Topic E.4

NUCLEAR FISSION

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered	Exam Relevance
Nuclear fission	P1 & P2 (SL + HL)
Chain reactions & criticality	200 MeV per fission
Reactor components	k: sub/critical/super
Energy calculations	$E = \Delta mc^2$
Safety & environment	Waste & thermal pollution

The Big Picture — How E.4 Fits Together

NUCLEAR FISSION
split a heavy nucleus → energy + neutrons → chain reaction

- **Fission**: ^{235}U splits, ↑ BE/A
- **Chain**: $k<1, =1, >1$, critical mass
- **Reactor**: fuel, moderator, control rods, coolant
- **Energy**: ~ 200 MeV, $E = \Delta mc^2$
- **Safety**: waste, pros & cons

§1 — Nuclear Fission

E.4 SL & HL

Definition

Fission: A heavy nucleus absorbs a slow (thermal) neutron and splits into two lighter nuclei (fission fragments) plus 2–3 neutrons and energy.

$^{1}_{0}n + ^{235}_{92}\text{U} \to ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3\,^{1}_{0}n$

Conservation Laws

In every nuclear reaction:
- Mass number A is conserved
- Proton number Z is conserved
- Energy-mass is conserved

TRICK Always check both A and Z when balancing fission equations. Set up simultaneous equations if two unknowns.

TRAP Do NOT confuse "fission" (heavy → light) with "fusion" (light → heavy). Both release energy but by moving toward higher BE/nucleon.

Binding Energy & Fission

Fission releases energy because products have **higher BE/nucleon** than U-235.

Energy released: $E = BE_{\text{products}} - BE_{\text{reactants}}$

U-235: BE/A ≈ 7.6 MeV
Fragments: BE/A ≈ 8.4 MeV
$\Rightarrow E \approx 200$ MeV per fission

NOTE Iron-56 has the highest BE/nucleon (8.79 MeV). Nuclei on either side can release energy by moving toward Fe-56.

FROM THE PHOTON QUESTION BANK
Conserve *both* A and Z when balancing; justify energy release as "products have higher BE/nucleon", not just "mass lost".

§2 — Chain Reactions

E.4 SL & HL

Multiplication Factor k

: $k = \dfrac{\text{neutrons in gen } (n+1)}{\text{neutrons in gen } n}$

- $k < 1$: subcritical (reaction dies)
- $k = 1$: critical (steady reactor)
- $k > 1$: supercritical (bomb)

TRICK For k: count neutrons available for fission only. Subtract neutrons lost (absorbed by control rods) and those escaping through walls from total produced.

TRICK **Two ways to steer the chain:** the number k (keep $=1$ for a reactor) is physically set by two parts — the *moderator* slows neutrons (raises k), *control rods* absorb them (lower k).

Critical Mass (HL)

Critical mass = minimum mass for sustained chain reaction ($k \geq 1$).
Determined by competition:
- Fission $\propto$ volume $\propto r^3$
- Leakage $\propto$ surface area $\propto r^2$

Larger mass $\Rightarrow$ smaller leakage fraction.

TRAP Critical mass is NOT the mass at which fission starts. Fission occurs in a single atom. Critical mass is about *sustaining* the chain reaction.

§3 — Nuclear Reactor Components

E.4 SL & HL

Component Summary Table

Component	Function	Example materials
Fuel rods	Contain fissile material; site of fission	Enriched U-235 ($\sim$3–5%)
Moderator	Slows fast neutrons to thermal energies by elastic collisions	Water (H_2O), heavy water (D_2O), graphite
Control rods	Absorb neutrons to regulate reaction rate; fully inserted $\rightarrow$ shutdown	Boron, cadmium, hafnium
Heat exchanger	Transfers thermal energy from coolant to secondary water circuit	Pressurised water, CO_2
Containment	Shields environment from radiation	Concrete, lead, steel

TRICK Moderator atoms should be **light** (similar mass to neutron $\Rightarrow$ maximum energy transfer per collision) and **poor neutron absorbers**.

TRAP Statement "the heat exchanger slows neutrons" is WRONG. The moderator slows neutrons. The heat exchanger only moves thermal energy to produce steam.

FROM THE PHOTON QUESTION BANK

Top-tested skill: *distinguish moderator (slows neutrons) from control rods (absorb neutrons).* Also know the chain nuclear$\rightarrow$thermal$\rightarrow$kinetic$\rightarrow$electrical.

PWR — Two Water Circuits

In a pressurised water reactor, water is **both moderator and coolant**, kept liquid by a **pressuriser**:
- **Primary circuit:** radioactive water, core $\rightarrow$ steam generator (heat exchanger).
- **Secondary circuit:** clean water boiled to steam $\rightarrow$ turbine $\rightarrow$ condenser; never touches the core.

Overall efficiency $\approx$ 30–40% (waste heat lost to environment).

§4 — Energy Calculations

E.4 SL & HL (Quantitative: HL)

Key Formulae

Mass defect: $\Delta m = Zm_p + (A-Z)m_n - m_{\text{nucleus}}$

Energy from mass defect: $E = \Delta m \cdot c^2$

Useful conversion: 1 u $\equiv 931.5$ MeV

Power from mass loss: $P = \dot{m}\,c^2$

Energy from fission rate: $P = R \cdot E_{\text{fission}}$

TRICK When using atomic masses (not nuclear masses), the electron masses cancel in the subtraction for Δm, so atomic masses can be used directly.

TRICK **Two ways to see the $\sim$200 MeV:** climb the BE/A curve (products more tightly bound) *or* mass defect $E = \Delta mc^2$ — same energy, counted two ways.

Energy Density Comparison

Fuel	Energy / MJ kg^{-1}
Coal	≈ 30
Oil	≈ 45
Enriched U (3%)	$\approx 5 \times 10^6$
Pure U-235	$\approx 8 \times 10^7$

Nuclear $\approx 10^5$–$10^6\times$ fossil fuels.

NOTE $E \approx 200\,$MeV per U-235 fission $= 3.2 \times 10^{-11}$ J. Use this if exact masses not given.

FROM THE PHOTON QUESTION BANK
$\Delta m > 0 \Rightarrow$ energy released; $1\,$u$\equiv 931.5\,$MeV. Power: $P = RE_{\text{fission}}$ or $P = \dot{m}c^2$ — convert mg h^{-1} $\to$kg s^{-1} first, then apply efficiency.

§6 — Fuel, Reprocessing & Weapons

E.4 SL & HL

Enrichment & Reprocessing

- Natural U is $< 1\%$ ^{235}U $\Rightarrow$ **enriched** to $\sim$3–5% for reactor fuel.
- **Reprocessing:** recover unused U and bred Pu-239 from spent fuel; separate waste.

Breeding Pu-239 & Weapons

^{238}U+n$\to$ ^{239}U$\xrightarrow{\beta^-}$ ^{239}Np$\xrightarrow{\beta^-}$ ^{239}Pu (fissile).
Reactor $=$ **controlled** ($k = 1$); weapon $=$ **uncontrolled** ($k \gg 1$). Enrichment/reprocessing $\Rightarrow$ proliferation risk.

TRAP Fast **breeder** reactor makes more fissile fuel (Pu-239 from U-238) than it burns — don't confuse "breeder" with "moderator".

§5 — Safety & Environment

E.4 SL & HL

Advantages

- Very high energy density
- Low CO_2 during operation
- Reliable baseload (weather-independent)
- Small land footprint

Disadvantages / Risks

- Long-lived radioactive waste (HLW)
- Meltdown / accident risk
- Thermal pollution (aquatic ecosystems)
- High construction cost
- Proliferation risk
- Uranium mining damage

TRAP "Nuclear power produces no pollution" is WRONG in IB exams. It produces radioactive waste and thermal pollution. Say: low *carbon* emissions, not pollution-free.

Five-Step Method for Fission Energy Calculations (HL)

1. Write balanced equation and identify all species. **2.** Find $\Delta m = m_{\text{reactants}} - m_{\text{products}}$ (in u). **3.** Convert: $E = \Delta m \times 931.5$ MeV (or $\times c^2$ in SI). **4.** Convert to joules if needed: $\times 1.602 \times 10^{-13}$. **5.** Scale to power: $P = R \times E_{\text{fission}}$ or $P = \dot{m}c^2$.