

THEME E · NUCLEAR AND QUANTUM PHYSICS

SL & HL

≈ 30 min read

IB Physics E.4 Fission — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). E.4 has **no additional higher level content**: everything on this page is examinable at both SL and HL. The one purple **HL** box is an optional link back to HL material in E.3. The page builds on mass defect and binding energy (E.3) and on energy, power and efficiency (A.3).

 SL E.4 questions HL E.4 questions Flashcards Chain reaction simulation Binding energy curve simulation

What this page covers

- ✓ Why energy is released when a heavy nucleus splits, both spontaneously and after absorbing a neutron
- ✓ Calculating the energy released in a fission reaction from masses or from binding energies
- ✓ What a chain reaction is, and how it is kept under control (critical, subcritical and supercritical)
- ✓ The job of the moderator, control rods, heat exchanger and shielding in a nuclear power station
- ✓ The properties of fission products and how spent fuel and nuclear waste are managed, including the impact of long-term storage

In one minute

- **Fission** is the splitting of a heavy nucleus into two smaller nuclei of similar mass, plus a few neutrons. It can be **spontaneous** or **neutron-induced** (e.g. uranium-235 absorbing a slow neutron).

- The products have a **greater binding energy per nucleon** than the original nucleus, so the total mass decreases and energy $E = \Delta m c^2$ is released — about 200 MeV per fission, mostly as kinetic energy of the fragments.
- Each fission releases 2–3 neutrons that can cause further fissions: a **chain reaction**. A reactor keeps exactly one neutron per fission going on to cause another fission.
- **Moderator**: slows neutrons down. **Control rods**: absorb neutrons. **Heat exchanger**: transfers thermal energy from the reactor coolant to water that becomes steam. **Shielding**: absorbs neutrons and γ radiation.
- Fission products are **neutron-rich, highly radioactive and hot**; some have very long half-lives, so spent fuel is cooled under water and then stored in sealed containers, eventually deep underground.

Contents

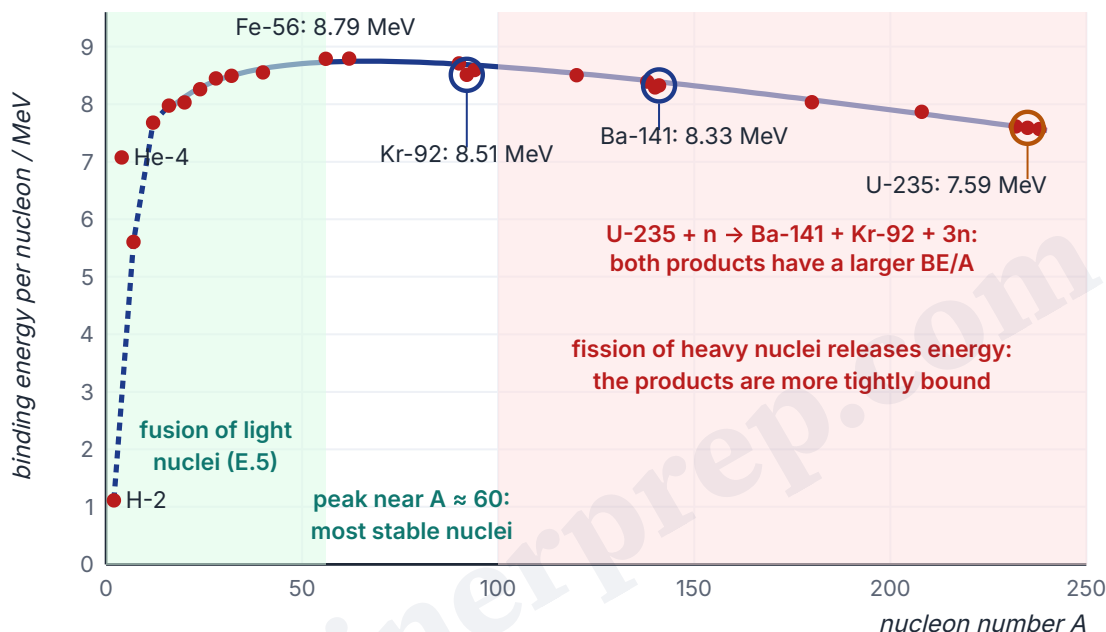
- | | |
|--|---------------------------------------|
| 1. Why fission releases energy | 7. Fission products and nuclear waste |
| 2. Calculating the energy released | 8. Exam tips |
| 3. Chain reactions | 9. Common misconceptions |
| 4. Inside a nuclear power station | 10. How this topic connects |
| 5. From fission rate to electrical power | 11. Key equations |
| 6. How the moderator works | 12. Check your understanding |

Why does splitting a heavy nucleus release energy?

Nuclear fission is the splitting of a heavy nucleus into two lighter nuclei of comparable mass, usually with the emission of two or three neutrons. Energy is released because the products have a greater total binding energy than the original nucleus, so their total mass is smaller.

- Binding energy per nucleon is about 7.6 MeV for uranium-235 but about 8.3–8.6 MeV for the medium-mass nuclei it splits into (E.3). Every nucleon ends up **more tightly bound**.

- More tightly bound means **less mass**: the products have less rest mass than the reactants. The mass decrease Δm appears as energy $E = \Delta m c^2$.
- Only a small fraction of the mass is converted — under 0.1 % — but per kilogram of fuel this is millions of times more energy than any chemical reaction.



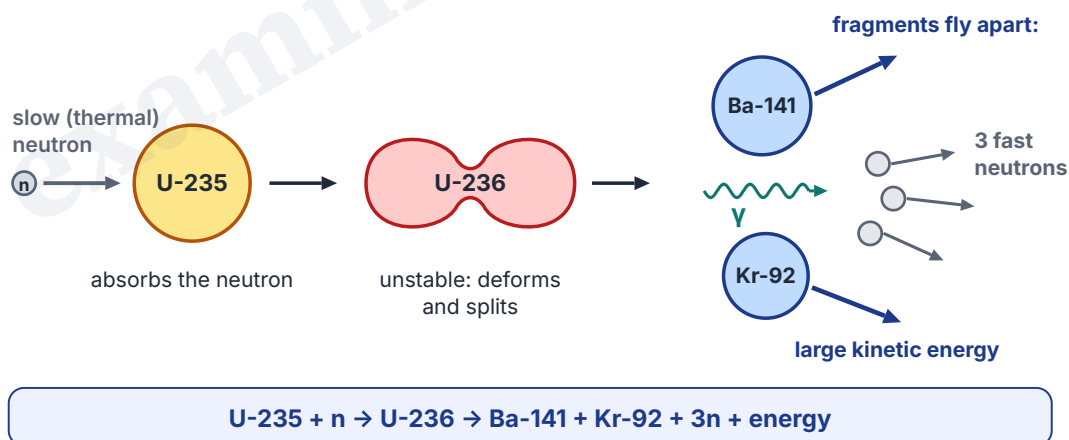
Binding energy per nucleon against nucleon number. Dots are values calculated from measured atomic masses; the solid line is a smooth curve fitted to them. Uranium-235 splits into barium-141 and krypton-92, both of which lie higher on the curve, so energy is released.

TRY IT YOURSELF

E.4 Binding energy curve simulation: pick a heavy nucleus and a pair of fission products, and see how the gain in binding energy per nucleon becomes the energy released.

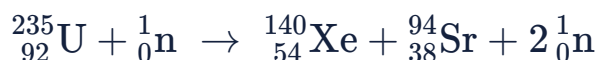
Spontaneous and neutron-induced fission

	Spontaneous fission	Neutron-induced fission
What triggers it	nothing: the nucleus splits on its own, at random, like any radioactive decay	the nucleus absorbs a neutron and becomes a highly unstable compound nucleus, which splits almost at once
Examples	californium-252 (about 3 % of its decays; used as a neutron source to start reactors); uranium-238 very rarely — roughly one decay in two million is fission, the rest are α decays	uranium-235 (and plutonium-239) absorbing a slow (thermal) neutron: $^{235}\text{U} + {}^1_0\text{n} \rightarrow {}^{236}\text{U} \rightarrow \text{fragments} + \text{neutrons}$
Can the rate be controlled?	no — set by the nuclide, unaffected by temperature or pressure	yes — by controlling the number of neutrons available
Use	source of the first neutrons; background neutron emission from heavy nuclides	energy production in nuclear power stations



Neutron-induced fission. A slow neutron is absorbed by uranium-235. The compound nucleus uranium-236 is unstable, deforms and splits into two fragments (here barium-141 and krypton-92) and three fast neutrons, with γ -ray photons. The fragments repel electrically and fly apart with large kinetic energy. Nucleus sizes are drawn proportional to $A^{1/3}$.

In every fission reaction **nucleon number and proton number are conserved**. Uranium-235 does not always split the same way: many different pairs of fragments are possible, with mass numbers mostly around 90–100 and 135–145, so equations with different products are all correct as long as they balance.



WORKED EXAMPLE 1 Easy · Deduce / State

In one neutron-induced fission of uranium-235, the products are xenon-140, an isotope of strontium and two neutrons: ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{54}^{140}\text{Xe} + {}_Z^A\text{Sr} + 2{}_0^1\text{n}$.

(a) Deduce Z and A for the strontium nucleus. (b) The stable isotope of strontium with the most neutrons is strontium-88. Compare the number of neutrons in the two strontium nuclei and state what this suggests about the fission product.

(a) Proton number: $92 + 0 = 54 + Z + 0 \Rightarrow Z = 38$

Nucleon number: $235 + 1 = 140 + A + 2 \times 1 \Rightarrow A = 94$

(b) Strontium-94 has $94 - 38 = 56$ neutrons; strontium-88 has $88 - 38 = 50$. The fission product has **6 more neutrons** than the heaviest stable isotope: it is **neutron-rich**, so it is radioactive and will decay by β^- emission (section 7).

How do you calculate the energy released in fission?

There are two equivalent routes. Use whichever matches the data you are given.

Route 1 — from masses

$$\Delta m = m_{\text{before}} - m_{\text{after}}$$

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

- m_{before} , m_{after} = total mass of all particles before and after; Δm = mass decrease (kg, or u), $c = 3.00 \times 10^8 \text{ m s}^{-1}$, E = energy released (J). $E = mc^2$ is in the data booklet; the expression for Δm is not.

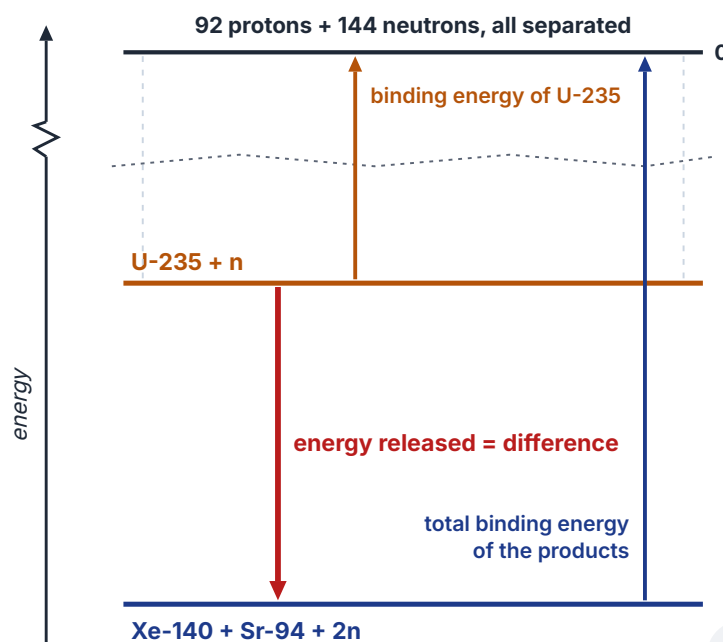
- Working in u: multiply Δm by **931.5 MeV** (data booklet: $1 \text{ u} = 931.5 \text{ MeV c}^{-2}$). Convert to joules with $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$.
- Include **every** particle: the incoming neutron on the left and all emitted neutrons on the right ($m_n = 1.008665 \text{ u}$).
- **Atomic or nuclear masses?** Either works if you are consistent. With atomic masses the electrons cancel, because the proton numbers balance ($92 = 56 + 36$): 92 electrons on each side.

Route 2 — from binding energies

$$E = \sum \text{BE}_{\text{products}} - \sum \text{BE}_{\text{reactants}}$$

$$\text{BE} = A \times (\text{BE per nucleon})$$

- BE = binding energy (MeV), A = nucleon number. Free neutrons have **zero** binding energy, so they do not appear in the sum.
- Multiply each binding energy per nucleon by **its own** nucleon number first, then subtract. Not in the data booklet — it follows from the definition of binding energy.



axis broken between 0 and -1740 MeV; the lower part is drawn to scale

Energy-level view of the reaction $\text{U-235} + n \rightarrow \text{Xe-140} + \text{Sr-94} + 2n$. The zero of energy is all 236 nucleons separated. The products lie lower by their larger total binding energy, so the difference between the two total binding energies is released (worked example 3 calculates it). The lower section is drawn to scale.

WORKED EXAMPLE 2 Medium · Calculate

For the reaction ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{56}^{141}\text{Ba} + {}_{36}^{92}\text{Kr} + 3{}_0^1\text{n}$, the atomic masses are: uranium-235, 235.043928 u; barium-141, 140.914411 u; krypton-92, 91.926156 u. Mass of a neutron = 1.008665 u.

(a) Calculate the energy released, in MeV and in J. (b) Calculate the percentage of the initial mass that is converted to energy.

(a) Mass before = $235.043928 + 1.008665 = 236.052593 \text{ u}$

Mass after = $140.914411 + 91.926156 + 3 \times 1.008665 = 235.866562 \text{ u}$

$\Delta m = 236.052593 - 235.866562 = 0.186031 \text{ u}$

$E = 0.186031 \times 931.5 = \mathbf{173 \text{ MeV}}$ (173.3 MeV)

$E = 173.3 \times 1.60 \times 10^{-13} = \mathbf{2.77 \times 10^{-11} \text{ J}}$

(b) $\frac{0.186031}{236.052593} \times 100 = \mathbf{0.079 \%}$

Going via kilograms, $\Delta m = 0.186031 \times 1.661 \times 10^{-27} = 3.09 \times 10^{-28} \text{ kg}$ and $E = \Delta m c^2 = 2.78 \times 10^{-11} \text{ J}$. The tiny difference comes from rounding in the data-booklet constants; both answers are accepted.

WORKED EXAMPLE 3 Medium · Show that / Explain (diagram-based)

Binding energies per nucleon: uranium-235, 7.591 MeV; xenon-140, 8.291 MeV; strontium-94, 8.594 MeV. Refer to the energy-level diagram above.

(a) Show that the energy released in $^{235}\text{U} + {}^1_0\text{n} \rightarrow {}^{140}\text{Xe} + {}^{94}\text{Sr} + 2 {}^1_0\text{n}$ is about 180 MeV. (b) Explain why the neutrons are left out of the calculation. (c) Explain why the answer differs from worked example 2.

(a) Total binding energies: U-235: $235 \times 7.591 = 1783.9 \text{ MeV}$; Xe-140: $140 \times 8.291 = 1160.7 \text{ MeV}$; Sr-94: $94 \times 8.594 = 807.8 \text{ MeV}$.

Products: $1160.7 + 807.8 = 1968.6 \text{ MeV}$

$E = 1968.6 - 1783.9 = \mathbf{185 \text{ MeV}}$ (184.7 MeV) $\approx 180 \text{ MeV}$

(b) A free neutron is not bound to anything, so its binding energy is **zero**; the neutrons add nothing to either side.

(c) The fragments are different. Xe-140 + Sr-94 have a larger total binding energy than Ba-141 + Kr-92 + one extra free neutron, so this split releases more energy. Every fission of U-235 releases roughly, but not exactly, 200 MeV.

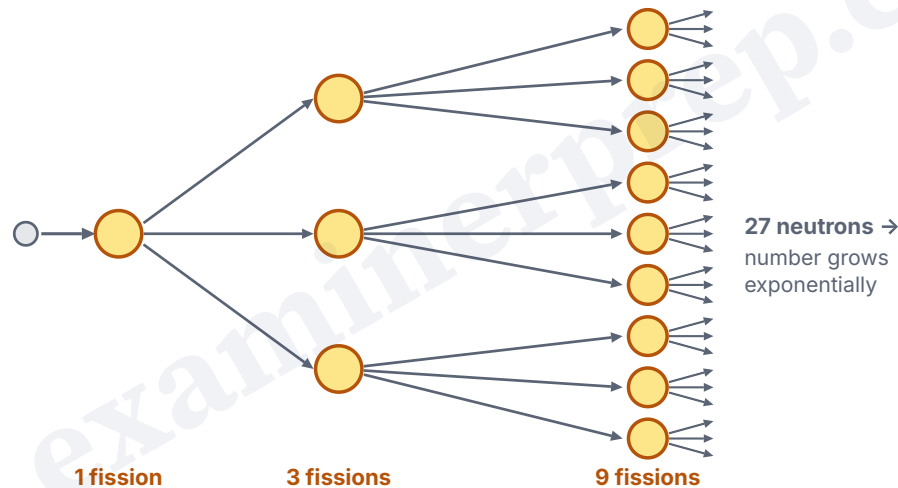
What is a chain reaction, and how is it controlled?

A chain reaction is a self-sustaining sequence of fissions in which neutrons released by one fission cause further fissions. It is steady when, on average, exactly one neutron from each fission goes on to cause another fission.

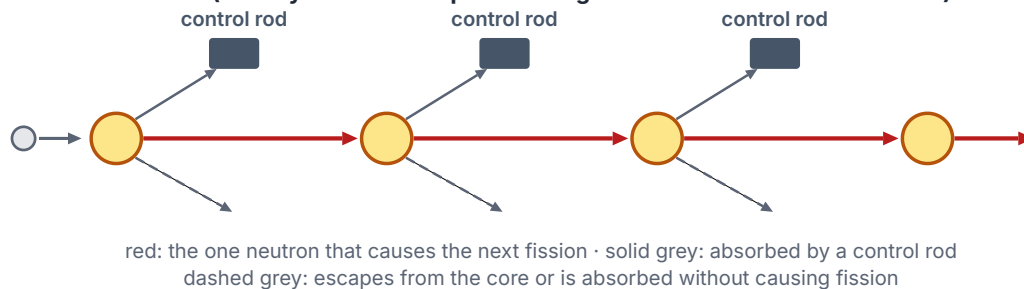
- Each fission of U-235 releases on average about 2.5 neutrons. Some escape from the fuel; some are absorbed by other nuclei without causing fission; some cause new fissions.

- If on average **more than one** neutron per fission causes another fission, the number of fissions per second rises exponentially (**supercritical**) — the principle of a nuclear weapon.
- If **exactly one** does, the rate is constant (**critical**) — the normal running state of a reactor.
- If **fewer than one** does, the reaction dies away (**subcritical**) — the state of a shut-down reactor.
- **Critical mass:** the minimum mass of fissile fuel in which a chain reaction can be sustained. In a small piece of fuel too many neutrons escape through the surface before they can cause fission; a larger mass has less surface area per unit volume, so fewer neutrons are lost.

Uncontrolled (each fission causes, on average, more than one further fission)



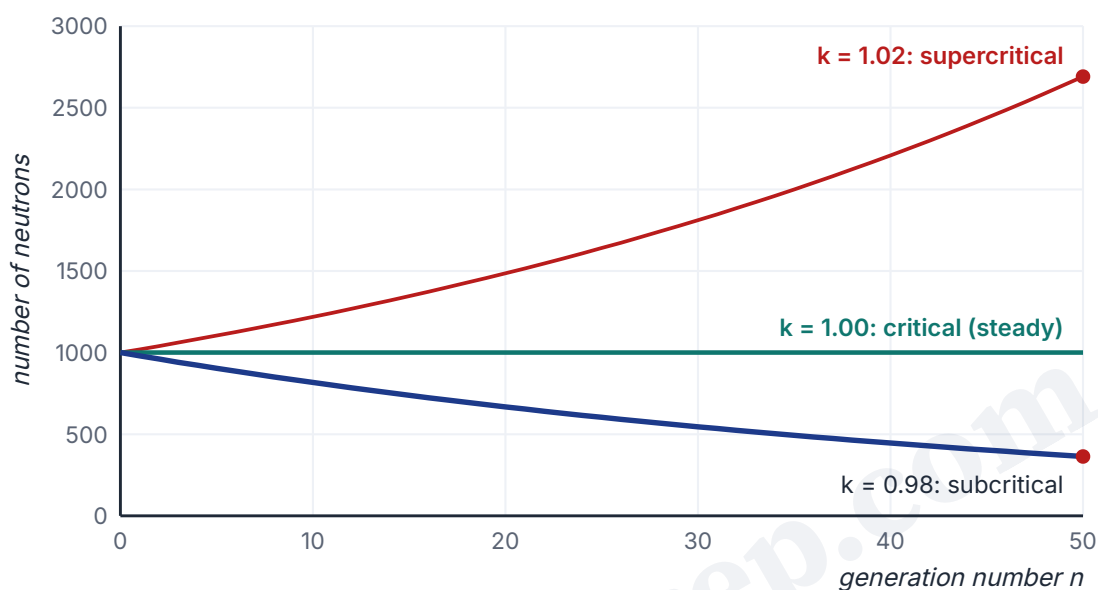
Controlled reactor (exactly one neutron per fission goes on to cause another fission)



rate of fission — and so power output — stays constant

Top: an uncontrolled chain reaction, drawn with three neutrons from each fission causing three more fissions, so the number of fissions grows $1 \rightarrow 3 \rightarrow 9 \rightarrow 27$. Bottom: a controlled chain reaction, in which the extra neutrons are absorbed by control rods or lost, so exactly one neutron per fission causes another fission.

The number of neutrons in one generation divided by the number in the previous generation is sometimes called the *multiplication factor* k (a useful idea, not a required term). After n generations the number of neutrons is $N_0 k^n$.



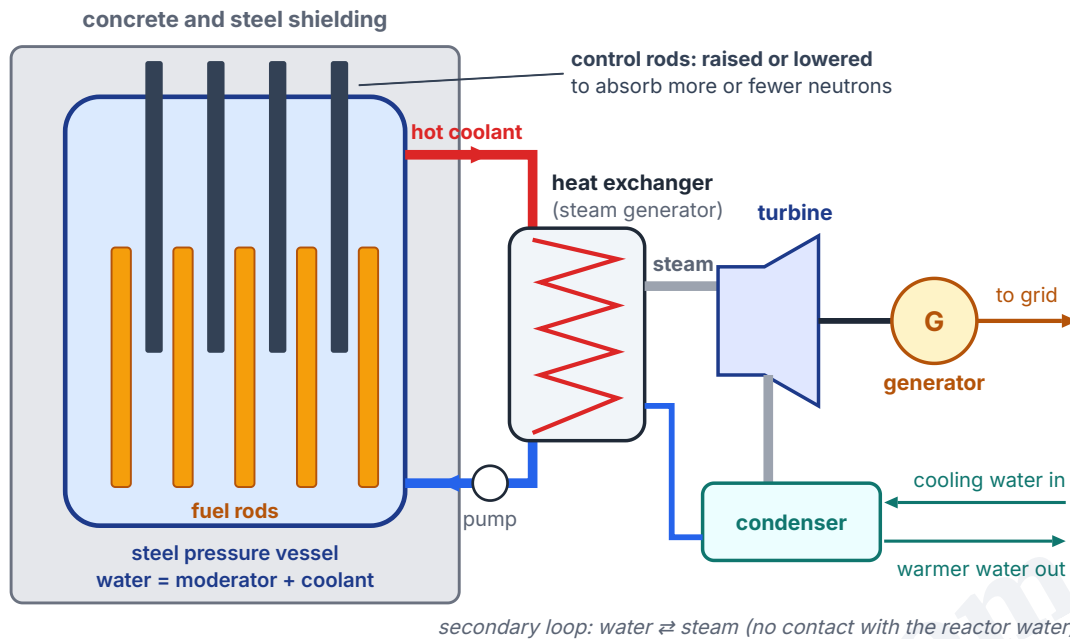
Number of neutrons against generation number, starting from 1000 neutrons, calculated from $N = 1000k^n$. A change of only 2 % in k either way makes the population grow to 2690 or fall to 364 within 50 generations. Generations in a reactor last a small fraction of a second, which is why control matters.

TRY IT YOURSELF

E.4 Fission chain reaction simulation: fire a neutron into a block of uranium-235, change the amount of fuel and insert control rods, and watch the reaction die away, stay steady or run away.

What do the main parts of a nuclear power station do?

A thermal-neutron power station turns the kinetic energy of fission fragments into thermal energy in the fuel, carries that energy away in a coolant, uses it to make steam, and drives a turbine and generator — exactly like a fossil-fuel power station from the steam onwards.



Schematic of a pressurised-water reactor power station. The water in the pressure vessel is both the moderator and the coolant; it circulates in a closed primary loop through the heat exchanger. Steam is made in a separate secondary loop, drives the turbine and generator, and is condensed back to water.

Part	What it is made of	Role
Fuel rods	uranium oxide, enriched from the natural 0.7 % to about 3–5 % uranium-235	contain the fissile nuclei; the kinetic energy of the fragments heats the rods
Moderator	water, heavy water or graphite — nuclei of low mass that absorb few neutrons	slows down the fast neutrons released by fission (about 2 MeV) to thermal energies (about 0.025 eV), at which they are far more likely to cause fission of U-235
Control rods	boron or cadmium — good neutron absorbers	inserted further to absorb more neutrons and reduce the fission rate; withdrawn to increase it; fully inserted to shut the reactor down
Coolant	water (or a gas such as CO ₂)	carries thermal energy away from the core; keeps the fuel at a safe temperature
Heat exchanger (steam generator)	tubes carrying hot coolant through water in a separate circuit	transfers thermal energy from the primary coolant to the secondary water, which boils to make steam; the radioactive coolant never reaches the turbine
Shielding	thick steel pressure vessel and concrete walls (several metres), plus the water	absorbs neutrons and γ radiation from the core so that workers and the public receive a negligible dose

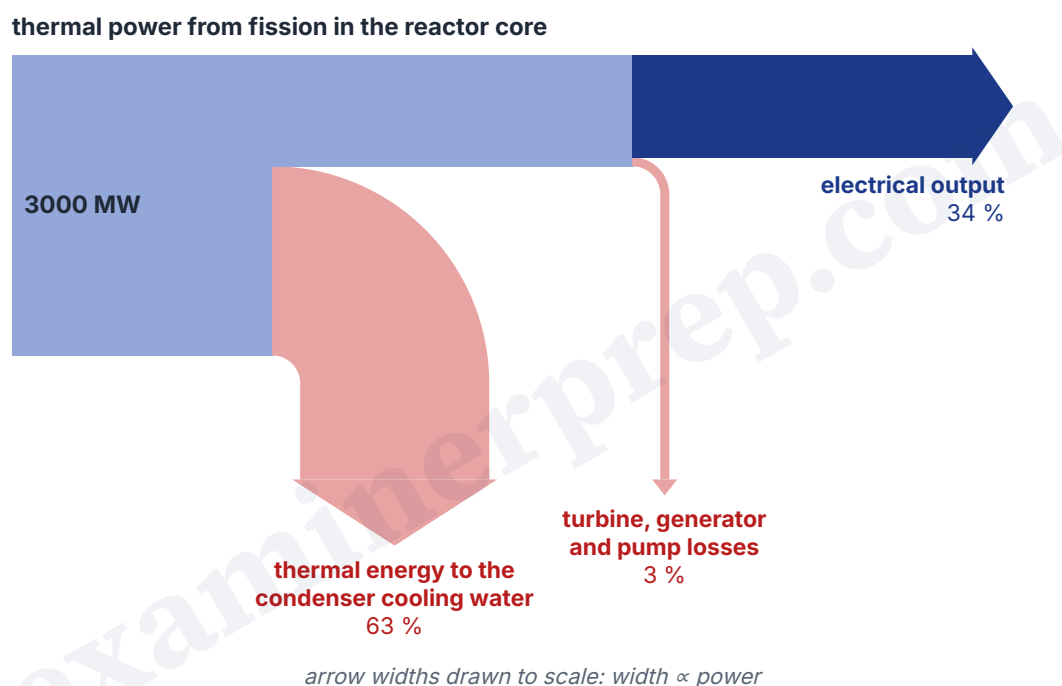
How does the fission rate set the power output?

Every fission releases a definite energy (about 200 MeV for U-235). The thermal power of the reactor is therefore fixed by how many fissions happen each second:

$$P_{\text{thermal}} = \frac{\text{fissions}}{\text{second}} \times \frac{\text{energy}}{\text{fission}}$$

$$\eta = \frac{\text{useful power out}}{\text{total power in}}$$

- P in W; energy per fission in J (convert from MeV). The power relation is not in the data booklet; the efficiency η is (A.3).
- Like any thermal power station, a nuclear station can convert only about a third of the thermal energy into electrical energy. Most of the rest is transferred to the cooling water at the condenser.



Sankey diagram, drawn to scale, for a station with a thermal power of 3000 MW and an overall efficiency of 34 %. The widths of the arrows are proportional to power.

WORKED EXAMPLE 4 Medium · Calculate / Determine (Sankey diagram)

A reactor core produces thermal power at a rate of 3.00 GW. Each fission of uranium-235 releases 200 MeV. The overall efficiency of the station is 34 %, as shown in the Sankey diagram. Mass of a U-235 atom = 235 u.

(a) Calculate the number of fissions per second. (b) Determine the mass of uranium-235 used up in one day. (c) Determine the electrical power output and the power transferred to the surroundings. (d) Coal releases 30 MJ kg^{-1} when burned. Estimate the mass of coal that would give the same thermal energy in one day.

$$(a) 200 \text{ MeV} = 200 \times 1.60 \times 10^{-13} = 3.20 \times 10^{-11} \text{ J}$$

$$\text{Rate} = \frac{3.00 \times 10^9}{3.20 \times 10^{-11}} = \mathbf{9.4 \times 10^{19} \text{ s}^{-1}} \quad (9.375 \times 10^{19} \text{ s}^{-1})$$

$$(b) \text{ Fissions per day} = 9.375 \times 10^{19} \times 86\,400 = 8.10 \times 10^{24}$$

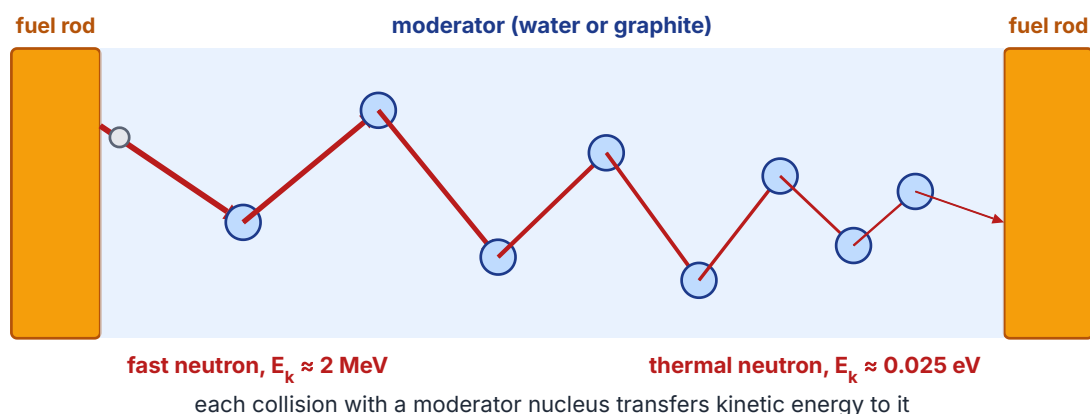
$$\text{Mass} = 8.10 \times 10^{24} \times 235 \times 1.661 \times 10^{-27} = \mathbf{3.16 \text{ kg}} \text{ per day}$$

$$(c) P_{\text{el}} = 0.34 \times 3.00 = \mathbf{1.02 \text{ GW}}; \text{ power to the surroundings} = 3.00 - 1.02 = \mathbf{1.98 \text{ GW}}$$

$$(d) \text{ Thermal energy per day} = 3.00 \times 10^9 \times 86\,400 = 2.59 \times 10^{14} \text{ J}; \text{ coal} \\ = \frac{2.59 \times 10^{14}}{30 \times 10^6} = \mathbf{8.6 \times 10^6 \text{ kg}} \text{ (about 8600 tonnes) — some 2.7 million} \\ \text{times the mass of U-235.}$$

How does the moderator slow neutrons down?

A fast neutron collides with moderator nuclei, giving some of its kinetic energy to the nucleus in each collision (momentum and, ideally, kinetic energy are conserved, A.2). The **closer the mass of the moderator nucleus to the neutron's mass**, the more energy is transferred per collision — which is why light nuclei are used. After many collisions the neutron is in thermal equilibrium with the moderator.



A fast neutron leaving one fuel rod is slowed by successive collisions with moderator nuclei; the thinning arrow shows its decreasing speed. It arrives at the next fuel rod as a thermal neutron, likely to cause fission.

WORKED EXAMPLE 5 Hard · Show that / Determine / Explain

In a graphite-moderated reactor, a neutron of speed v collides head-on with a stationary carbon-12 nucleus. Take the mass of the carbon nucleus to be 12 times the mass m of the neutron. After the collision the neutron moves back along its original line with speed $\frac{11}{13}v$.

(a) Determine the speed of the carbon nucleus after the collision. (b) Show that the collision is elastic. (c) Show that the neutron keeps about 72 % of its kinetic energy. (d) Estimate the minimum number of such collisions needed to slow a 2.0 MeV neutron to 0.025 eV. (e) Explain why hydrogen nuclei (in water) slow neutrons in fewer collisions.

(a) Take the neutron's initial direction as positive. Momentum: $mv =$

$$m\left(-\frac{11}{13}v\right) + 12mV$$

$12V = v + \frac{11}{13}v = \frac{24}{13}v \Rightarrow V = 2v/13 \approx 0.154v$, in the neutron's original direction.

(b) Kinetic energy after, as a fraction of $\frac{1}{2}mv^2$: $\left(\frac{11}{13}\right)^2 + 12\left(\frac{2}{13}\right)^2 = \frac{121}{169} + \frac{48}{169} = 1$. Total kinetic energy is unchanged, so the collision is **elastic**.

(c) Fraction kept = $\left(\frac{11}{13}\right)^2 = \frac{121}{169} = 0.716 \approx 72\%$

(d) After n collisions $E = E_0(0.716)^n$. Need $\frac{E_0}{E} = \frac{2.0 \times 10^6}{0.025} = 8.0 \times 10^7$.

$$n = \frac{\ln(8.0 \times 10^7)}{\ln(1/0.716)} = 54.5 \Rightarrow \text{at least } \mathbf{55 \text{ collisions}}$$

(e) A hydrogen nucleus (proton) has almost the same mass as a neutron, so in a head-on collision it can take **almost all** of the neutron's kinetic energy. Much more energy is transferred per collision, so fewer collisions are needed.

Real collisions are mostly glancing, not head-on, so a neutron needs more than 55 collisions in graphite. The answer to (d) is a minimum.

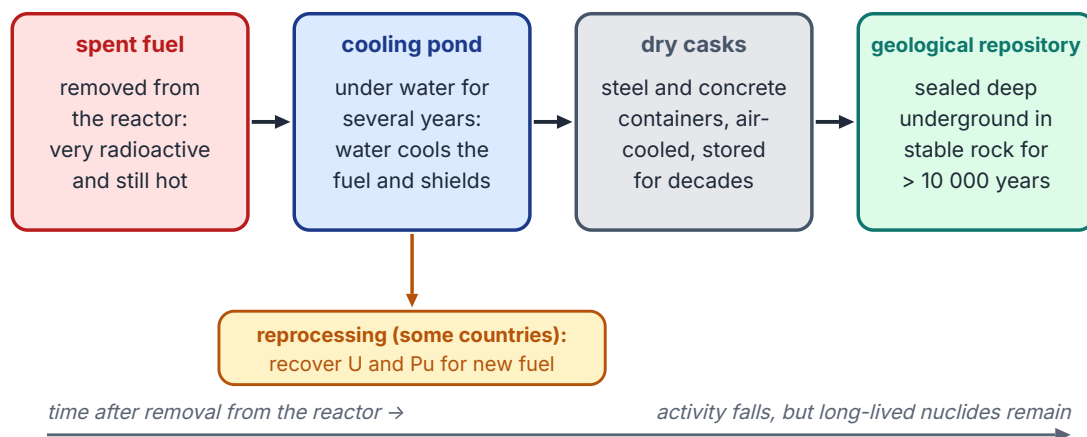
What are the properties of fission products, and how is nuclear waste managed?

Fission products are medium-mass nuclei with too many neutrons to be stable. They are highly radioactive, mostly β^- and γ emitters, they release thermal energy as they decay, and some have very long half-lives.

- **Neutron-rich.** Heavy nuclei need proportionally more neutrons than medium nuclei to be stable. When U-235 splits, the fragments inherit this high proportion of neutrons, so each decays by a series of **β^- decays** (a neutron becomes a proton) towards a stable nuclide, e.g. $\text{Kr-92} \rightarrow \text{Rb-92} \rightarrow \text{Sr-92} \rightarrow \text{Y-92} \rightarrow \text{Zr-92}$ (stable) and $\text{Ba-141} \rightarrow \text{La-141} \rightarrow \text{Ce-141} \rightarrow \text{Pr-141}$ (stable).
- **Highly radioactive.** Many fragments have short half-lives, so freshly removed (spent) fuel has an enormous activity and emits penetrating γ radiation.
- **Hot.** The energy of these decays keeps heating the fuel even after the chain reaction has stopped ("decay heat"). Spent fuel must be **cooled**, or it can melt.
- **Long-lived.** Some fission products (and plutonium and other heavy nuclides made when U-238 absorbs neutrons) have half-lives of thousands to millions of years, so the waste stays hazardous for that long.
- **Other waste:** neutrons make structural materials radioactive; gloves, clothing and tools pick up contamination. These are lower-level wastes, handled separately.

HL Link to E.3: where fission fragments sit on the N-Z chart

The neutron-to-proton ratio of U-235 is $143/92 = 1.55$. Kr-92 ($56/36 = 1.56$) and Ba-141 ($85/56 = 1.52$) keep almost the same ratio, but the stable nuclides of similar mass have far lower ratios (for example 1.33 for Kr-84 and 1.46 for Ba-138). The fragments therefore lie **above the stability belt**, which is why they decay by β^- emission: each decay lowers N by one and raises Z by one. This is an application of the HL understanding in E.3; E.4 itself has no extra HL content.



Managing spent fuel. It is cooled under water for several years, then stored in air-cooled steel and concrete casks, and is intended for permanent disposal deep underground. Some countries reprocess it to recover uranium and plutonium.

The impact of long-term storage

- **Timescale.** The waste must be isolated from people and groundwater for many thousands of years — far longer than any human institution has existed. The storage must be safe without relying on future maintenance.
- **Containment.** High-level waste can be vitrified (set in glass), sealed in corrosion-resistant canisters and buried in geologically stable rock, so that multiple barriers prevent radioactive nuclides reaching groundwater.
- **Responsibility and ethics.** Future generations inherit the hazard without the benefit of the electricity. Choosing a site needs public consent; transport carries its own risk; stored plutonium raises security concerns (proliferation).
- **Perspective.** The volume of high-level waste is small compared with fossil-fuel waste (worked example 4 shows the mass of fuel is millions of times smaller), and it is contained rather than released into the atmosphere.

Exam tips for E.4

EXAM TIP 1 — MODERATOR SLOWS, CONTROL RODS ABSORB

The commonest lost mark in E.4. The moderator **slows down** (reduces the kinetic energy of) neutrons by collisions; it does not absorb them. Control rods **absorb** neutrons; they do not slow them down. Write the verb, and say

why: slow neutrons are more likely to cause fission of U-235; absorbing neutrons reduces the rate of fission.

EXAM TIP 2 — BINDING ENERGY: MULTIPLY BEFORE YOU SUBTRACT

The energy released is the difference between **total** binding energies, $\sum A \times (\text{BE per nucleon})$. Subtracting binding energies per nucleon (e.g. $8.4 - 7.6 = 0.8 \text{ MeV}$) and stopping there gives an answer about 200 times too small. Use each nuclide's own nucleon number, and remember free neutrons contribute zero.

EXAM TIP 3 — COUNT THE NEUTRONS IN A MASS-DEFECT CALCULATION

Put the incoming neutron on the left and **every** emitted neutron on the right. Keep 5–6 decimal places in the masses until the subtraction: the mass difference (about 0.2 u) is less than 0.1 % of the total mass (about 236 u), so rounding masses early destroys the answer.

EXAM TIP 4 — DESCRIBE THE HEAT EXCHANGER AS AN ENERGY TRANSFER

A heat exchanger "transfers thermal energy from the coolant (primary circuit) to water in the secondary circuit, turning it into steam". It does **not** "convert heat into electricity", and it does not slow or absorb neutrons. Mention that keeping the circuits separate keeps radioactive coolant away from the turbine.

EXAM TIP 5 — NUCLEAR WASTE: PROPERTIES, THEN MANAGEMENT

For "outline the problems of nuclear waste", give a **property** and its **consequence**: highly radioactive → must be shielded; hot from decay → must be cooled; long half-lives → must be isolated for thousands of years. For "discuss", give both sides and reach a judgement.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Energy is released because chemical bonds in the uranium are broken.	Chemical energies are a few eV per atom; fission releases about 200 MeV per nucleus.	The energy comes from the increase in nuclear binding energy, i.e. the decrease in rest mass.
The products have more mass because they are "more stable".	More tightly bound nuclei have <i>less</i> mass per nucleon.	The products have less total mass; the mass decrease $\times c^2$ is released.
Binding energy is energy stored in the nucleus and released when it splits.	Binding energy is the energy needed to <i>separate</i> a nucleus; more binding energy means less energy in the nucleus.	Energy is released because the products have more binding energy than the reactant.
Fast neutrons are best at causing fission, so the moderator speeds them up.	U-235 is far more likely to absorb a slow neutron; fast neutrons tend to pass through or be captured by U-238.	The moderator slows neutrons to thermal energies.
A nuclear power station can explode like a nuclear bomb.	Reactor fuel is only a few per cent U-235 and the reaction is kept critical, not supercritical.	Reactor accidents involve overheating and release of radioactive material, not a nuclear explosion.
Spent fuel stops being dangerous when the reactor is switched off.	Fission products keep decaying, emitting radiation and heat.	Spent fuel must be cooled and shielded for years and isolated for thousands of years.

How this topic connects

Where the energy of a fission goes: kinetic energy first

Almost all of it first appears as **kinetic energy**. Typical shares of the roughly 200 MeV per U-235 fission: about 168 MeV as kinetic energy of the two fragments,

which repel each other electrically; about 5 MeV as kinetic energy of the neutrons; about 7 MeV as prompt γ -ray photons; and, later, about 8 MeV from β particles, 7 MeV from γ rays and 12 MeV carried by antineutrinos as the fragments decay. The fragments travel less than a millimetre in the fuel, transferring their kinetic energy to the random motion of the surrounding atoms — **internal (thermal) energy** of the fuel (B.1). The antineutrinos escape, so about 195 of the 207 MeV is recovered as thermal energy.

From binding energy to reactor power output

The increase in total binding energy in one fission gives the energy per fission (worked example 3, about 200 MeV for U-235). The thermal power is then (fissions per second) $\times$ (energy per fission), and the rate of fission is set by the neutron population, which the control rods regulate. Turning it round, a required power output fixes the fission rate and the mass of fuel used each day (worked example 4: 3.16 kg of U-235 for 3.00 GW). Energy, power and efficiency are from A.3.

Nuclear fission and climate change: weighing the case for and against

For: fission produces no CO_2 during operation, so over its life cycle a nuclear station emits far less greenhouse gas per unit of electrical energy than coal or gas (B.2); its enormous energy density means small fuel volumes; and it provides steady output whatever the weather, complementing wind and solar. **Against:** high-level waste must be isolated for thousands of years; accidents, though rare, can contaminate large areas; plants are expensive and slow to build, so they may cut emissions later than cheaper renewables; and fissile material raises security concerns. A balanced conclusion: fission can make a significant low-carbon contribution, but whether it should depends on economic, social and ethical judgements as well as physics — science can inform the decision but cannot make it alone.

Tools & NOS — risk, ethics and modelling

- **Ethics (NOS):** the same physics gave both nuclear weapons and nuclear power. Scientists working on fission in the 1940s had to weigh their

responsibility for how their work would be used — a recurring question whenever science has powerful applications.

- **Risk and evidence:** public perception of nuclear risk often differs from measured risk (deaths or dose per unit of energy produced). Comparing technologies fairly needs data over the whole life cycle — mining, operation, waste and accidents.
- **Exponential models (Tools):** both the chain reaction ($N_0 k^n$) and the decay of waste (E.3) are exponential processes. A spreadsheet that iterates the generations shows how sensitive the neutron population is to small changes in k .
- **Energy accounting (Tools):** a Sankey diagram drawn to scale makes the 34 % efficiency and the large thermal transfer to the cooling water obvious at a glance.

Key equations

Equation	Use	In data booklet?
$E = mc^2$	energy released from the mass decrease	yes (E.3)
$1 \text{ u} = 1.661 \times 10^{-27} \text{ kg} = 931.5 \text{ MeV c}^{-2}$	mass in u $\times$ 931.5 = energy in MeV	yes (constants)
$\Delta m = m_{\text{before}} - m_{\text{after}}$	mass decrease in a fission reaction	no — from the definition
$E = \sum \text{BE}_{\text{products}} - \sum \text{BE}_{\text{reactants}}; \text{ BE} = A \times \text{BE per nucleon}$	energy released from binding energies	no — from the definition
$P = (\text{fissions per second}) \times (\text{energy per fission})$	thermal power of a reactor	no — from $P = \frac{\Delta W}{\Delta t}$ (A.3)
$\eta = \frac{\text{useful power out}}{\text{total power in}}$	efficiency of the power station	yes (A.3)

Check your understanding

1. Each fission of U-235 releases 200 MeV. Calculate the energy released by the fission of 1.0 kg of U-235 and compare it with burning 1.0 kg of coal (30 MJ kg⁻¹).

Nuclei in 1.0 kg = $\frac{1.0}{235 \times 1.661 \times 10^{-27}} = 2.56 \times 10^{24}$. Energy = $2.56 \times 10^{24} \times 3.20 \times 10^{-11} = 8.2 \times 10^{13}$ J — about 2.7×10^6 times the 30 MJ from 1 kg of coal.

2. A fission reaction releases 180 MeV. Calculate the decrease in mass, in u and in kg.

$\Delta m = \frac{180}{931.5} = 0.193$ u; $0.1932 \times 1.661 \times 10^{-27} = 3.21 \times 10^{-28}$ kg.

3. State the difference between the role of the moderator and the role of the control rods, and explain what an operator does to reduce the power output.

The moderator slows neutrons down (so they are more likely to cause fission of U-235); the control rods absorb neutrons. To reduce the power, the control rods are inserted further, absorbing more neutrons, so fewer fissions occur per second.

4. A reactor contains 2000 neutrons in one generation and each generation has 0.97 times as many neutrons as the one before. Calculate the number after 30 generations and state whether the reactor is critical, subcritical or supercritical.

$2000 \times 0.97^{30} = 802$ neutrons (about 800). Fewer than one neutron per fission goes on to cause another fission, so the reactor is **subcritical** and the chain reaction dies away.

5. Explain why spent fuel is stored under water for several years after it is removed from a reactor.

The fission products are highly radioactive. Their decay releases energy, so the fuel keeps heating up; the water removes this thermal energy and prevents the fuel from overheating. The water also absorbs radiation (shielding), protecting workers. After several years the short-lived products have decayed, and the fuel can be moved to dry storage.

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