(a) A released neutron can: (i) cause a further fission of a uranium-235 nucleus; (ii) be absorbed by a nucleus without causing fission (for example in fuel, fission products or control rods); (iii) escape from the surface of the fuel without interacting. **(1 mark** any two fates; **1 mark** the third fate.)

(b) Slow neutrons are much more likely to be absorbed by uranium-235 and cause fission, so slowing the fast fission neutrons keeps the chain reaction going. The moderator is made of light nuclei: when a fast neutron collides with a nucleus of similar, small mass, it transfers a large fraction of its kinetic energy in each collision, so it slows down efficiently. **(1 mark** slow neutrons more likely to cause fission; **1 mark** collisions with light nuclei transfer kinetic energy / slow the neutrons.)

(c) The control rods absorb neutrons. Pushing them further into the core absorbs more neutrons, so fewer neutrons go on to cause further fissions and the reaction rate decreases (the core moves toward a subcritical state). **(1 mark: more neutrons absorbed ⇒ fewer fissions ⇒ reaction rate falls.)**

Question 6

(a) Any two correct differences, for example: fusion joins light nuclei together while fission splits heavy nuclei apart; fusion requires temperatures of millions of degrees while fission can proceed at ordinary temperatures once a neutron is absorbed; fusion releases more energy per kilogram of fuel; fusion fuel (hydrogen isotopes) is far more abundant than uranium; fusion does not produce long-lived high-level radioactive waste, while fission does. **(1 mark** each correct difference, to a maximum of 2 marks.)

(b) Both nuclei are positively charged, so they repel each other electrostatically as they approach. At temperatures of millions of degrees the nuclei move fast enough to get within about 1–3 fm of one another, where the attractive strong nuclear force can overcome the repulsion and bind the nuclei together. **(1 mark** both nuclei positive ⇒ electrostatic repulsion; **1 mark** high speed / kinetic energy needed to approach within range of the strong nuclear force.)

Question 7

(a) From outside the body, alpha radiation is stopped by the dead outer layer of the skin and cannot reach a tumour inside the body. Placed inside the body next to the tumour, the alpha source is highly effective because alpha radiation is densely ionising and deposits all of its energy over a very short range, delivering a large dose to the tumour while sparing tissue beyond that range. **(1 mark** externally: alpha stopped by skin / cannot reach the tumour; **1 mark** internally: short range + dense ionisation concentrates the dose in the tumour.)

(b) Ionising radiation damages DNA, and cells that are dividing rapidly are more sensitive to this damage and less able to repair it. Tumour cells divide much more rapidly than most surrounding healthy cells, so they are killed preferentially, while the slower-dividing healthy cells are more likely to repair the damage and survive. **(1 mark** radiation damages DNA / rapidly dividing cells more sensitive; **1 mark** healthy cells divide more slowly and repair more effectively.)

Question 8

(a) Radiation from the environment (for example from rocks, building materials and cosmic rays) is always present and is counted by the detector. Subtracting the background leaves the count rate due to the sample alone. **(1 mark: background from the environment must be removed to isolate the sample's count rate.)**

(b) At $t = 60\,\text{s}$: $340 - 20 = 320$ counts per second; at $t = 120\,\text{s}$: $180 - 20 = 160$ counts per second. **(1 mark: both corrected values correct.)**

(c) Correcting every reading gives 640, 320, 160, 80, 40 counts per second. The count rate halves from 640 to 320 in the first 60 s, and again from 320 to 160 in the next 60 s, so the halving time is constant. The half-life is therefore $60\,\text{s}$. **(1 mark** corrected data show a constant halving time, checked over two intervals; **1 mark** correct value $60\,\text{s}$.)

(d) The independent variable is the time; the dependent variable is the count rate. **(1 mark: both variables correctly identified.)**

(e) Any one sensible improvement, for example: repeat the measurements and average the results; continue recording for more half-lives so the halving pattern is checked over a longer time; measure the background for longer so its value is better determined; keep the source and detector in exactly the same positions throughout. **(1 mark: one valid improvement.)**