Fission

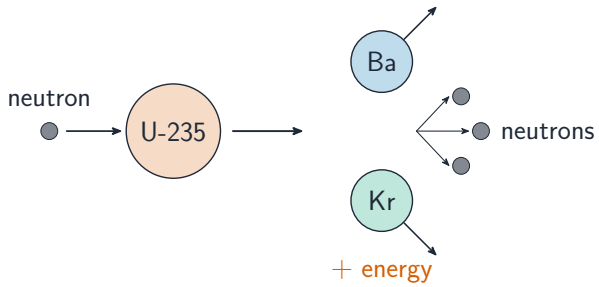
E.4 · SL

Why cool a shut-down reactor?

> Stopping the chain does not remove decay heat.

- Radioactive products already formed continue decaying.
- Neutron control and thermal-energy removal are different tasks.
- Follow the energy: fission $\rightarrow$ fuel heat $\rightarrow$ turbine $\rightarrow$ generator.

Neutron-induced fission



- One possible U-235 channel produces barium, krypton and three neutrons.
- Fragment identities, neutron counts and immediate channel energies vary.

Balancing a fission equation

- Nucleons: $1 + 235 = 141 + 92 + 3$.
- Protons: $0 + 92 = 56 + 36$.

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

Spontaneous fission needs no incoming neutron; not every neutron absorption causes fission.

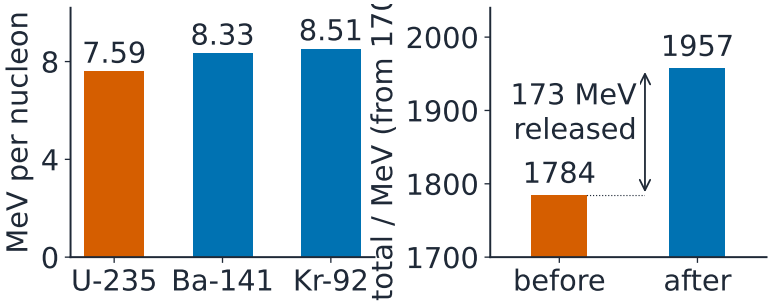
Energy from the mass difference

1. **Known.** Atomic masses: U-235 235.043930 u; Ba-141 140.914411 u; Kr-92 91.926156 u; n 1.008665 u. Three neutrons leave; 1 u $c^2 = 931.5$ MeV.
2. **Initial.** $m_i = 235.043930 + 1.008665 = 236.052595$ u.
3. **Final.** $m_f = 140.914411 + 91.926156 + 3(1.008665) = 235.866562$ u.
4. **Energy.** $Q = (m_i - m_f)c^2 = 0.186033 \times 931.5 = 173.29$ MeV.

Decision

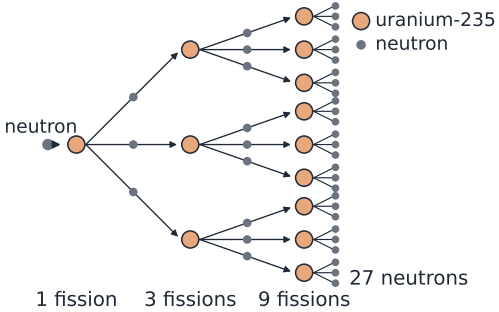
About 2.77×10^{-11} J using 1 MeV $= 1.60 \times 10^{-13}$ J.

Energy from binding energy



- Released energy equals the total binding-energy increase, not a per-nucleon difference alone.
- Displayed values are rounded; free neutrons have zero nuclear binding energy.

Chain reactions



- The drawing assumes every shown neutron causes another fission.
- Real neutron escape and non-fission absorption reduce successful successors.

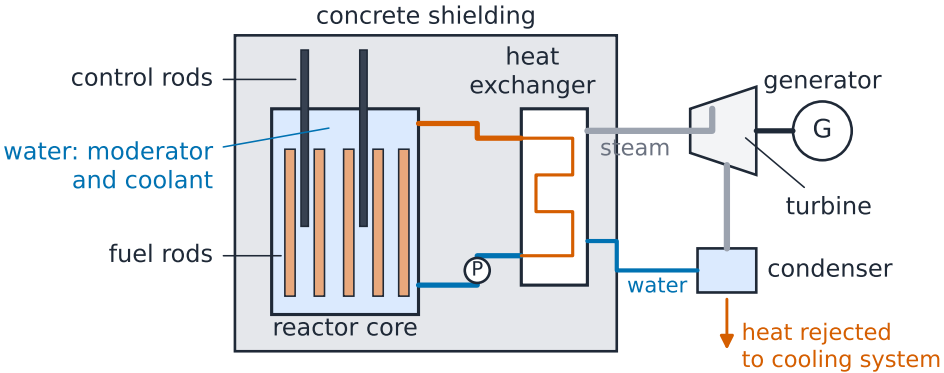
Check: a steady reactor

Your turn

At steady expected fission power, how many successor fissions does each fission cause on average after neutron losses?

A. Zero
B. Exactly one
C. Exactly two
D. Three

Inside a power station



Pressurised-water model: separate **coolant** loops; the condenser rejects heat.

Moderator and control rods

Moderator

Slows neutrons by collisions with suitable light nuclei.

Materials can include water and graphite.

Control rods

Absorbs neutrons using suitable absorber material.

Insertion reduces the neutrons available to continue the chain.

Shutdown, shielding and containment

Neutron chain and heat

Absorbers suppress the self-sustaining chain.

Existing radioactive products still release heat.

Radiation and material

Shielding attenuates transmitted radiation.

Containment and fuel barriers limit release of radioactive material.

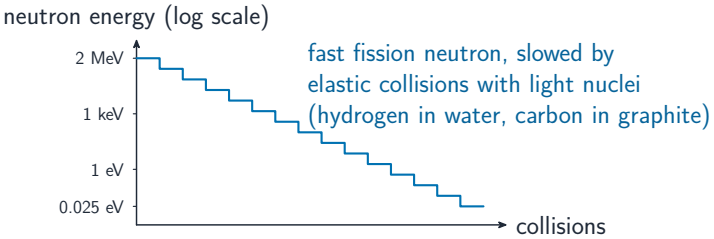
How much fuel?

1. **Known.** 1000 MW electrical; $\eta = 0.33$; deposited heat 200 MeV $= 3.20 \times 10^{-11}$ J per fission; nucleus mass $235 \times 1.661 \times 10^{-27}$ kg; 86400 s/day.
2. **Thermal input.** $P_{\mathrm{th}} = P_{\mathrm{el}}/\eta = 10^{9}/0.33 \approx 3.03 \times 10^{9}$ W.
3. **Fission rate.** $\dot{N} = P_{\mathrm{th}}/E_f \approx 9.47 \times 10^{19}$ per second.
4. **Daily mass.** $m = \dot{N}\Delta t\, m_U \approx 3.19$ kg.

Decision

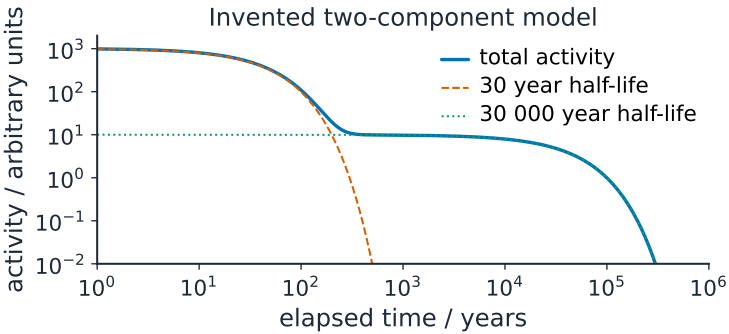
Assigned ideal model: uranium-235 fissioned, not total fuel loaded.

The moderator slows neutrons



Slow neutrons are more likely to cause fission

Fission products



- Invented 30 year and 30 000 year activity components, not a real inventory.
- A mixture can have changing dominant components and no single half-life.

Managing the waste

> Waste routes depend on half-lives, activity, heat and material form.

- Storage manages cooling and shielding; reprocessing leaves radioactive residues.
- Geological disposal aims at long-term passive isolation; not all spent fuel is vitrified.

Fission and climate change

For

Low direct operational carbon emissions.

High fuel energy density; can supply sustained electricity.

Against

Waste, heat management and accident risk.

Costs, construction time and security concerns.

Exam tips

> One successor fission per fission on average gives a steady expected chain.

- Balance nucleon and proton numbers, and count the neutrons.
- Use either masses or binding energies, never a mix.
- The **moderator** slows neutrons; control rods absorb them.

Check yourself

Try these

For n + U-235 $\rightarrow$ Xe-140 + Sr-94 + x n, find x; check $92 = 54 + 38$.

Explain why moderating neutron energy and absorbing neutrons are different functions.

A station supplies 600 MW electrical at $\eta = 0.32$. Assign 3.20×10^{-11} J deposited per fission, 3.16×10^{7} s operation and nucleus mass $235 \times 1.661 \times 10^{-27}$ kg. Find U-235 mass fissioned.