Nuclear Reactors

From the chain reaction to the power station — and what can go wrong

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Outline

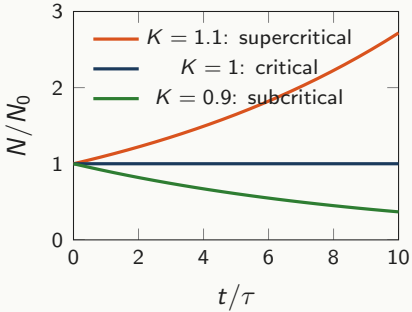
1. **Using the chain reaction**
   critical mass, fission weapons, enrichment
2. **Physics of a fission reactor**
   components, the four-factor formula, criticality and size, kinetics, feedback and breeding
3. **Types of reactors**
   BWR, PWR, PHWR (CANDU), AGR, fast breeders, Generation IV
4. **Problems with nuclear reactors**
   operation; safety (Windscale, Three Mile Island, Chernobyl, Fukushima); waste; decommissioning

Where we left off: neutrons

- Fission of $^{235}\mathrm{U}$ by a **thermal** neutron releases on average $\nu \simeq 2.4$ fast neutrons, $\langle E \rangle \simeq 2\,\mathrm{MeV}$.
- Collisions with light nuclei (the **moderator**) slow them down to $E \simeq 0.025\,\mathrm{eV}$, where $\sigma_f(^{235}\mathrm{U}) \simeq 584\,\mathrm{b}$.
- If each fission causes on average K new fissions:

$$N(t) = N_0\, e^{(K-1)\,t/\tau}$$

τ: mean time between generations.



Today: how K is used — and how it is controlled.

Using the chain reaction

Applications of chain reactions

1. **Atomic bomb** (fission bomb) — an uncontrolled, very fast chain reaction in $^{235}\mathrm{U}$ or $^{239}\mathrm{Pu}$.
   - A minimum amount of fissile material is needed to sustain the chain reaction: the **critical mass**.

2. **Nuclear power station** — converts the heat released by the chain of fissions into electricity.
   - The chain reaction is held at $K = 1$ by **control rods** that absorb the neutrons emitted in fission.

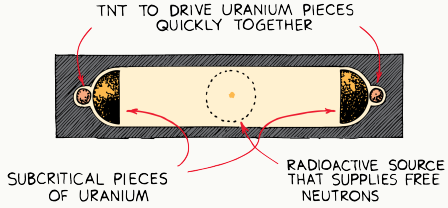
Bare-sphere critical masses

	mass	diameter
$^{235}\mathrm{U}$	$\approx 52\,\mathrm{kg}$	$\approx 17\,\mathrm{cm}$
$^{239}\mathrm{Pu}$	$\approx 10\,\mathrm{kg}$	$\approx 10\,\mathrm{cm}$

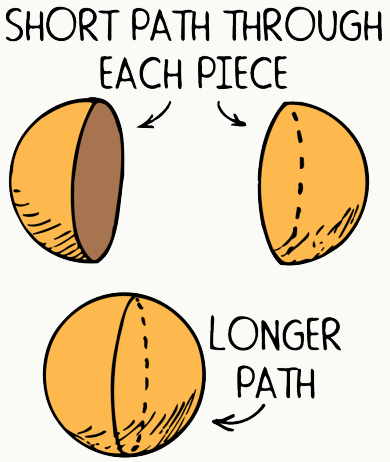
A neutron *reflector* around the core (or compression of the material) lowers these values considerably.

Critical mass: why size matters

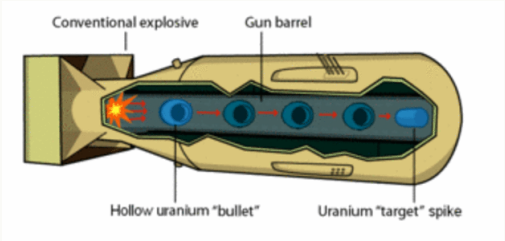
- Two pieces of pure $^{235}\mathrm{U}$ are stable if each is **subcritical**. Brought together quickly, the combined mass can become **supercritical**: a fission bomb.
- Each piece is subcritical because a neutron has a *short path* to the surface: it is likely to escape before causing a fission. The combined piece offers a longer path.



Simplified gun-type fission bomb



The gun-type design

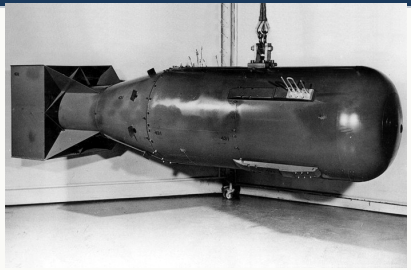


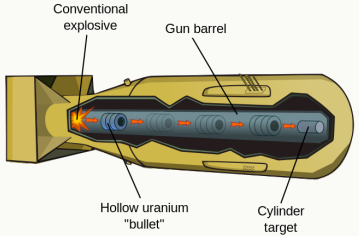
- A conventional explosive fires a hollow uranium "bullet" onto a uranium "target". Assembly takes $\sim$1 ms: slow, but fast enough for uranium.
- Building the bomb is not the hard part: **obtaining almost pure $^{235}\mathrm{U}$ is**. It took over two years to produce enough for Hiroshima, and it is still slow and costly.

Note

Just so you know how it works: what interests us is **not bombs but nuclear power stations**.

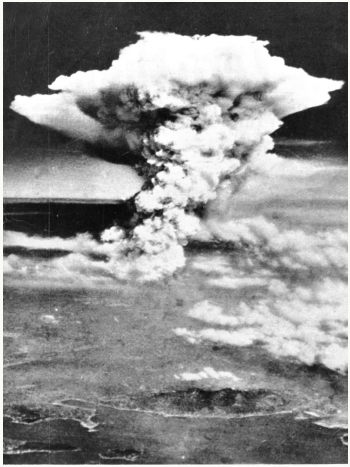
The first atomic bomb — Little Boy





- Gun-type $^{235}\mathrm{U}$ bomb, dropped on **Hiroshima, 6 August 1945**.
- Fuel: 64.1 kg of uranium (38.5 kg projectile + 25.6 kg target), enriched on average to $\approx 80\,\%$ $^{235}\mathrm{U}$, i.e. ≈ 51.3 kg of $^{235}\mathrm{U}$.
- Yield ≈ 15 kt of TNT $= 6.3 \times 10^{13}$ J. At 200 MeV per fission this is 2.0×10^{24} fissions, i.e. only ≈ 0.8 kg **of** $^{235}\mathrm{U}$ — about 1.5 % of the fuel. The rest was blown apart before it could react.

Hiroshima, 6 August 1945



The mushroom cloud over Hiroshima



Hiroshima from the air after the bombing

The city after the explosion

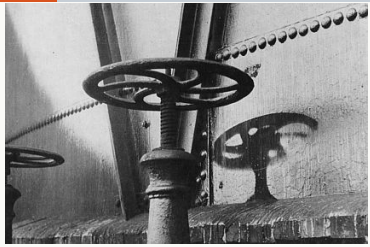




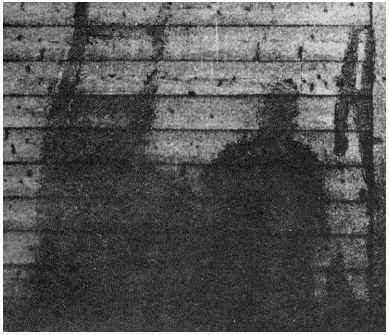


The Prefectural Industrial Promotion Hall — today the Atomic Bomb Dome

“Shadows” burnt into the city





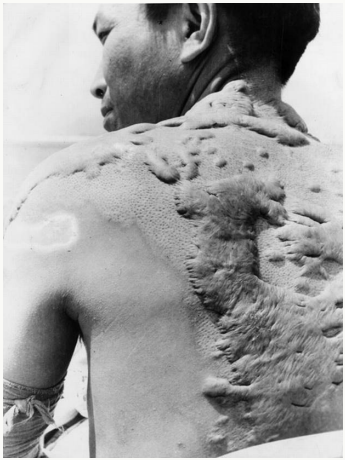


The intense thermal flash bleached the surfaces it reached. Objects — and people — in its path left permanent “shadows” on walls, steps and valves.

The human cost





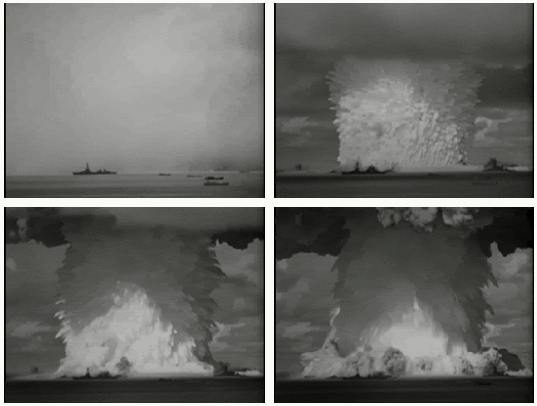


Around 70 000 people died immediately in Hiroshima; by the end of 1945 the toll had roughly doubled, from burns, injuries and acute radiation syndrome.

Three days later (9 August) a plutonium bomb, *Fat Man*, destroyed Nagasaki.

Nuclear weapons

- Work with **fast neutrons** — they need **no moderator**.
- Highly enriched uranium — **at least 80%** $^{235}\mathrm{U}$.
- Large quantities of fissile material (uranium, plutonium) are assembled so as to exceed the **critical mass**: fast neutrons, even with their small cross sections, then trigger a colossal explosion.



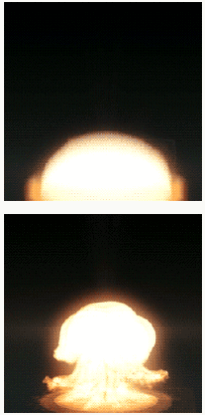
Underwater test, Bikini Atoll (1946): four frames of the explosion

Holding the bomb together

One of the biggest initial problems was precisely to **slow down the disassembly**, so that the chain reaction had time to spread through the whole fuel.

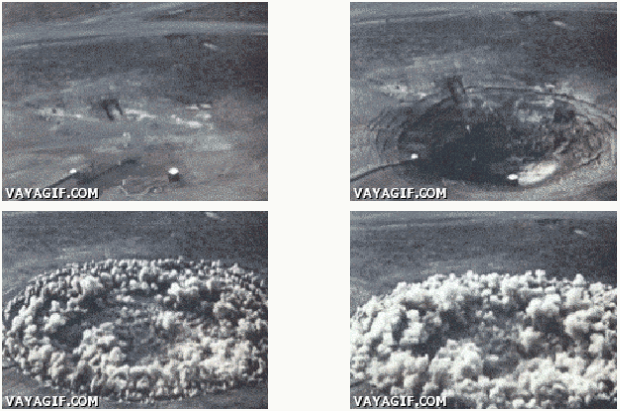
In a supercritical mass a new generation follows every $\sim 10\,\text{ns}$: about 80 generations ($2^{80} \sim 10^{24}$ fissions) in under a microsecond.





Growth of a fireball in the first seconds

Nuclear tests



Crater formation in an underground test



Atmospheric test

- Over 2 000 nuclear tests since 1945.
- 1963: Partial Test Ban Treaty — no tests in the atmosphere, under water or in space.
- 1996: Comprehensive Test Ban Treaty (not yet in force).

Plutonium: why a gun-type bomb does not work

- Plutonium is made in reactors,

$$^{238}\mathrm{U} + \mathrm{n} \longrightarrow {}^{239}\mathrm{U} \xrightarrow{\beta^-} {}^{239}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}\mathrm{Pu},$$

  and separated *chemically* — far easier than enriching uranium.

- But some $^{239}\mathrm{Pu}$ captures a further neutron and becomes $^{240}\mathrm{Pu}$, which undergoes **spontaneous fission**: a constant background of stray neutrons.

- In a gun-type device the two pieces approach at $\sim 300\,\mathrm{m/s}$: the assembly takes about a **millisecond**. A stray neutron starts the chain reaction while the mass is barely critical (*pre-detonation*): a tiny yield — a *fizzle*.

The solution: implosion

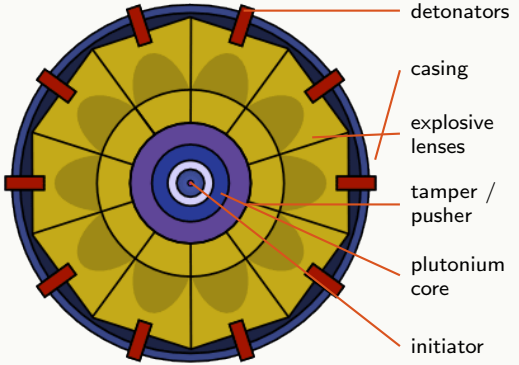
Compress a subcritical Pu sphere with a converging shock wave from conventional explosives.

- Assembly in a few **microseconds**.
- Higher density $\Rightarrow$ shorter mean free path ($\lambda = 1/n\sigma$) $\Rightarrow$ fewer neutrons escape. Critical mass $\propto 1/\rho^2$: doubling ρ makes the same mass **supercritical**.

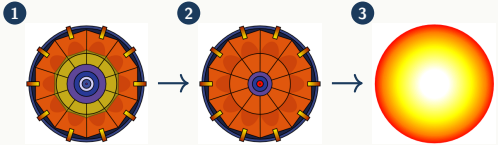
Fat Man (Nagasaki, 1945)

6.2 kg of Pu, ≈ 21 kt: ≈ 1.1 kg fissioned ($\approx 18\,\%$; *Little Boy*: $1.5\,\%$). First tested at *Trinity*, 16 July 1945.

The implosion design

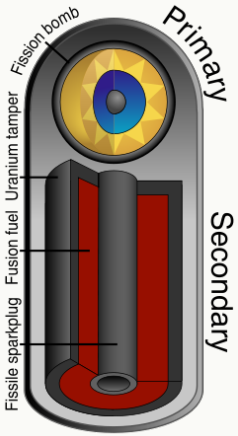


Cross-section before firing.



1. The 32 detonators fire together; the lenses shape the blast into one **converging spherical** shock wave.
2. The shock crushes the core to about **twice** its normal density.
3. At maximum compression the initiator releases neutrons: the chain reaction starts.

Thermonuclear bombs



- **Teller–Ulam design**: a fission bomb (**primary**) is used to ignite **fusion** in a second stage (**secondary**).
- X-rays from the primary compress and heat the secondary; a fissile "spark plug" at its centre helps ignition.
- Fusion fuel: lithium-6 deuteride. Neutrons produce the tritium *in situ*:

$$\mathrm{n} + {}^{6}\mathrm{Li} \longrightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He}$$
$${}^{2}\mathrm{H} + {}^{3}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\,\mathrm{MeV}$$

- No critical mass for fusion: the yield can be made very large — *Ivy Mike* (1952) ≈ 10 Mt; *Tsar Bomba* (1961) ≈ 50 Mt.

Uranium enrichment

- $^{235}\mathrm{U}$ undergoes fission when it absorbs a *thermal* neutron; $^{238}\mathrm{U}$ generally does not. Natural uranium has only **0.72%** of $^{235}\mathrm{U}$ (and **99.28%** of $^{238}\mathrm{U}$). A chain reaction generally needs a **higher fraction of** $^{235}\mathrm{U}$.
- The isotopes are chemically identical: they must be separated by **physical** processes, using their different masses.

Gaseous diffusion

- Uses a gas, uranium hexafluoride: $^{235}\mathrm{UF}_6$ (349 u), $^{238}\mathrm{UF}_6$ (352 u).
- Same temperature $\Rightarrow$ same mean kinetic energy: lighter molecules are faster.
- $^{235}\mathrm{UF}_6$ hits the porous membrane 0.43% more often, and passes through it slightly more easily.

$$\frac{v_{235}}{v_{238}} = \sqrt{\frac{352}{349}} = 1.0043$$

Enrichment: thousands of stages

- The gas leaving each chamber is only slightly enriched. With an ideal separation factor $\alpha = 1.0043$ per stage, going from isotope ratio R_0 to R takes $n = \ln(R/R_0)/\ln\alpha$ stages:

  $0.72\% \to 3\%$ (reactor grade): $n \approx 340$

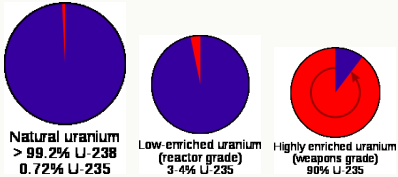
  $0.72\% \to 90\%$ (weapons grade): $n \approx 1\,700$

  Real stages are far from ideal: plants used **thousands** of them.

- Today the **gas centrifuge** dominates: the heavier $^{238}UF_6$ concentrates near the wall, the lighter $^{235}UF_6$ near the axis. Much larger separation per stage, and ~ 50 times less energy than diffusion.



The UF_6 molecule



Natural uranium, reactor grade, weapons grade

Physics of a fission reactor

Nuclear fission reactors

- A litre of petrol can be used to cause a violent explosion — or burnt slowly in a car engine. In the same way, uranium can be used in a bomb or **in a controlled way** in a reactor.
- A fission reactor generates energy through a **controlled** chain reaction. Reactors are furnaces that heat water to produce steam for a turbine.

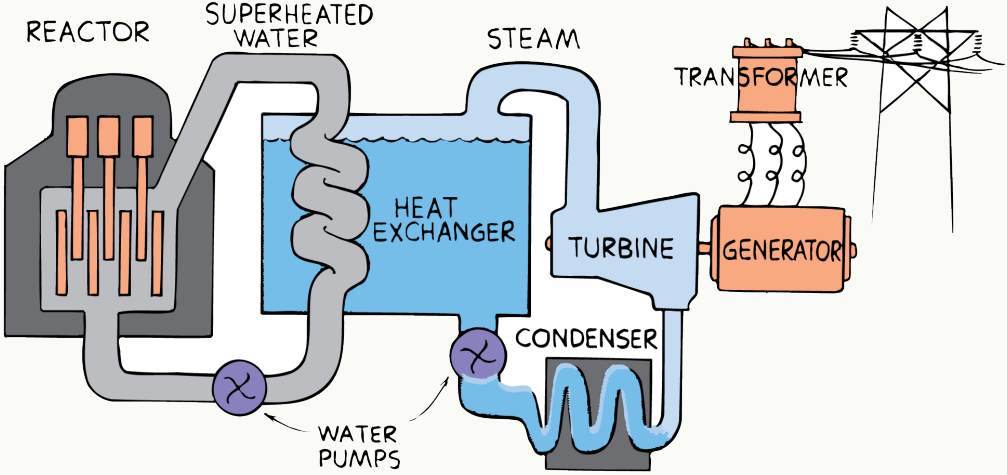
Basic components of a reactor

1. **Nuclear fuel**
2. **Moderator**
3. **Control rods**
4. **Cooling system**

A $1\,\mathrm{GW_e}$ power station during one year

Nuclear: $\approx 25\,\mathrm{t}$ of enriched fuel, of which only $\approx 1.1\,\mathrm{t}$ of $^{235}\mathrm{U}$ undergoes fission.
Coal: $\approx 3\,\mathrm{Mt}$ of coal — some 30 000 railway wagons — emitting $\approx 8\,\mathrm{Mt}$ of $\mathrm{CO_2}$.

The nuclear fission power station



How much energy? The fission budget

Energy released per fission of $^{235}\mathrm{U}$	
Kinetic energy of fragments	$\approx 167\,\mathrm{MeV}$
Prompt neutrons	$\approx 5\,\mathrm{MeV}$
Prompt γ rays	$\approx 7\,\mathrm{MeV}$
β decay of fragments	$\approx 7\,\mathrm{MeV}$
γ decay of fragments	$\approx 6\,\mathrm{MeV}$
Antineutrinos (escape)	$\approx 10\,\mathrm{MeV}$
Total	$\approx 200\,\mathrm{MeV}$

About 190 MeV is recovered as heat; $\approx 7\%$ **comes from radioactive decay** and keeps being released after shutdown.

1 kg of $^{235}\mathrm{U}$

$$N = \frac{1\,000\,\mathrm{g}}{235\,\mathrm{g\,mol^{-1}}}\,N_A = 2.56 \times 10^{24}\ \text{nuclei}$$

$$E = N \times 200\,\mathrm{MeV} \approx 8.2 \times 10^{13}\,\mathrm{J} \approx 950\,\mathrm{MW\,d}$$

Hard coal: $\approx 29\,\mathrm{MJ/kg} \Rightarrow \approx 2\,800\,\mathrm{t}$ of coal, i.e. some **30 railway wagons**.

Rule of thumb: fissioning 1 g of $^{235}\mathrm{U}$ gives $\approx 1\,\mathrm{MW}$ of heat for one day.

Fuel and moderator

Fuel

The fuel must be a **fissile** material. Some reactors can run on natural uranium, but as a rule uranium **enriched to 3–5%** $^{235}\mathrm{U}$ or plutonium is required. **Plutonium has first to be produced in other reactors.**

Moderator

- A substance that **slows the neutrons down until they are thermal**, the regime in which the fission cross section is largest.
- It must have a **low neutron-absorption cross section**: we want to moderate the neutrons, not make them disappear.
- From the previous lecture: the best moderators have **low** A — the most common are graphite and water (the hydrogen in $\mathrm{H_2O}$).

Choosing a moderator

A moderator should:

1. **be cheap and abundant;**
2. **be chemically stable;**
3. **have a low mass number** A (so that collisions slow the neutrons efficiently);
4. **be liquid or solid** (high density helps moderation);
5. **have a low neutron-capture cross section.**

	1 cheap	2 stable	3 low A	4 dense	5 low capt.
Graphite	✓	✓	×	✓	✓
H_2O	✓	✓	✓	✓	×
D_2O	×	✓	✓	✓	✓

- **Graphite**: $A = 12$, so more collisions are needed — larger reactors.
- **H_2O**: hydrogen captures neutrons, $\mathrm{n} + \mathrm{p} \longrightarrow \mathrm{d} + \gamma$ ($\sigma_a = 0.33\,\mathrm{b}$).
- **D_2O**: deuterium hardly captures them ($\sigma_a = 0.000\,5\,\mathrm{b}$, giving some radioactive tritium, $\mathrm{n} + \mathrm{d} \longrightarrow \mathrm{t} + \gamma$). Only 1 H atom in 6400 is D: heavy water is expensive.

Can a reactor run on natural uranium?

Natural uranium is uranium as it comes out of the mine: **0.72 %** $^{235}\mathrm{U}$, 99.28 % $^{238}\mathrm{U}$, with no enrichment.

With so little $^{235}\mathrm{U}$, the chain reaction only just closes: almost every neutron has to survive. The moderator decides whether it does.

Moderator	Natural uranium?
H_2O	**no**: too much capture
Graphite (pure)	yes: Chicago Pile-1 (1942), Magnox (UK)
D_2O	yes: CANDU (Canada), PHWR (India)

Yes, there is a limit

- The margin above criticality is **small**: graphite must be free of boron — impure graphite was one reason the German wartime programme failed.
- As $^{235}\mathrm{U}$ is used up and fission products absorb neutrons, the reactor soon falls below critical: natural fuel reaches only $\approx 7\,\mathrm{GWd/t}$ (*burn-up*), against $\approx 50\,\mathrm{GWd/t}$ for enriched fuel.
- So CANDU reactors **refuel continuously**, without shutting down.

Light-water reactors (most of the world's fleet) need 3–5 % enrichment.

Moderators compared

From the previous lecture: in an elastic collision with a nucleus of mass number A, the average decrease of $\ln E$ is

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1}$$

($\xi = 1$ for hydrogen), so the number of collisions needed to go from E_0 to E is

$$n = \frac{\ln(E_0/E)}{\xi}, \quad \ln \frac{2\,\text{MeV}}{0.025\,\text{eV}} \approx 18.2$$

A good moderator also needs a large scattering and a small absorption: the **moderating ratio** $\xi\Sigma_s/\Sigma_a$.

	ξ	collisions 2 MeV→0.025 eV	moderating ratio
H_2O	0.93	≈ 20	≈ 60
D_2O	0.51	≈ 35	≈ 5000
Graphite	0.16	≈ 115	≈ 200

H_2O moderates best per collision (it fits in a compact core), but absorbs; D_2O is the best overall moderator; graphite is cheap and absorbs little, but needs large volumes.

Control rods and cooling

Control rods

Made of materials with a **large neutron-absorption cross section**: they stop the reaction by reducing the number of available neutrons. Examples: **boron** ($^{10}\mathrm{B}$), **cadmium**, **hafnium**, the rare earths **gadolinium** and **europium**, and silver–indium–cadmium alloys.

Cooling

Usually water, although some reactors use gases or liquid metals. The coolant **carries the heat to the turbines** (which then generate electricity) and **prevents the core from melting**.

Reactors are *homogeneous* if fuel and moderator are mixed, and *heterogeneous* if they are kept separate (fuel rods in a moderator).

The first reactor, Chicago Pile-1, built by **Fermi and Szilard** (2 December 1942), was a "pile" of uranium lumps embedded in graphite blocks.

The four-factor formula

To run a reactor we must keep the multiplication factor at $K = 1$:

$$N(t) = N_0 \, e^{(K-1)\, t/\tau}$$

What determines K, and how can we keep it equal to 1?

- First neglect geometry: an **infinite** mass of fuel, where no neutron leaks out. We calculate K_∞ by following one generation of neutrons.
- Each fission of $^{235}\mathrm{U}$ produces on average $\nu = 2.43$ neutrons. Does that mean $K_\infty = 2.43$? No:
  - some neutrons are captured without fission (cross section σ_c),
  - only the others cause fission (cross section σ_f),
  - and more are lost along the way while they slow down.
- The number of neutrons that continue the chain is therefore smaller than ν.

First factor: η — neutrons per absorption in the fuel

η = average number of fission neutrons produced per **thermal neutron absorbed in the fuel**:

$$\eta = \nu \frac{\sigma_f}{\sigma_f + \sigma_c}$$

i.e. ν times the **probability that an absorption causes fission**.

$E = 0.025\,3$ eV	σ_c (b)	σ_f (b)
^{235}U	97	584
^{238}U	2.75	0

Pure ^{235}U:

$$\eta = 2.43 \times \frac{584}{584 + 97} = 2.08$$

Natural uranium (0.72% ^{235}U, 99.28% ^{238}U):

$$\bar{\sigma}_f = 0.0072 \times 584 = 4.20\,\text{b}$$

$$\bar{\sigma}_c = 0.0072 \times 97 + 0.9928 \times 2.75 = 3.43\,\text{b}$$

$$\boxed{\eta = 2.43 \times \frac{4.20}{4.20 + 3.43} = 1.34}$$

Second and third factors: ε and p

Fast-fission factor ε

The fission neutrons are *fast*. Before slowing down, a few cause **fast fission** — in $^{235}\mathrm{U}$ and also in $^{238}\mathrm{U}$, which has a threshold of $\approx 1\,\mathrm{MeV}$:

$$\varepsilon = \frac{\text{total number of fission neutrons produced}}{\text{number of neutrons from thermal fission}} \gtrsim 1, \qquad \varepsilon \simeq 1.03 \text{ (natural uranium)}$$

Resonance-escape probability p

While slowing down from $\sim 2\,\mathrm{MeV}$ to $0.025\,3\,\mathrm{eV}$, neutrons cross the region of the huge $^{238}\mathrm{U}$ capture **resonances** (6–200 eV). To avoid them, fuel and moderator are separated: neutrons slow down in the moderator, away from the uranium. p is the probability of **escaping resonance capture**; typically $p \approx 0.9$ (depends on the design).

$$N \xrightarrow{\text{fission}} \eta N \xrightarrow{\text{fast fission}} \varepsilon\eta N \xrightarrow{\text{moderation}} p\varepsilon\eta N$$

Fourth factor f and the four-factor formula

Thermal-utilisation factor f

Once thermalised, neutrons should reach the uranium as quickly as possible, so there should not be too much moderator: thermal neutrons are also absorbed by the moderator and the structures. Graphite has only $\sigma_a = 0.003\,4\,\text{b}$, but there is a lot of it in a reactor. f is the **fraction of thermal neutrons absorbed in the fuel**; it depends on the design and is typically $f \approx 0.9$.

$$N \xrightarrow{\text{fission}} \eta N \xrightarrow{\text{fast fission}} \varepsilon\eta N \xrightarrow{\text{moderation}} p\varepsilon\eta N \xrightarrow{\text{utilisation}} fp\varepsilon\eta N$$

The four-factor formula

$$K_\infty = \eta\,\varepsilon\,p\,f \qquad \text{natural U:} \quad K_\infty = 1.34 \times 1.03 \times 0.9 \times 0.9 \approx 1.12$$

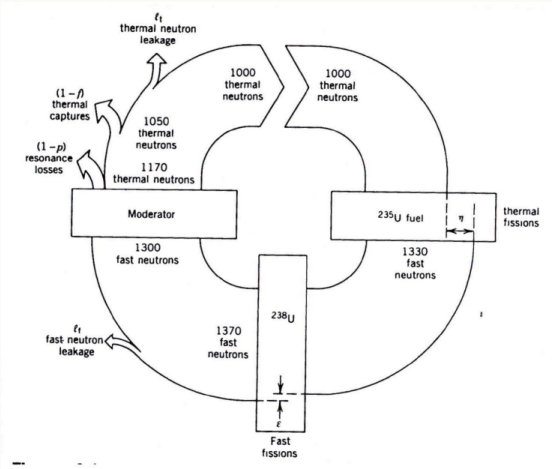
A finite reactor: neutron leakage

- $K_\infty \approx 1.12 > 1$ for natural uranium. Does it then explode? We know it does not: we must account for the **finite size** of the reactor.
- Neutrons that reach the surface leave the core and are lost to the chain. Let
  - l_f = fraction of *fast* neutrons that escape,
  - l_t = fraction of *thermal* neutrons that escape.
- The four-factor formula becomes the **six-factor formula**:

$$K = K_\infty P_{\mathrm{NL}} = \eta\, \varepsilon\, p\, f\, (1 - l_f)(1 - l_t)$$

where P_{NL} is the **non-leakage probability**, which depends on the size and shape of the reactor. **How can we calculate P_{NL}?**

The neutron cycle in a thermal reactor



From neutron-diffusion theory:

$$K = K_\infty P_{\mathrm{NL}} = \frac{K_\infty}{1 + B^2 M^2}$$

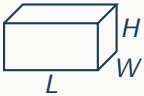
- M — **migration length**, from birth (fast) to absorption (thermal): $M^2 = L^2 + \tau_F$ (L: thermal diffusion length; τ_F: Fermi age — despite its name, an **area**).
- B — **buckling**: a geometric factor measuring the curvature of the neutron flux in a critical reactor.

Geometry: buckling and migration length

$$P_{\mathrm{NL}} = \frac{1}{1 + B^2 M^2}$$



Sphere $B^2 = \left(\frac{\pi}{R}\right)^2$



Box $B^2 = \left(\frac{\pi}{L}\right)^2 + \left(\frac{\pi}{W}\right)^2 + \left(\frac{\pi}{H}\right)^2$



Cylinder $B^2 = \left(\frac{\pi}{H}\right)^2 + \left(\frac{2.405}{R}\right)^2$

Very large slab, one finite dimension a: $B^2 = (\pi/a)^2$. 2.405: first zero of the Bessel function J_0.

M is a property of the medium:

Moderator	M (cm)
H_2O	5.84
D_2O	174
Graphite	62

Larger B (smaller, more "curved" core) $\Rightarrow$ more leakage.

Example: the critical size of a uranium–graphite pile

What is the minimum radius of a sphere of natural uranium and graphite that makes a critical reactor?

$$K = \frac{K_\infty}{1 + B^2 M^2}, \qquad B^2 = \frac{\pi^2}{R^2}$$

$$K = \frac{K_\infty}{1 + \dfrac{\pi^2 M^2}{R^2}} \qquad \begin{array}{l} K \to 0 \quad (R \to 0) \\ K \to K_\infty \quad (R \to \infty) \end{array}$$

Natural uranium: $K_\infty = 1.12$; graphite: $M = 62\,\mathrm{cm}$.

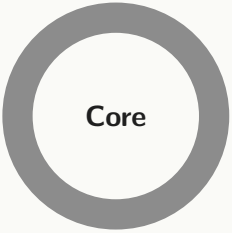
Criticality, $K = 1$:

$$1 = \frac{K_\infty}{1 + \dfrac{\pi^2 M^2}{R_c^2}} \;\Rightarrow\; R_c = \frac{\pi M}{\sqrt{K_\infty - 1}}$$

$$R_c = \frac{\pi \times 0.62\,\mathrm{m}}{\sqrt{0.12}} \approx 5.7\,\mathrm{m}$$

Note the sensitivity to $K_\infty - 1$: with $K_\infty = 1.11$ one gets $R_c \approx 5.9\,\mathrm{m}$. CP-1 indeed needed $\sim 350\,\mathrm{t}$ of graphite.

Making reactors smaller



reflector

- **Reflector**: a layer around the core that scatters escaping neutrons back in. Good reflectors have low absorption cross sections (graphite, beryllium, water). The theory is rather complex.
- **Enrichment**: take pure $^{235}\mathrm{U}$ (same ε, p, f):

$$K_\infty = f\,p\,\varepsilon\,\eta = 0.9 \times 0.9 \times 1.03 \times 2.08 = 1.74$$

$$R_c = \frac{\pi \times 0.62\,\mathrm{m}}{\sqrt{1.74 - 1}} \approx 2.3\,\mathrm{m}$$

Exercise

Repeat the calculation for a **cube**. Which shape needs the least fuel?

Answer: $a_c = \sqrt{3}\,\pi M/\sqrt{K_\infty - 1} \approx 9.9\,\mathrm{m}$ (natural U); the sphere.

Useful nuclear data (thermal neutrons, 0.025 3 eV)

Isotope	ν	σ_c (b)	σ_f (b)
$^{238}\mathrm{U}$	—	2.75	0
$^{235}\mathrm{U}$	2.43	97	584
$^{239}\mathrm{Pu}$	2.87	270	748

Moderator	Migration length M (cm)
Water	5.84
Heavy water	174
Graphite	62

Geometry	Buckling B^2
Sphere, radius R	$(\pi/R)^2$
Box, $L \times W \times H$	$\frac{\pi^2}{L^2} + \frac{\pi^2}{W^2} + \frac{\pi^2}{H^2}$
Cylinder, $R \times H$	$\frac{\pi^2}{H^2} + \frac{2.405^2}{R^2}$

σ_c: radiative capture (n, γ).
Total absorption: $\sigma_a = \sigma_c + \sigma_f$.

M values are approximate and depend on purity and temperature (especially for D_2O).

Why can a reactor be controlled at all? Delayed neutrons

- Prompt neutrons only: generation time $\ell \sim 10^{-4}$ s. With $K = 1.001$ the power would grow with period $T = \ell/(K-1) = 0.1$ s — a factor $e^{10} \approx 22\,000$ in one second!
- But a fraction $\beta = 0.65\%$ of the neutrons from $^{235}\mathrm{U}$ fission are **delayed**: emitted after the β decay of fission fragments (e.g. $^{87}\mathrm{Br} \to {}^{87}\mathrm{Kr}^{*} \to {}^{86}\mathrm{Kr} + n$), with mean delay $\bar{t} \approx 13$ s.
- Effective generation time: $\ell_{\mathrm{eff}} \approx \ell + \beta\,\bar{t} \approx 0.08$ s $\Rightarrow$ $T \approx 80$ s: time enough for control rods to act.

Reactivity

$$\rho = \frac{K-1}{K}$$

$\rho < \beta$: **delayed-critical** — slow, controllable.

$\rho \geq \beta$: **prompt-critical** — the reactor multiplies on prompt neutrons alone and the power runs away in milliseconds.

$\rho = \beta$ defines one "dollar" of reactivity.

$^{239}\mathrm{Pu}$ has $\beta \approx 0.2\%$ only: plutonium-fuelled cores are harder to control.

Feedback: reactivity coefficients and xenon

Temperature and void coefficients: how does ρ change when the core heats up?

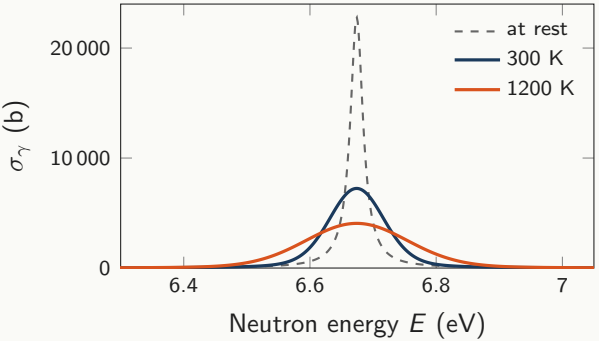
- **Doppler effect**: hotter fuel broadens the $^{238}\mathrm{U}$ capture resonances $\Rightarrow$ p and ρ decrease. Prompt, and negative in any $^{238}\mathrm{U}$-rich fuel (next slides).
- **Void coefficient** (steam bubbles in the coolant). With water as moderator, less water means less moderation $\Rightarrow$ ρ decreases: **self-stabilising**.
- If water is mainly an *absorber* and graphite moderates (RBMK), voids **increase** ρ: a positive coefficient.

Xenon poisoning

- $^{135}\mathrm{Xe}$ has the largest known thermal absorption cross section, $\sigma_a \approx 2.6 \times 10^6$ b.
- Produced mainly via $^{135}\mathrm{I}$ ($t_{1/2} = 6.6\,\mathrm{h}$) $\rightarrow$ $^{135}\mathrm{Xe}$ ($t_{1/2} = 9.1\,\mathrm{h}$); burnt by neutron capture during operation.
- After a power reduction, xenon builds up (peak after $\sim 10\,\mathrm{h}$): the reactor may be impossible to restart for a day — the "**xenon pit**".

Both effects will reappear at Chernobyl.

The Doppler effect in the fuel



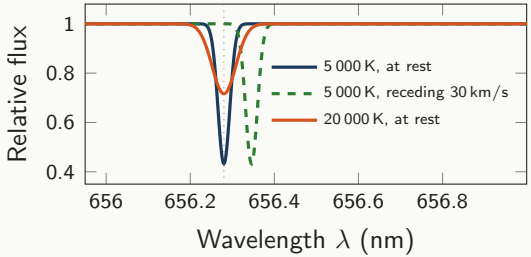
The 6.67 eV capture resonance of ^{238}U (Breit–Wigner, Doppler-broadened). Peak 22 800 → 7 200 → 4 100 b; same area.

Same physics as the Doppler broadening of spectral lines in a hot gas.

"Doppler" refers to the **relative velocity** between neutron and nucleus.

- The resonance sits at a fixed energy in the neutron–nucleus frame.
- The ^{238}U nuclei vibrate thermally: a nucleus moving *towards* the neutron raises the collision energy, one moving *away* lowers it.
- Averaged over these velocities the resonance looks **wider and lower**. Doppler width $\Delta = \sqrt{4E_0kT/A}$: 0.054 eV at 300 K, 0.11 eV at 1 200 K (natural width 0.025 eV).

The same effect in starlight



Hydrogen Hα absorption line ($\lambda_0 = 656.28\,\text{nm}$), thermal Doppler profile only; equal line strength in all three cases.

A moving source changes the wavelength we receive: $\Delta\lambda/\lambda_0 = v_r/c$, with v_r the velocity along the line of sight. Two different consequences →

In the reactor only case 2 occurs: the ^{238}U nuclei are the "atoms" and the resonance is the "line".

1. Star moves: shift

All atoms share the star's velocity: every line moves by the *same* amount. 30 km/s away ⇒ $\Delta\lambda = +0.066\,\text{nm}$. Used to find exoplanets.

2. Atoms jiggle: broadening

Each atom has its own thermal velocity, towards or away from us: the line is *smeared* symmetrically, with width $\Delta\lambda_D/\lambda_0 = \sqrt{2kT/mc^2}$: 0.020 nm at 5 000 K, 0.040 nm at 20 000 K for H. Hotter ⇒ wider and shallower.

Real stellar lines are also widened by pressure, rotation and turbulence. The redshift of distant galaxies is mainly due to the expansion of space.

Why a broader resonance captures more neutrons

Same area — so why more capture?
Self-shielding:

- At the peak the mean free path in UO_2 is only some tens of µm: neutrons at that energy are all captured at the surface of the fuel pellet.
- The interior is *shielded*: there, capture is limited by how many neutrons arrive, not by σ.
- Broadening moves part of the resonance into the **wings**, where σ is moderate and the whole pellet absorbs.

Net result: more captures in $^{238}\mathrm{U}$ $\Rightarrow$ the resonance escape probability p falls $\Rightarrow$ k and ρ fall.

Prompt

Depends only on the **fuel** temperature, which rises within milliseconds of a power increase; coolant and moderator effects wait seconds for the heat to flow out. Doppler is the **first brake** on a power excursion.

Negative — with a caveat

Negative whenever capture in $^{238}\mathrm{U}$ dominates (all commercial reactors): -2 to -4 pcm/K in a PWR ($1\,\mathrm{pcm} = 10^{-5}$). Weaker in fuels with little $^{238}\mathrm{U}$. At Chernobyl it was far too small to offset the RBMK's **positive void** coefficient.

Breeding: making fuel from fertile nuclei

- $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$ are not fissile, but they are **fertile**: neutron capture followed by two β^- decays produces a fissile nucleus.

$$^{238}\mathrm{U} + \mathrm{n} \longrightarrow {}^{239}\mathrm{U} \xrightarrow[23.5\,\mathrm{min}]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.36\,\mathrm{d}]{\beta^-} {}^{239}\mathrm{Pu}$$

$$^{232}\mathrm{Th} + \mathrm{n} \longrightarrow {}^{233}\mathrm{Th} \xrightarrow[22\,\mathrm{min}]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27\,\mathrm{d}]{\beta^-} {}^{233}\mathrm{U}$$

- **Conversion ratio** C = fissile nuclei produced / fissile nuclei consumed. Light-water reactors: $C \approx 0.6$ — about a third of the energy they produce over a fuel cycle comes from plutonium made in the core.
- $C > 1$: a **breeder reactor**. One neutron must sustain the chain and *more than one* must be captured in fertile material, so we need $\eta > 2$: this favours **fast neutrons** with $^{239}\mathrm{Pu}$ ($\eta \approx 2.9$ for fast spectra).

Nature got there first: the Oklo reactors

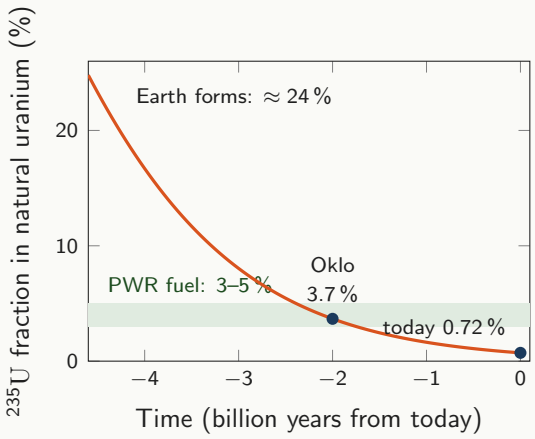
- Everywhere on Earth — and in meteorites — uranium has the same isotopic composition: **0.720 %** $^{235}\mathrm{U}$.
- 1972: at the French enrichment plant of Pierrelatte, uranium from the **Oklo** mine (Gabon) showed **0.717 %**. Some samples later went down to 0.44 %. Some $^{235}\mathrm{U}$ was **missing**.
- No chemical process separates isotopes. The only way to destroy $^{235}\mathrm{U}$ selectively is **fission**.

Predicted by P. Kuroda in 1956. About 16 natural reactor zones are known, all at Oklo.

Explanation (F. Perrin, 1972)

- About **2 billion years ago**, natural chain reactions ran in a rich uranium deposit, moderated by **groundwater**.
- Self-regulating: the heat boiled the water away, the reaction stopped, water returned — cycles of roughly half an hour on, a few hours off, for some 100 000 years.
- Proof: fission products (Nd, Ru, Xe, ...) with the isotopic ratios of $^{235}\mathrm{U}$ fission were found in the rock.

Why Oklo was possible then — and not now



$^{235}\mathrm{U}$ decays **six times faster** than $^{238}\mathrm{U}$: $t_{1/2} = 0.704\,\mathrm{Gyr}$ vs $4.47\,\mathrm{Gyr}$. So in the past there was relatively *more* $^{235}\mathrm{U}$. Running both decays backwards:

$$\left.\frac{N_{235}}{N_{238}}\right|_{t\ \mathrm{ago}} = 0.00725\; e^{(\lambda_5 - \lambda_8)\,t}.$$

With $\lambda_5 - \lambda_8 = 0.830\,\mathrm{Gyr}^{-1}$ and $t = 2\,\mathrm{Gyr}$: ratio ≈ 0.038, i.e. $\approx 3.7\,\%$ $^{235}\mathrm{U}$.

So

Natural uranium was then as enriched as **modern PWR fuel**: ordinary water could moderate it. Today (0.72 %) uranium + light water can **never** be critical.

Types of reactors

Types of reactors











Classification by type of nuclear reaction

- **Nuclear fission** — all commercial reactors. They run on uranium or plutonium; thorium is also possible. Two broad classes:
  - **Thermal reactors** — by far the most common. A **moderator** slows the neutrons down until they are thermalised. Thermal neutrons have a large fission cross section on $^{235}\mathrm{U}$ and $^{239}\mathrm{Pu}$ and a small absorption cross section on $^{238}\mathrm{U}$: natural or slightly enriched uranium can be used. The moderator is often also the coolant — usually water under high pressure, to raise its boiling point.
  - **Fast-neutron reactors** — no moderator, and coolants with little moderating power. Fission cross sections are much smaller at high energy, so the fuel must be more fissile: **$\sim$15–20% $^{235}\mathrm{U}$, or plutonium**. They produce less long-lived waste (they can burn actinides) but are harder to build and operate.
- **Nuclear fusion** — still experimental; fuel: hydrogen isotopes (deuterium and tritium).

Classification by moderator, coolant and generation

Moderator (thermal reactors only)

- Graphite
- Water (light or heavy)
- Light elements (beryllium, BeO)
- Organic compounds (hydrocarbons)

Coolant

- Water (light or heavy)
- Liquid metals (Na, Pb) — water cannot cool a fast reactor: it is also a moderator
- Gas — helium or CO_2
- Molten salts (fluorides)

Generation

- **I** — prototypes and early power reactors (1950s–60s)
- **II** — first commercial fleets, 1 965–1 996
- **III / III+** — improved safety, 1996 – today (ABWR, EPR, AP1000)
- **IV** — under development (fast, very-high-temperature, molten-salt reactors, . . .)

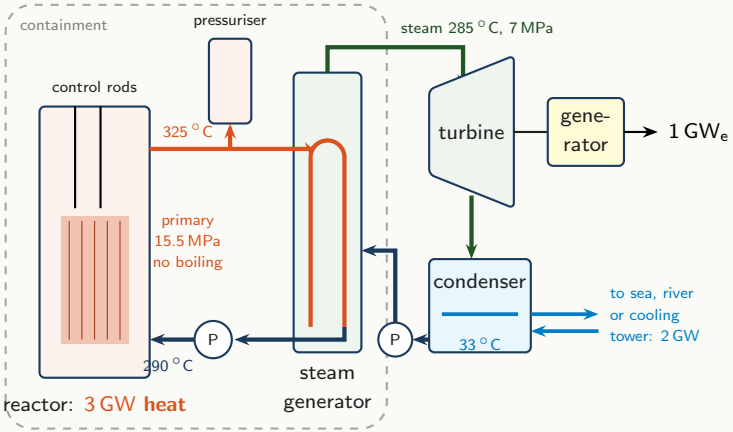
Classification by use

- **Electricity** — nuclear power stations.
- **Propulsion** — naval (submarines, aircraft carriers, icebreakers); space propulsion is under study.
- **Breeder reactors** — produce fissile material from fertile nuclei, $^{238}\mathrm{U} \rightarrow {}^{239}\mathrm{Pu}$ or $^{232}\mathrm{Th} \rightarrow {}^{233}\mathrm{U}$. Once running, they can be refuelled with natural (or depleted) uranium or thorium.
- **Plutonium production** for nuclear weapons.
- **Isotope production** — e.g. $^{99}\mathrm{Mo}$ (parent of $^{99m}\mathrm{Tc}$, the most used isotope in medical imaging), $^{60}\mathrm{Co}$ for radiotherapy and sterilisation. ($^{241}\mathrm{Am}$ for smoke detectors is recovered from reactor plutonium.)
- **Neutron sources** for science and industry.
- **Research reactors** — research, education and training. Much smaller; about 220 operate worldwide. Portugal's research reactor (RPI, Sacavém) ran from 1961 to 2016.

Technologies in use

- **BWR** — Boiling Water Reactor.
- **PWR** — Pressurised Water Reactor: about two thirds of the reactors in operation.
- **PHWR** — Pressurised Heavy Water Reactor, e.g. CANDU (*CANada Deuterium Uranium*).
- **GCR / AGR** — Gas-Cooled Reactors (Magnox) and Advanced Gas-cooled Reactors, developed and used mainly in the United Kingdom.
- **RBMK** — *Reaktor Bolshoy Moshchnosti Kanalny* ("high-power channel reactor"): a Soviet design, graphite-moderated and water-cooled, for electricity and plutonium. Large and less stable, but it uses ordinary water and slightly enriched uranium.
- **LMFBR** — Liquid Metal Fast Breeder Reactor: liquid-metal coolant, no moderator; "breeders" because they produce fuel while operating.
- Others: **PBR** (Pebble-Bed), **MSR** (Molten Salt), **AHR** (Aqueous Homogeneous) reactors, ...

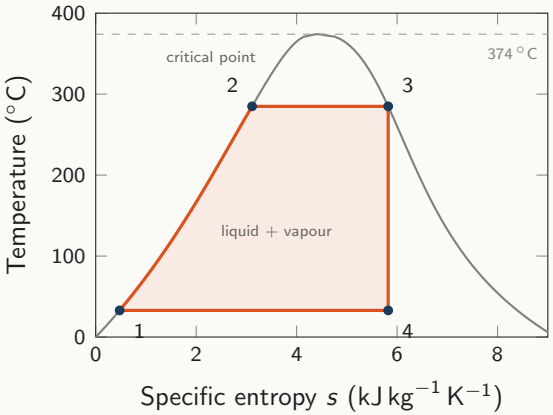
From fission heat to electricity: the PWR



PWR plant (schematic). Red: primary; blue/green: secondary water and steam; light blue: cooling water.

- The reactor is just a **heat source**; the rest is a conventional steam plant.
- **Primary**: 15.5 MPa, so it does not boil at 325 °C; radioactive, stays in the containment.
- **Steam generator**: heat crosses thousands of U-tubes into the **secondary**, which boils.
- **BWR**: boils in the core; steam goes *directly* to the turbine.

The thermodynamic cycle: Rankine



Ideal cycle for PWR secondary conditions (6.9 MPa / 5 kPa), computed with the IAPWS-IF97 steam tables.

1→2 **Pump**, then **heating** to boiling.

2→3 **Boiling** at constant $T = 285\,^{\circ}\mathrm{C}$.

3→4 **Turbine**: expansion; exit $\approx 68\,\%$ vapour.

4→1 **Condenser**: heat rejected at $33\,^{\circ}\mathrm{C}$.

Enclosed area = work per kg of steam.

Efficiencies

Carnot, $1 - T_c/T_h = 1 - \frac{306}{558}$	$45\,\%$
Ideal Rankine (this cycle)	$38\,\%$
Real PWR (turbine losses, ...)	$\approx 33\,\%$

The primary must stay liquid, so $T_h \lesssim 290\,^{\circ}\mathrm{C}$: **two thirds** of the heat goes to the environment.

Thermodynamic cycles of the different reactor types

Reactor	How the steam is made	Steam	Net efficiency
BWR	**direct**: boils in the core	saturated, 285 °C, 7 MPa	≈ 33 %
PWR	indirect: steam generators	saturated, 280 °C, 6–7 MPa	33–35 %
PHWR (CANDU)	indirect (D_2O primary)	saturated, 260 °C, 4.7 MPa	30–32 %
RBMK	direct, boiling in pressure tubes	saturated, 280 °C, 7 MPa	≈ 31 %
AGR	CO_2 gas at 640 °C → steam	superheated, 540 °C, 16 MPa	≈ 41 %
LMFBR	Na → intermediate Na loop → steam	superheated, 500 °C	40–42 %
HTGR (HTR-PM)	helium → steam	superheated, 565 °C	≈ 40 %

All Rankine (steam) cycles

The hotter the coolant, the hotter the steam and the higher the efficiency: gas- and sodium-cooled reactors beat water-cooled ones.

Future: Brayton (gas turbine)

Hot helium or supercritical CO_2 drives a gas turbine directly: 45–50 %. Not yet commercial.

Typical values; individual plants vary.

Nuclear power in the world today

World fleet (October 2026)	
Operable power reactors	443
Net capacity	$\approx 406\,\mathrm{GW_e}$
Under construction	79
Share of world electricity (2025)	$\approx 9\%$
Research reactors	≈ 220

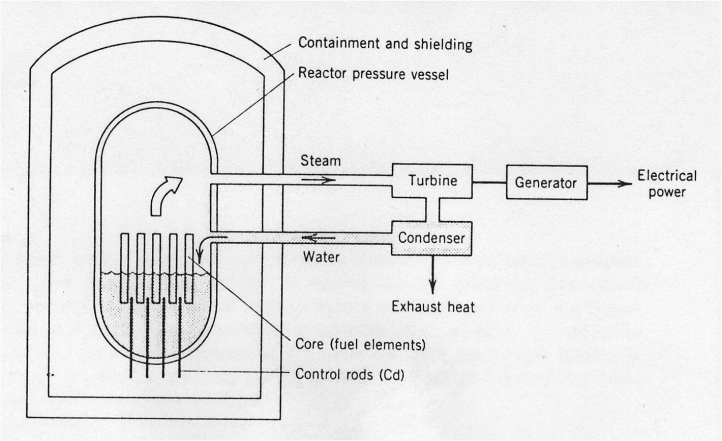
Source: World Nuclear Association, *Nuclear Power in the World Today*, updated 23 Oct 2026.

- Most reactors are light-water reactors (PWR and BWR) of Generation II, many now licensed to run for 60 years.
- Most new construction is in Asia (China, India), with Generation III+ designs.
- **Small modular reactors** (SMRs, $\lesssim 300\,\mathrm{MW_e}$), built in factories, are a major focus of current development.

BWR — Boiling Water Reactor

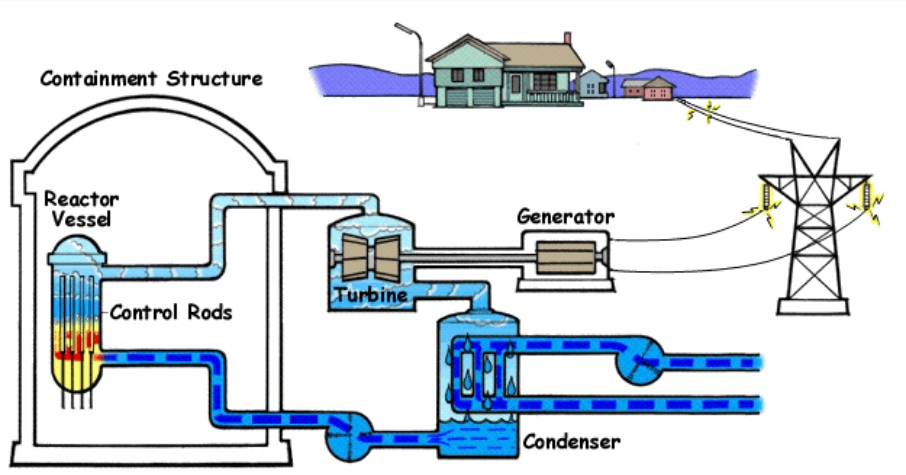
- The moderator is **ordinary liquid water**: a *light-water reactor* (LWR).
  - A good moderator: lots of hydrogen (**low** A), so neutrons lose a large fraction of their energy per collision.
  - But its **neutron-capture cross section is high** ($\mathrm{n} + \mathrm{p} \longrightarrow \mathrm{d} + \gamma$).
  - **Therefore the fuel has to be enriched uranium** (≈3–5 %).
- The same water cools the core ("coolant") and, boiling, **drives the turbine directly**.
- **Control rods**: materials with a large neutron-absorption cross section (B, Cd, Hf, Ag–In–Cd, . . .).

BWR — Boiling Water Reactor

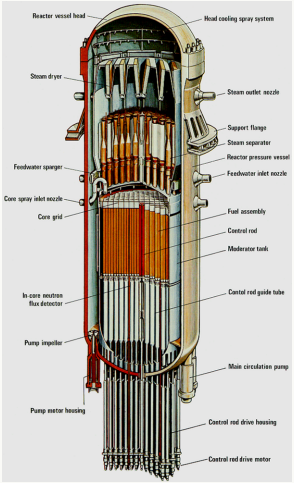


The water itself acts as moderator and coolant and, once boiled and passed through the turbine, generates the electricity.

BWR — Boiling Water Reactor



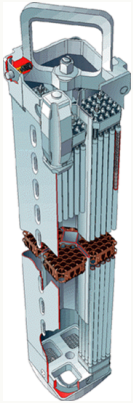
BWR: the reactor core



Thermal power of the core	$\approx 3\,500\,\mathrm{MW_{th}}$
Vessel outer diameter	$\approx 6\,\mathrm{m}$
Vessel outer height	$\approx 22\,\mathrm{m}$
Vessel wall thickness	$\approx 15\,\mathrm{cm}$
Coolant flow	$\approx 13\,000\,\mathrm{kg/s}$
Feedwater temperature	$\approx 215\,^{\circ}\mathrm{C}$
Steam temperature (outlet)	$\approx 286\,^{\circ}\mathrm{C}$
Pressure	$\approx 7\,\mathrm{MPa}$ ($\approx 70\,\mathrm{atm}$)

Control rods are inserted from below (hydraulically, under pressure): the top of the vessel is occupied by the steam separators and dryers.

BWR: fuel



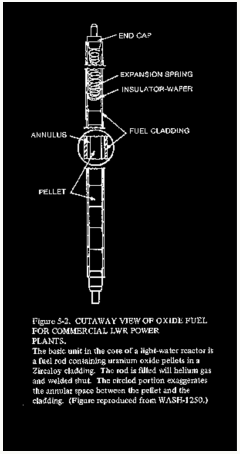
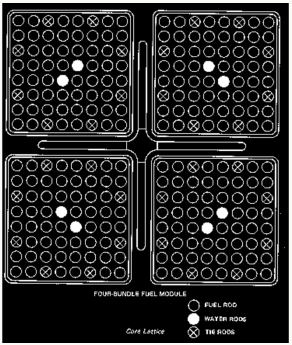


Figure 5-2. CUTAWAY VIEW OF OXIDE FUEL FOR COMMERCIAL LWR POWER PLANTS.
The basic unit in the core of a light-water reactor is a fuel rod containing uranium oxide pellets in a Zircaloy cladding. The rod is filled with helium gas and welded shut. The circled portion exaggerates the annular space between the pellet and the cladding. (Figure reproduced from WASH-1250.)

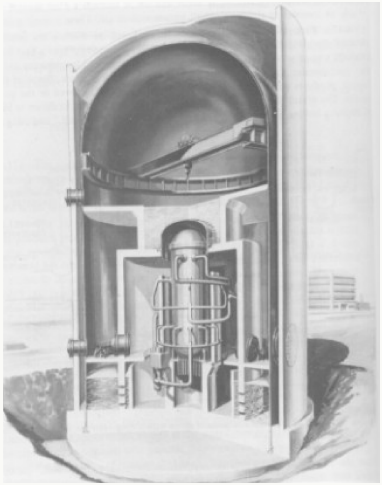


Four fuel assemblies around a cruciform control blade

UO_2 pellets: diameter	1.04 cm
height	1.04 cm
Number of assemblies	746
Active length	3.6 m
Total number of fuel rods	46 376
Fuel mass	155 000 kg
Number of control rods	177
Fuel temperature (centre)	1 820 °C
Melting point of UO_2	2 865 °C

Pellets are stacked in **Zircaloy** cladding tubes, filled with helium and welded shut.

The containment building



- The reactor is enclosed in a **containment building** — steel and reinforced concrete — for safety: the last barrier between radioactive material and the environment.
- Barriers in series: fuel matrix → cladding → reactor vessel → containment.
- BWRs operate mainly in the USA and Japan (Germany shut down its last reactors in April 2023). Today most LWRs are PWRs, with comparatively few BWRs.

Thermal power vs electrical power

- MW_{th} (megawatt thermal): total heat produced in the core.
- The electrical output is about **one third** of it: a $3\,500\,MW_{th}$ reactor delivers $\approx 1\,200\,MW_e$.
- The rest goes to the condenser and cooling towers (or to a river or the sea) — hence the size of the cooling systems of any thermal power station.
- Why heat the feedwater to $\approx 215\,^\circ C$? Preheating with steam bled from the turbine raises the average temperature at which heat is added, and so the efficiency.

The Carnot limit

$$\eta_{max} = 1 - \frac{T_C}{T_H}$$

BWR steam at $286\,^\circ C$ ($T_H = 559\,K$), condenser at $30\,^\circ C$ ($T_C = 303\,K$):

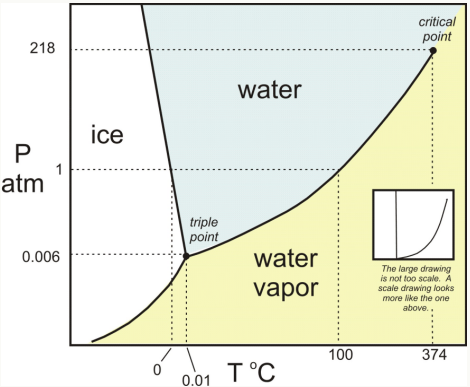
$$\eta_{max} \approx 46\%$$

Real plants: ≈ 33–37%.

Coal and gas plants run hotter (supercritical steam at $\sim 600\,^\circ C$): $\eta \approx 45\%$.

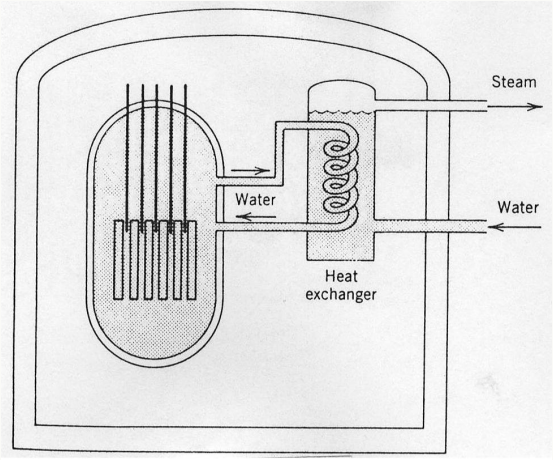
PWR — Pressurised Water Reactor

- The moderator is also **liquid water** — so the fuel is also enriched uranium.
- Water is moderator and coolant, **but is not used directly to produce electricity**.
- The water **does not boil**: it is kept under high pressure, in a closed circuit through the core (the *primary circuit*). A steam generator transfers the heat to a *secondary circuit*, which drives the turbine.



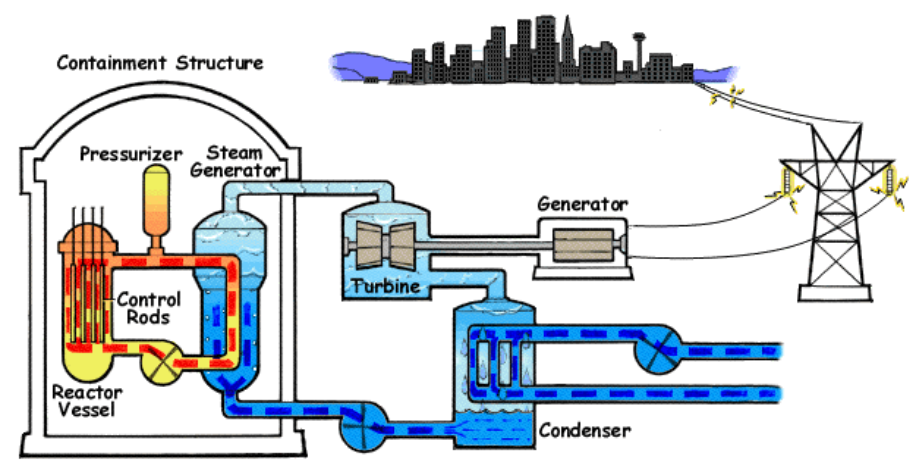
Phase diagram of water: at 15.5 MPa water is still liquid at 325 °C

PWR — Pressurised Water Reactor

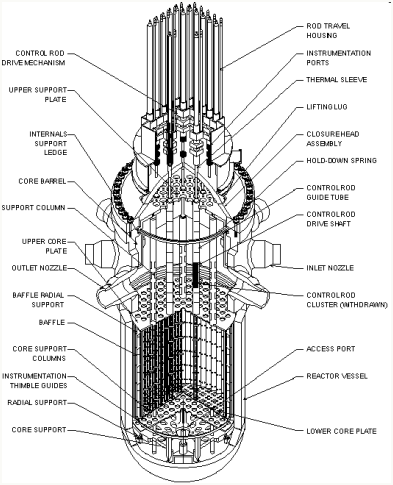


- Since the water of the primary circuit never leaves the containment, **radioactive contamination by impurities in the water** (dangerous even at the parts-per-million level) does not reach the turbine.
- The PWR vessel is smaller than that of a BWR.
- Simpler, more stable operation (no boiling in the core).
- The most widely used reactor in the world: USA, France, China, Russia, Japan, South Korea, United Kingdom, ...

PWR — Pressurised Water Reactor

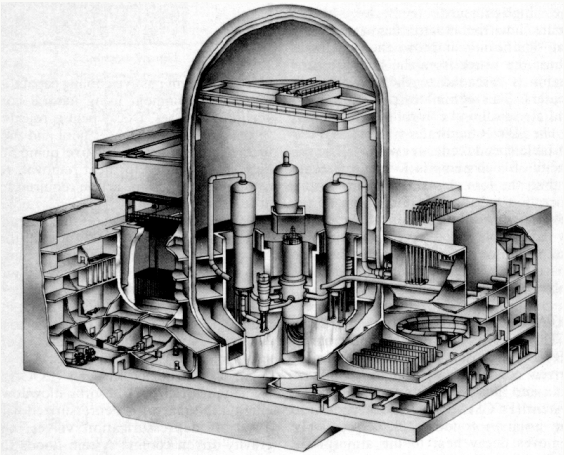


PWR: the reactor vessel



- **Control rods are inserted from above.**
- Greater safety: they are held by electromagnets — if the power fails, they drop into the core. Gravity always works...
- **Refuelling**: every 18–24 months, about 1/3 of the fuel is replaced.

PWR: size and pressure



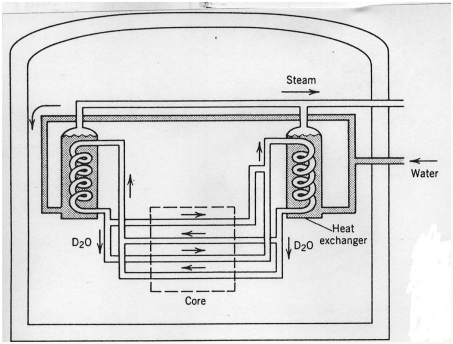
Vessel diameter	$\approx 4.5\,\mathrm{m}$
Vessel height	$\approx 13\,\mathrm{m}$
Pressure	$\approx 15.5\,\mathrm{MPa}$ (150 atm)
Water temperature	290–325 °C

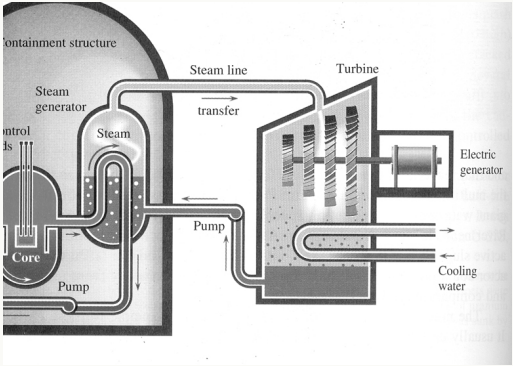
- The **smaller size** allows PWRs to be used for **propulsion**: submarines (an *Ohio*-class submarine is 170 m long) and aircraft carriers.
- The pressure is higher to keep the water liquid. Liquid water transfers heat far better than steam and, being denser, moderates better.

PHWR — Pressurised Heavy Water Reactor (CANDU)

- The moderator is **heavy water**, D_2O.
  - A very good moderator: deuterium has **low** A and, above all, a **very low neutron-capture cross section** ($\mathrm{n} + \mathrm{d} \longrightarrow \mathrm{t} + \gamma$ — the tritium produced is radioactive...).
  - Consequently, the fuel can be **natural uranium**.
- The coolant can be heavy water itself or ordinary water; otherwise they work on the same principle as PWRs.
- Fuel is in hundreds of horizontal pressure tubes inside a low-pressure moderator tank (*calandria*): they can be **refuelled while running**.
- Heavy water is expensive and difficult to produce (but so is enriched uranium).

PHWR — Pressurised Heavy Water Reactor

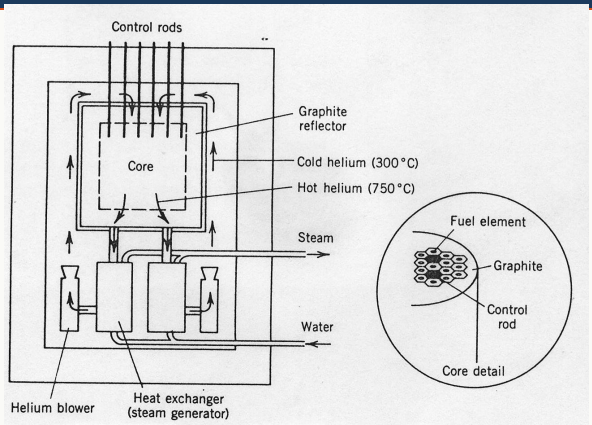




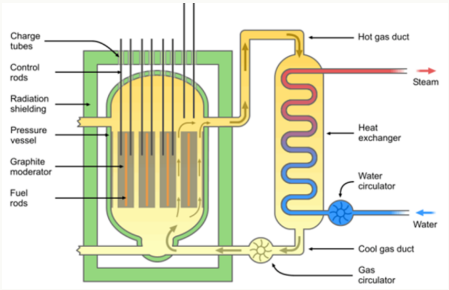
AGR — Advanced Gas-cooled Reactor

- The moderator is **graphite**.
  - A good moderator: **low** A and a **low neutron-capture cross section**.
  - But graphite, a solid, cannot be both moderator and coolant.
- The coolant is a gas (CO_2, or helium in other designs) — not dense enough to act as a moderator.
- The earlier Magnox reactors used natural uranium metal; the AGR uses **slightly enriched UO_2** ($\approx$2.5–3.5 %).
- A British design: the UK is the only country to operate AGRs, now near the end of their lives. (Soviet graphite reactors, the RBMKs, were water-cooled.)

AGR — Advanced Gas-cooled Reactor



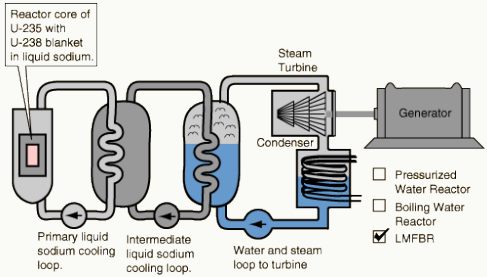
Can be refuelled on load and needs refuelling less often.



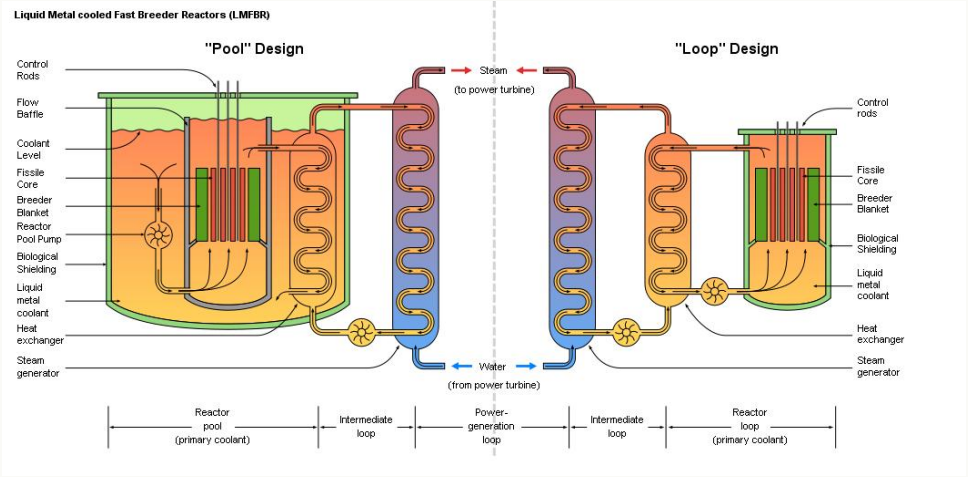
Operates at higher temperatures (gas at $\approx 650\,^{\circ}\mathrm{C}$): efficiency $\approx 41\%$.

LMFBR — Liquid Metal Fast Breeder Reactor

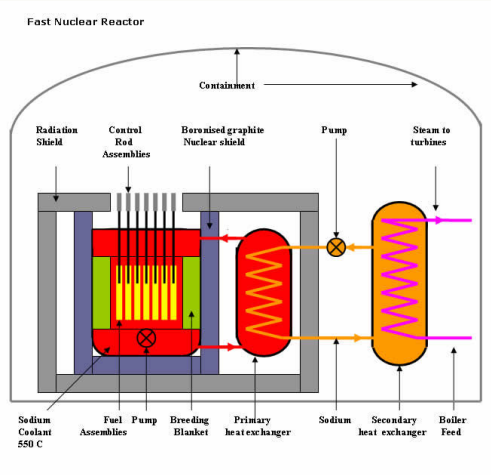
- **No moderator** — the aim is to use fast neutrons.
- Used to produce nuclear fuel ($^{239}\mathrm{Pu}$, $^{233}\mathrm{U}$) from fertile material ($^{238}\mathrm{U}$, $^{232}\mathrm{Th}$), while also producing energy.
- Cooled by a **liquid metal** (typically sodium): excellent heat transfer at atmospheric pressure, but sodium burns in air and reacts violently with water.
- Examples: Phénix and Superphénix (France), BN-600 and BN-800 (Russia).



LMFBR — Liquid Metal Fast Breeder Reactor



Fast reactors and Generation IV



- "Pool" design: the primary sodium circuit sits in one tank; an intermediate loop isolates the radioactive sodium from the water–steam circuit.
- **Generation IV International Forum**, six concepts: sodium-, lead- and gas-cooled fast reactors, very-high-temperature reactors, molten-salt reactors and supercritical-water reactors.
- Goals: much better use of uranium (up to $\sim$60 times more energy per tonne of ore), burning long-lived actinides, passive safety, high-temperature heat for industry.

Problems with nuclear reactors

Problems with nuclear reactors



The Three Mile Island complex (Pennsylvania, USA)

- Operation
- Safety
- Waste
- Decommissioning

Operation

- Costs and risks of **mining** the fuel (uranium).
- Fuel processing (uranium enrichment):
  - **proliferation risks**;
  - a large excess of **depleted uranium**;
  - intrinsic radiation hazards of handling radioactive material.

Tokaimura criticality accident (Japan, 30 September 1999)

- At a fuel-conversion plant, workers preparing fuel for an experimental fast reactor poured $\approx 16\,\mathrm{kg}$ of uranium enriched to 18.8% into a precipitation tank meant for at most $\approx 2.4\,\mathrm{kg}$.
- The solution **went critical**: a chain reaction ran for about 20 hours. Two of the three workers died; several hundred people received measurable doses.
- According to the IAEA, the main causes were human error and serious breaches of safety principles.

Operation: refuelling

- **Refuelling** is periodic, with its own costs and risks:
  - some reactors must be shut down completely to be refuelled (LWRs);
  - others can be refuelled on load (CANDU, AGR, RBMK, ...).
- At the end of each operating cycle the fuel must be replaced. In practice this happens **before all the fissile material is used up**: fission products accumulate and absorb neutrons (*poisons*), until the chain reaction can no longer be sustained.
- The fraction of fuel replaced is about 1/4 in a BWR and 1/3 in a PWR.
- A typical LWR fuel assembly stays 4–6 years in the core and "burns" $\approx$ 4–5% of its heavy atoms.

INES — International Nuclear Event Scale

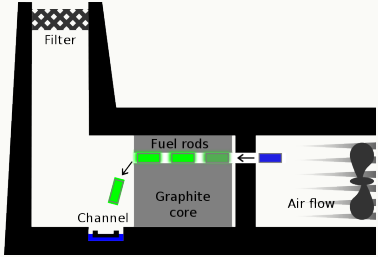
Level		Event	Facility
7	Major accident	Chernobyl (USSR, 1986)	power reactor
		Fukushima (Japan, 2011)	three power reactors
6	Serious accident	Kyshtym (USSR, 1957)	waste tank at a reprocessing plant
5	Wider consequences	Windscale (UK, 1957)	plutonium-production reactor
		Three Mile Island (USA, 1979)	power reactor
4	Local consequences	Tokaimura (Japan, 1999)	fuel plant: criticality accident

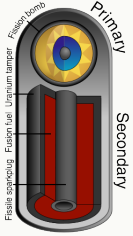
1–3: incidents; 0: deviation. Each level $\approx 10\times$ more severe. Orange: reactors.

- Numerous safety systems, with built-in **redundancy**.
- Causes: human error, design flaws, broken protocols; at Fukushima, a tsunami.
- Accidents also happen in the **fuel cycle**. (INES dates from 1990: older events rated later.)
- Next slides: the four major **reactor** accidents.

Windscale (United Kingdom, 1957)

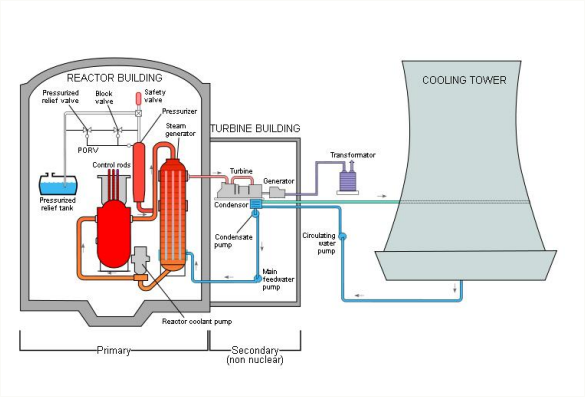
- Windscale (now Sellafield, near Seascale, Cumbria) had two **air-cooled graphite piles**, built to produce plutonium for the first British bomb.
- To regain nuclear cooperation with the USA (formalised in 1958), the UK had to show it could build a **hydrogen bomb**, which needed tritium: $\mathrm{n} + {}^{6}\mathrm{Li} \longrightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He}$. The piles were pushed beyond their design to make it.
- Neutron irradiation displaces carbon atoms in graphite, storing **Wigner energy**, released periodically by controlled heating (annealing).
- During an annealing, on **10 October 1957**, the fuel in Pile 1 caught fire. Radioactivity, notably $\approx 740\,\mathrm{TBq}$ of ${}^{131}\mathrm{I}$, was released; milk from $\sim 500\,\mathrm{km}^2$ was discarded. Clean-up is still going on.





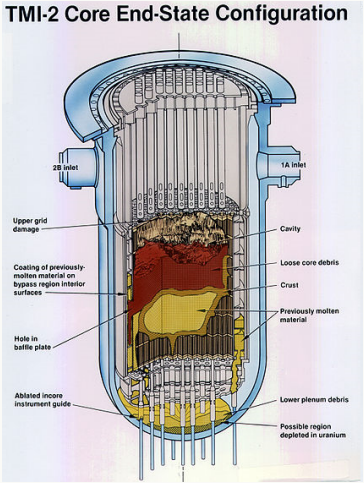
Fusion bomb, or hydrogen bomb (Teller–Ulam design).

Three Mile Island (USA, 1979)



- 28 March 1979: **partial meltdown** of the core of Unit 2 (a PWR).
- Release of $\approx 93\,\mathrm{PBq}$ of radioactive noble gases and $\approx 560\,\mathrm{GBq}$ of the particularly dangerous $^{131}\mathrm{I}$.
- Cause: a relief valve stuck open, while an indicator suggested it had closed. Misreading the situation, operators **reduced the emergency cooling**: technical failure plus human error.

Three Mile Island: what happened to the core

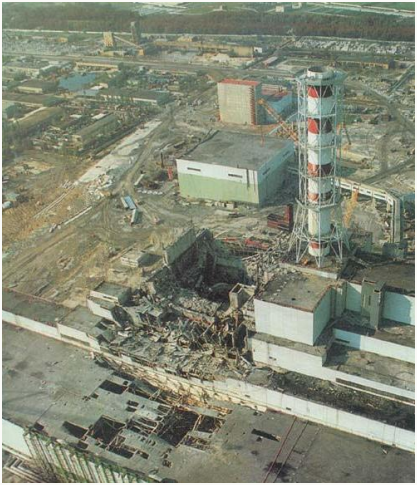


- With coolant escaping, the top of the core was uncovered and overheated.
- Above $\sim 1\,000\,^{\circ}\mathrm{C}$ the **zirconium cladding of the fuel rods reacted with the steam**, releasing more heat and producing **hydrogen**:

$$\mathrm{Zr} + 2\,\mathrm{H_2O} \longrightarrow \mathrm{ZrO_2} + 2\,\mathrm{H_2}$$

- About half of the core melted. Hydrogen accumulated and burnt in the containment (a small explosion).
- The containment held: health consequences outside the plant were very small.

Chernobyl (USSR, 1986)



- 26 April 1986, Unit 4 (RBMK), in Ukraine, then part of the Soviet Union.
- The **worst nuclear accident in history**: a radioactive cloud reached the Soviet Union, Eastern Europe, Scandinavia and the United Kingdom — some **400 times** more radioactive material than the Hiroshima bomb.
- Large areas of Ukraine, Belarus and Russia were heavily contaminated: 116 000 people evacuated in 1986, some 350 000 eventually resettled.
- Two workers died in the explosion; 28 died of acute radiation syndrome within months.

Chernobyl: what happened



Solidified "lava" (corium) under the reactor

Two official explanations — **human error** or **design flaws** in the RBMK. Today: a combination of both.

- During a safety test at low power, the emergency shutdown (*scram*) inserted the control rods **slowly**, and their graphite tips first *added* reactivity at the bottom of the core.
- The power rose to $\sim 30\,\mathrm{GW}$, ten times the nominal value. The fuel disintegrated; a huge **steam explosion** blew off the massive reactor lid and ruptured the cooling channels.
- Air and high temperatures set the **graphite on fire**: radioactive material was carried high into the atmosphere for ten days.

Chernobyl: the physics of the accident

Ingredients

1. **Xenon poisoning**: the reactor had been run at reduced power for hours; to keep it running, operators withdrew almost all control rods.
2. **Positive void coefficient**: in an RBMK the graphite moderates and the water mostly absorbs. Boiling $\Rightarrow$ fewer neutrons absorbed $\Rightarrow$ more power $\Rightarrow$ more boiling.
3. **Positive scram**: the rods had graphite displacers; entering, they first replaced water by graphite at the bottom of the core.

Result: prompt criticality

The added reactivity exceeded the delayed-neutron fraction, $\rho > \beta$: the reactor became **prompt-critical**, with power rising on a time scale of milliseconds — no control system can act that fast.

After 1986 all RBMKs were modified: higher enrichment, more absorbers and faster rods, reducing the void coefficient.

Western LWRs have a negative void coefficient by design: losing water stops the chain reaction.

Pripyat: a ghost town



Pripyat (about 50 000 inhabitants in 1986), with the Chernobyl plant on the horizon

Fukushima (Japan, 2011)



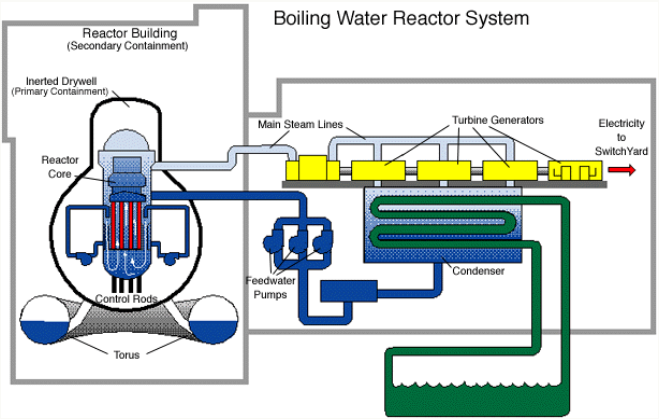
- 11 March 2011: Tōhoku earthquake (magnitude 9.0) followed by a tsunami.
- Fukushima Daiichi, run by TEPCO, on the Pacific coast.
- Rated **level 7** on the INES scale — the same as Chernobyl, but with much smaller releases.

Fukushima Daiichi



- The Fukushima Daiichi complex had **six reactors**.
- Problems occurred in **reactors 1 to 4**.
- Reactors 5 and 6 remained essentially unscathed, although they too had cooling difficulties.
- Reactor 4 was shut down for maintenance, with no fuel in the core (it was all in the spent-fuel pool). It nevertheless suffered a hydrogen explosion — hydrogen that came from reactor 3 through a shared vent line.
- **Anti-tsunami protective wall**: about 6 m high; the tsunami reached 13–15 m.

The Fukushima reactors

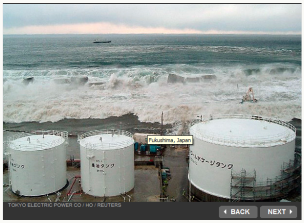


- **BWRs** of a *General Electric* design (Mark I containment), more than 35 years old.
- Unit 1: construction began 1967, in service 1971; Unit 2: 1974; Unit 3: 1976.
- Key elements: **control rods** (from below) and the **water-injection pumps** for cooling.

11 March 2011

Following the earthquake, **all operating reactors shut down safely**. However, the plant was left **without any source of electricity**.







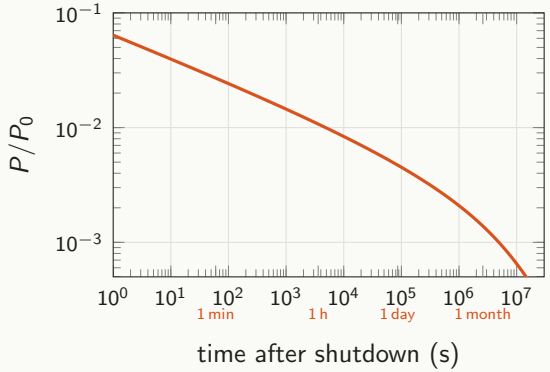


Station blackout

- The reactors shut down normally: the control rods were inserted into the cores, stopping the fission chain reaction.
- The earthquake, however, cut the power lines, isolating the plant from the rest of the Japanese grid.
- The tsunami swept through the site and flooded the **basement rooms with the emergency diesel generators**, designed to power the plant in exactly this kind of emergency. Once flooded, they stopped.
- Batteries lasted only hours.

The reactor cooling systems stopped: the pumps that injected and circulated water through the cores **had no electricity**... But a core that is not producing fission energy still produces heat. How much?

Decay heat: a reactor cannot simply be switched off



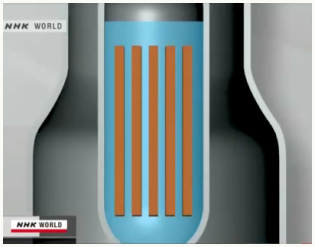
Way–Wigner approximation (t in s, T_0: operating time):

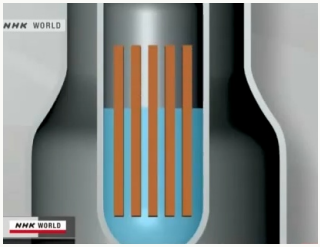
$$\frac{P(t)}{P_0} \approx 0.066 \left[t^{-0.2} - (t + T_0)^{-0.2} \right]$$

2 400 $\mathrm{MW_{th}}$ unit (Fukushima 2–3), 1 year of operation:

t	P	water boiled off
1 s	150 MW	
1 h	26 MW	≈ 40 t/h
1 day	11 MW	≈ 18 t/h
1 week	6 MW	≈ 10 t/h

Fuel uncovered



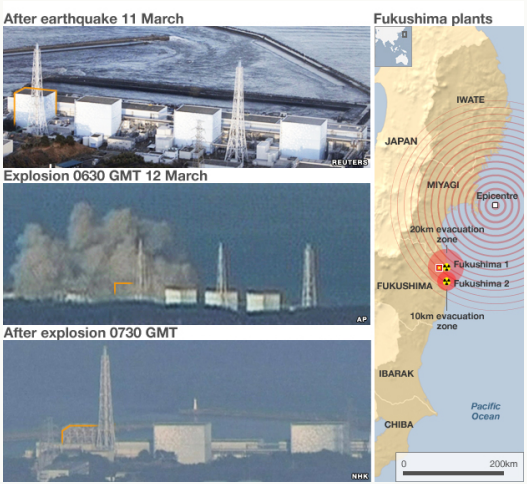


- The consequence: **the water inside the cores boiled away** and the fuel rods were exposed.
- Without cooling, the fuel heats up uncontrollably — **even without fission reactions**.
- Above $\sim 900\,^{\circ}\mathrm{C}$, and violently above $1\,200\,^{\circ}\mathrm{C}$, the zirconium cladding is **oxidised by steam**, releasing heat ($\approx 6\,\mathrm{MJ}$ per kg of Zr) and hydrogen:

$$\mathrm{Zr} + 2\,\mathrm{H_2O} \longrightarrow \mathrm{ZrO_2} + 2\,\mathrm{H_2}$$

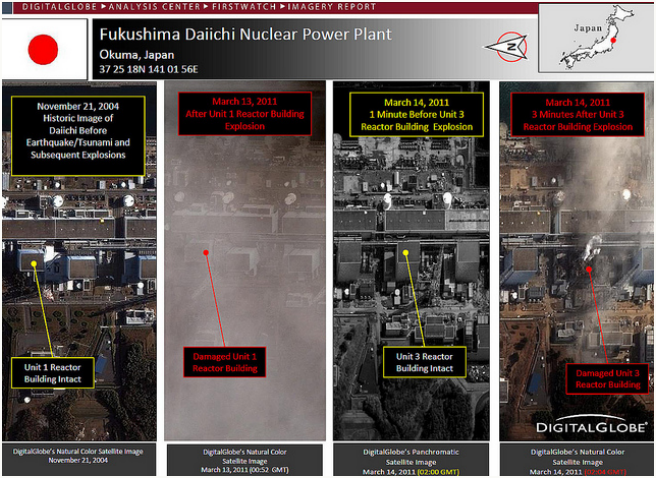
Free hydrogen inside an overheated nuclear reactor is not a good idea!

Venting and hydrogen explosions

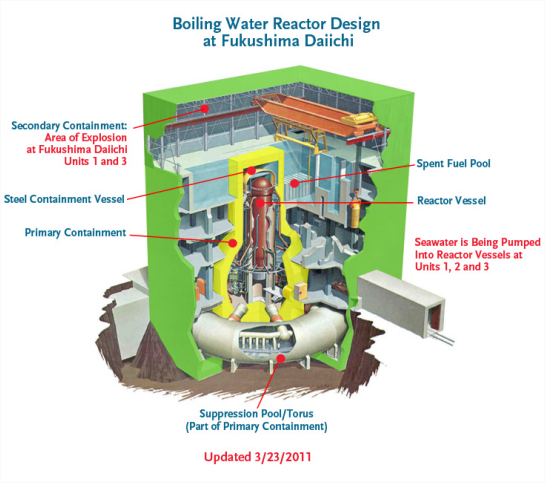


- With hydrogen building up and the pressure rising from the steam, it was decided to **vent** the reactors, letting radioactive steam escape into the atmosphere.
- The hydrogen, mixing with the oxygen of the air in the reactor buildings, caused **large explosions** (units 1, 3 and 4, 12–15 March).

Before and after

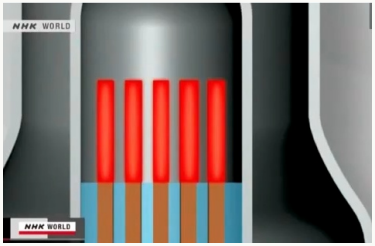


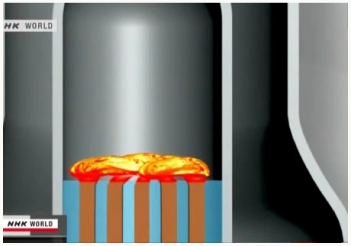
The spent-fuel pools



- The loss of electricity also stopped the **cooling of the spent-fuel pools**, which in a Mark I design sit at the top of the reactor building.
- The spent fuel — still producing decay heat — began to heat up and the pools to evaporate.
- And for the pools there was no redundancy... Water had to be sprayed from outside by helicopters and fire engines.

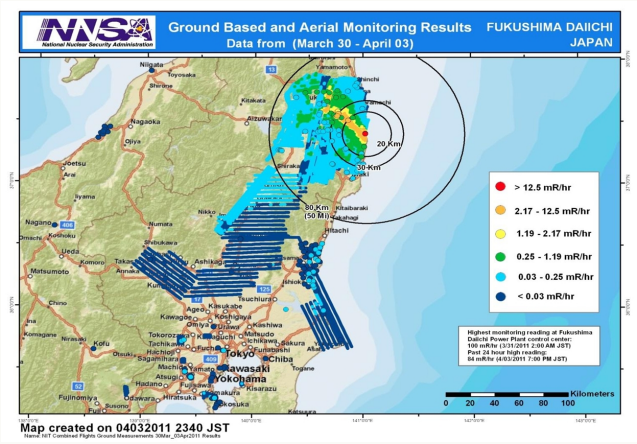
Meltdown





- Without cooling, the fuel heated up until it melted: **core meltdown** (units 1, 2 and 3).
- By then the containments were damaged — by the earthquake, the hydrogen explosions and the molten core itself — and **highly radioactive water** leaked from the bottom of the reactors.
- In a desperate attempt to cool the reactors, **seawater** was injected. This is avoided at all costs: salt ruins the cores, and the water becomes highly radioactive.

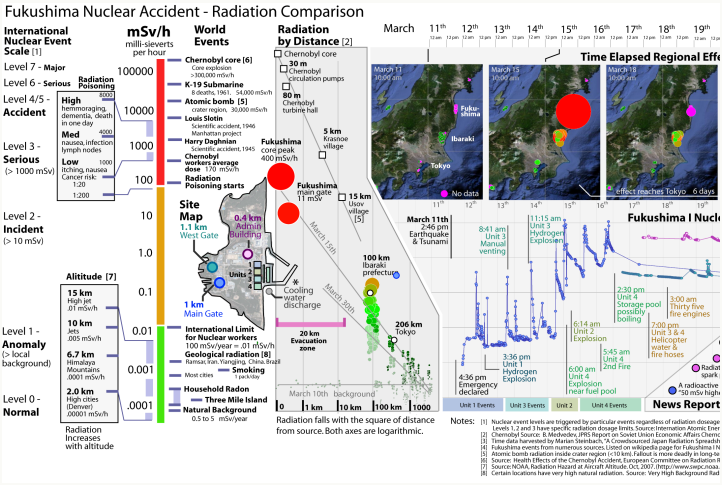
Radioactive releases



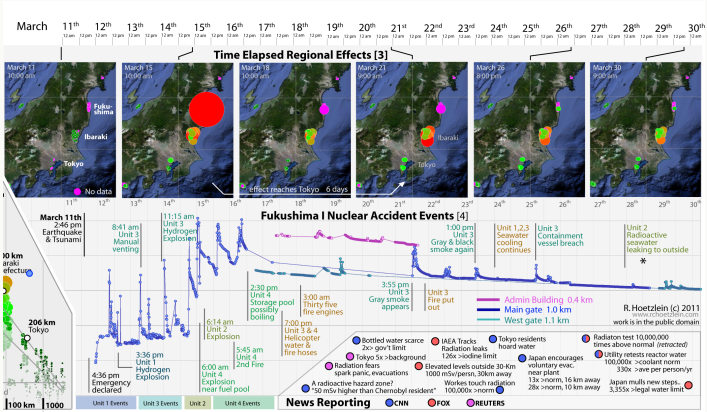
1 mR (10 µSv) ≈ one year living next to a normally operating plant

- Estimates vary, but the releases were about **10–20% of those of Chernobyl**.
- Radioactive isotopes (mainly $^{131}\mathrm{I}$, $^{134}\mathrm{Cs}$, $^{137}\mathrm{Cs}$) were spread over a large area around the plant, and into the ocean.
- The winds carried part of the plume far away, including towards Tokyo (≈14 million inhabitants).

Fukushima: radiation in perspective (I)



Fukushima: radiation in perspective (II)



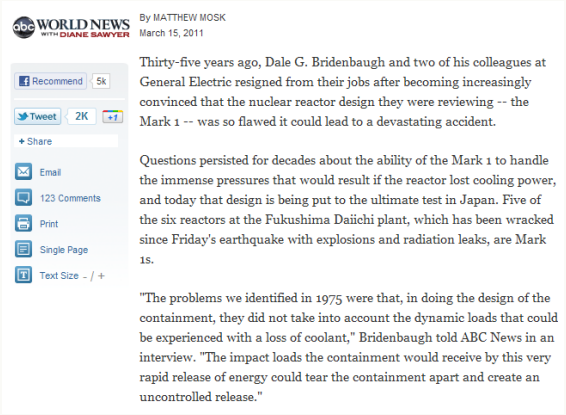
Fukushima: conclusions

- **Not everything went wrong**: the reactors shut down and there was no uncontrolled chain reaction.
- The plant had **multiple, redundant safety systems** — but all depended on electricity, and the sea wall was too low.
- The circumstances were **extreme**: one of the largest earthquakes and tsunamis ever recorded, which killed almost 20 000 people.
- No deaths from acute radiation (one later cancer death of a worker was attributed to radiation in 2018). The evacuation itself was linked to over 2 000 deaths, mostly of elderly people.
- Germany decided to abandon nuclear power (last reactors shut in April 2023). Japan stopped all its reactors, restarting some since 2015.
- Cost (Japanese government, 2016): over **¥21 trillion** (≈\$190 billion) for decommissioning (30–40 years), decontamination and compensation.

Warnings that had been ignored

Many of the problems that occurred at Fukushima — **hydrogen release, poor cooling of the spent-fuel pools, uncontrolled heating in an accident** — had been pointed out years before by critics of nuclear power. And even by *industry insiders*...

In 1976, three General Electric engineers resigned after concluding that the Mark I containment could fail under the loads of a loss-of-coolant accident.



abc WORLD NEWS WITH DIANE SAWYER

By MATTHEW MOSK
March 15, 2011

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Thirty-five years ago, Dale G. Bridenbaugh and two of his colleagues at General Electric resigned from their jobs after becoming increasingly convinced that the nuclear reactor design they were reviewing -- the Mark 1 -- was so flawed it could lead to a devastating accident.

Questions persisted for decades about the ability of the Mark 1 to handle the immense pressures that would result if the reactor lost cooling power, and today that design is being put to the ultimate test in Japan. Five of the six reactors at the Fukushima Daiichi plant, which has been wracked since Friday's earthquake with explosions and radiation leaks, are Mark 1s.

"The problems we identified in 1975 were that, in doing the design of the containment, they did not take into account the dynamic loads that could be experienced with a loss of coolant," Bridenbaugh told ABC News in an interview. "The impact loads the containment would receive by this very rapid release of energy could tear the containment apart and create an uncontrolled release."

Waste

- Normal reactor operation produces **highly radioactive waste**: of the order of 10 000 t of spent fuel per year worldwide.
- Spent fuel can be **reprocessed** (France does so; the USA does not):
  - extraction of plutonium and uranium, reused as fuel (MOX);
  - extraction of radioactive isotopes for medical and industrial use.
- Every treatment of spent fuel still leaves **highly radioactive waste**.
- This waste has to be **stored safely**.

Waste categories

Low- and intermediate-level waste: most of the volume, little of the radioactivity. High-level waste: about **3% of the volume but 95% of the radioactivity**.

Storing waste for geological times

- Most reactors **store spent fuel on site** for some time: first in pools, then in dry casks.
  - *This avoids the problems of transporting radioactive waste...*
- Ultimately the waste must be kept in places specifically designed to isolate it for **geological timescales**:
  - some isotopes in high-level waste have half-lives of tens of thousands, or even millions, of years ($^{239}\mathrm{Pu}$: 24 000 yr; $^{129}\mathrm{I}$: 1.6×10^7 yr);
  - **safety: which engineering works can guarantee their integrity over such periods?**
- Deep mines or galleries built for the purpose: is the geology stable? Can the water tables be contaminated?

Geological repositories: a failure and a first



Schacht Asse II (Germany)

A former salt mine where about 126 000 drums of low- and intermediate-level waste were placed between 1967 and 1978 as a "pilot project". The mine is unstable and **saline water flows in**. The waste is to be retrieved — an operation now planned to begin only in **2033**.

Onkalo (Olkiluoto, Finland)

The world's first deep geological repository for spent fuel: copper canisters in crystalline bedrock at about 430 m depth. In 2026 the Finnish safety authority (STUK) concluded there is no obstacle to an operating licence; Posiva aims to be ready to begin disposal by the end of 2026.

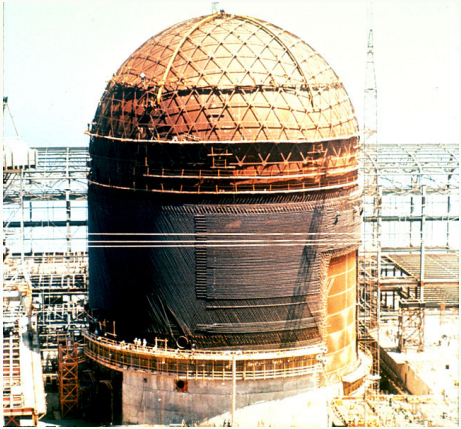
Decommissioning

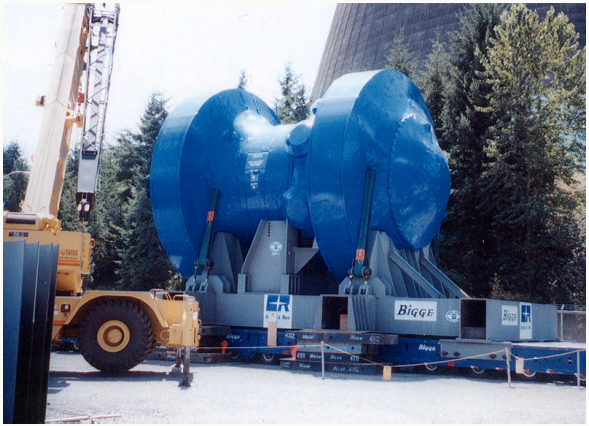
- What do we do with a reactor when it stops operating?
  - **Original design lives**: 30–40 years.
  - **Today**: many reactors licensed for 60 years (some in the USA for 80); new designs aim at 60+ years.
- The plant cannot simply be dismantled: not only the fuel but **all the surrounding materials are radioactive** (neutron activation).
  - A **lengthy** process: in many cases 30–40 years are allowed to pass before dismantling starts ("safe storage").
  - A **very expensive** process: from 100–800 million euros per reactor — often more.
- A **serious problem**, with costs that must be taken into account in the economic debate on nuclear power.

Decommissioning

- A technical but also administrative process, considered complete when the site can be released from regulatory control — **free of radiation** above natural levels.
- It essentially consists of the clean-up of radioactive materials and the demolition of the plant.
- The International Atomic Energy Agency defines three strategies:
  1. **immediate dismantling**;
  2. **deferred dismantling** ("safe store"), after decades of waiting for short-lived activity to decay;
  3. **entombment**: the plant is sealed in place — it must be prepared for this purpose.
- Most reactors in the world have not yet reached the end of their lives. This problem will soon become **central worldwide**.

Decommissioning in practice





Summary

- A reactor is a chain reaction held at $K = 1$, with $K = \eta\,\varepsilon\,p\,f\,P_{\mathrm{NL}}$.
- Enrichment, moderator and geometry decide whether K can reach 1; control rods hold it there.
- **Delayed neutrons** make control possible; **negative feedback** makes it robust.
- Water reactors (PWR, BWR) dominate; heavy-water and graphite designs can use less enriched fuel; fast reactors can breed.
- The accidents had different causes: a graphite fire, a stuck valve, a prompt-critical excursion, a loss of power. A common thread: **heat must always be removed**, even after shutdown.
- Waste and decommissioning are long-term, costly problems.

The cost/benefit of a nuclear reactor has to take all these factors into account.